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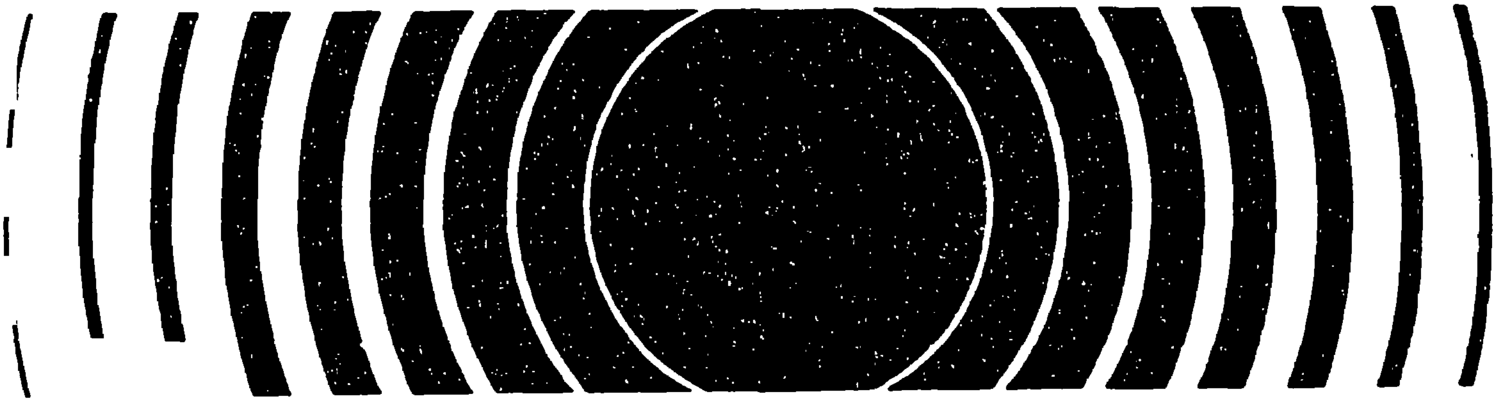
Indoor Radon And Radon Decay Product Measurement Device Protocols



ERRATA SHEET

October 28, 1992

The document "Indoor Radon and Radon Decay Product Measurement Device Protocols" can be purchased through the National Technical Information Service (NTIS) for $26 (microfiche $12.50). The sales phone number for NTIS is 703-487-4650, and the NTIS reference number is PB-92-206-176 (the EPA number is EPA-402-R-92-004).

On page 2-3, section 2.1.7.2, the sentence, "The CR monitor should be programmed to run continuously, recording periodically (hourly or more frequently) the radon concentration for at least 48 hours" should be changed to "The CR monitor should be programmed to run continuously, recording periodically the radon concentration for at least 48 hours."

The document listed in the reference section as "Protocols for Radon and Radon Decay Product Measurements in Homes" is not a final document as of November 5, 1992. It should be listed as (Summer Draft) "Protocols for Radon and Radon Decay Product Measurements in Homes."

EPA-402-R-92-004

INDOOR RADON
AND
RADON DECAY PRODUCT
MEASUREMENT DEVICE PROTOCOLS

July 1992

Prepared for:

U.S. Environmental Protection Agency
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Washington, D.C. 20460

CONTENTS

Section 1: GENERAL CONSIDERATIONS

Section 2: INDOOR RADON MEASUREMENT DEVICE PROTOCOLS

Section 3: INDOOR RADON DECAY PRODUCT MEASUREMENT DEVICE PROTOCOLS

LIST OF EXHIBITS

Exhibit Number and Title Page

DISCLAIMER

Mention of trade names or commercial products in this document does not constitute EPA endorsement or recommendation for their use.

ACKNOWLEDGEMENTS

This document represents the cumulative efforts of many dedicated individuals within the radon measurement community and the U.S. Environmental Protection Agency. Several key components of this document were prepared by the authors acting as interpreters of the substantial field experience and technical knowledge provided by these individuals, and their assistance is gratefully acknowledged.

SIGNIFICANT CHANGES IN THIS REVISION

This protocol document updates and supersedes the U.S. Environmental Protection Agency (EPA) document entitled, "Indoor Radon and Radon Decay Product Measurement Protocols," and issued in March, 1989 (U.S. EPA 1989a). The updating reflects new information, new procedures, and new measurement devices, including a new interim protocol for unfiltered track detectors. The EPA's testing recommendations are summarized in Section 1.2. This measurement strategy reflects the changes made in the most recent edition of "A Citizen's Guide to Radon" (U.S. EPA 1992a). More information is also provided in the EPA measurement guidance document, "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c). Guidance on radon measurements in schools and for real estate transactions is also available (U.S. EPA 1989b, 1992b).

This edition contains some clarifications and new information on quality assurance. The addition of a Glossary provides definitions and formulas for several of the technical terms used in the document, including accuracy, precision, and the values used to quantify these parameters.

The two previous editions of these protocols (U.S. EPA 1986, 1989a) used the value coefficient of variation (COV), defined as the standard deviation divided by the mean, as the expression used for the goal (at 4 pCi/L or 0.02 WL) of 10 percent for precision. The COV should decrease with increasing concentration. This edition explains that there is a variety of ways to calculate and express precision, including the COV and the relative percent difference, defined as the difference between two duplicates divided by their mean. It is important to monitor precision over the entire range of radon levels that are encountered routinely in the measurement program, and that a systematic and documented method for evaluating changes in precision be part of the standard operating procedures. While a limited precision error is desirable (e.g., COV of $\leq$ 10% at 4 pCi/L), it is most important to maintain the total error of any individual device (including both errors in precision and accuracy) to within ± 25 percent of the "true" radon or decay product concentration for concentrations at or above 4 pCi/L (0.02 Working Levels when the equilibrium ratio is 0.5).

To limit errors in accuracy, this edition recommends that users calibrate their measurement systems at least once every 12 months. Participation in the National Radon Measurement Proficiency (RMP) Program will not satisfy the need for annual calibration, as this Program is a performance test, not a calibration procedure.

The 1986 and 1989 versions of the measurement protocols recommended that known exposure measurements, or spikes, be conducted at a rate of a few percent of the total number of measurements. These measurements are those for which the detectors are exposed to a known radon concentration in a calibration chamber and analyzed routinely. The results are used to monitor the accuracy of the entire system. This edition clarifies this recommendation, specifying that spikes be conducted at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. This reduces the number of spikes necessary for large users and clarifies the need for spikes by all users.

A significant change in this version of the Measurement Protocols is the requirement that all devices used for measurements in homes, schools, or workplaces be deployed for a minimum of 48 contiguous hours. It is important to understand that this minimum measurement period applies to all cases when the result of the measurement is given to a homeowner or building official to determine the need for further measurements or remedial action. The exceptions to the 48-hour measurement period are for those cases when the results will not be reported to a homeowner or building official, but will be used by a mitigator or researcher within the context of their project or research. For example, in-progress diagnostic measurements made in the process of performing mitigation can help to determine points of radon influx. Results of these measurements will be used to assist the contractor to better understand the dynamics of radon within that building, and will be part of a series of measurements, including pre- and post-mitigation 48-hour measurements. Radon researchers testing the effects of mitigation techniques, measurements methods, or strategies may also need to perform measurements of flexible durations.

The Agency has implemented a requirement for a minimum measurement period for several reasons. First, it will help ensure consistency among measurement programs, thereby ensuring that measurement results of at least a minimum quality become the basis for decisions by homeowners, school officials, and others responsible for authorizing further measurements or mitigation. This will become increasingly important as radon is measured in more and different types of buildings, and as a more diverse group of people, many without technical backgrounds, find the need to compare and understand these results. Second, a minimum measurement period will guarantee that a certain number of hours, including daily radon cycles, will be incorporated into the result reported to the persons responsible for making a decision about that building.

A period of 48 hours for the minimum measurement period is a policy decision that was arrived at after careful scrutiny of the possible options. It is important that the complete measurement result includes the effects of daily fluctuations in radon levels, so the minimum period needed to be a multiple of a 24-hour day. The Agency deems a single 24-hour period as too short because of the possibility of unforeseen circumstances occurring during the 24 hours; this possibility is diminished if two 24-hour periods form the duration of the measurement. One possible unforeseen circumstance is the improper implementation of closed-building conditions. A longer measurement period increases the chance of identifying such occurrences and helps minimize their impact. Finally, it was deemed important to include two daily cycles so that periods of low and high radon concentrations are well represented in the overall result.

There may be some situations when it is impossible to terminate the measurement at exactly 48 hours; therefore, a grace period of two hours will be allowed. A measurement made over a period of at least 46 hours is sufficient and is considered a two-day measurement. This grace period applies to all measurement methods.

Concerns have been raised regarding the requirement of a minimum distance of 30 inches from the floor for placement of detectors. The change from 20 inches to 30 inches was made in the March 1989 Protocols (U.S. EPA 1989a). This distance is not thought to be critical, so this version again recommends a minimum distance of at least 20 inches. In addition, the 1989 edition was not specific regarding the minimum distance between the measurement location and an exterior wall; this revision clarifies that distance to be about one meter, or three feet. Suspended detectors should also be about six to eight feet above the floor (i.e., within the general breathing zone).

Sections 2.6 (Evacuated Scintillation Cells), 2.7 (Pump/Collapsible Bags), and 2.8 (Radon Grab Sampling) of the previous protocol document (U.S. EPA 1989a) describe methods that share common features. For this reason, the three measurement methods are combined into one section in this revision. In addition, the Appendices A and B of the previous document are now part of their corresponding protocols. The radon grab sampling and pump/collapsible bags methods are not appropriate for purposes of determining the need for further measurements or for mitigation because they do not comply with the 48-hour minimum measurement period.

This revision also reflects the method designations used in the National RMP Program. 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. The new designations are as follows:

RADON AND RADON DECAY PRODUCT MEASUREMENT METHODS

METHOD CATEGORY	Abbreviations	
	Common	RMP Method
Continuous Radon Monitors	CRM	CR
Alpha Track Detectors	ATD	AT
Electret Ion Chambers	EIC/EC	
Short Term		ES
Long Term		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		GS
Activated Charcoal		GC
Pump-Collapsible Bag		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 1: GENERAL CONSIDERATIONS

1.1 INTRODUCTION AND BACKGROUND

The risk of lung cancer due to exposure to radon and its decay products is of concern to State and Federal health officials. There is increased awareness that indoor radon concentrations may pose a significant health threat, and that there are areas in the country where some indoor levels are such that even short-term exposures can cause a significant increase in risk. It is extremely important that homes and other buildings be tested to determine if elevated radon levels are present indoors. However, in the process, the collection of unreliable or misleading data must be avoided.

There are many Federal, State, university, and private organizations now performing measurements or planning measurement programs. It is important for these different groups to follow consistent procedures to assure accurate and reproducible measurements, and to enable valid intercomparison of measurement results from different studies.

The objective of this document is to provide information, recommendations, and technological guidance for anyone providing measurement services using 15 radon and radon decay product measurement methods. The EPA has evaluated these techniques and found them to be satisfactory. However, the Agency has not conducted large-scale field tests using the unfiltered track detection technique, and an interim protocol has been prepared with the assistance of researchers who have field experience with this method. As the EPA and others acquire more experience with this interim technique, the guidelines may be revised.

These Protocols provide method-specific technological guidance that can be used as the basis for standard operating procedures. In keeping with good laboratory practices, each radon measurement company should develop its own detailed instrument-specific procedures that incorporate recommendations found in this and other radon-related EPA protocol and guidance documents. Mere duplication of sections of this report will not constitute an adequate standard operating procedure.

The recommendations contained in this report are similar to those being developed by industry and other groups (e.g., the American Society of Testing and Materials [ASTM 1991] and the American Association of Radon Scientists and Technologists [AARST 1991a]). This report is a guidance document; however, one condition of participation in the EPA National Radon Measurement Proficiency (RMP) Program is conformance with these protocols.

1.2 GENERAL GUIDANCE ON MEASUREMENT STRATEGY, MEASUREMENT CONDITIONS, DEVICE LOCATION SELECTION, AND DOCUMENTATION

1.2.1 Measurement Strategy

The choice of measurement strategy depends upon the purpose of the radon measurement and the type of building where the measurement is made, such as a home, school or workplace. EPA's recommendations for measuring radon in various situations are outlined in documents such as the second edition of "A Citizen's Guide to Radon" (U.S. EPA 1992a), the EPA "Home Buyer's and Seller's Guide to Radon" (U.S. EPA 1992b), the "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c), and in "Radon Measurements in Schools: An Interim Report" (U.S. EPA 1989b). The following discussion on measurement conditions, device location selection, and documentation apply to measurements made in all types of buildings.

1.2.2 Measurement Conditions

The following conditions should exist prior to and during a measurement period to standardize the measurement conditions as much as possible. This list may be applied to each of the measurement methods discussed in Sections 2 and 3. However, there may also be method-specific conditions that are mentioned in the applicable protocol.

- Short-term measurements lasting 90 days or less should be made under closed-building conditions. To the extent reasonable, all windows, outside vents, and external doors should be closed (except for normal entrance and exit) for 12 hours prior to and during the measurement period. Normal entrance and exit includes opening and closing a door, but an external door should not be left open for more than a few minutes. These conditions are expected to exist as normal living conditions during the winter in northern climates. For this reason, short-term measurements should be made during winter periods whenever possible.

- 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 of up to a week in duration.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operating during measurements and for at least 12 hours before measurements are initiated. Air conditioning systems that recycle interior air may be operating. Normal operation of permanently installed air-to-air heat exchangers may also continue during closed-building conditions.

- In buildings where permanent radon mitigation systems have been installed, these systems should be functioning during the measurement period.

- Short-term tests lasting just two or three days should not be conducted if severe storms with high winds (e.g., > 30 mph) or rapidly changing barometric pressure are predicted during the measurement period. Weather predictions available on local news stations can provide sufficient information to determine if these conditions are likely.

- In southern climates, or when measurements must be made during a warm season, the closed-building conditions are satisfied by meeting the criteria listed above. The closed-building conditions must be verified and maintained more rigorously, however, when they are not the normal living conditions.

1.2.3 Measurement Device Location Selection

The following criteria should be applied to select the location of the detector within a room. For further guidance on selecting an appropriate area in a building in which to place the measurement device, the reader should refer to the relevant documents mentioned in section 1.2.1. The following list may be applied to each of the measurement methods discussed in Sections 2 and 3. However, there may be method-specific location criteria that will be mentioned in the applicable protocol.

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

- The measurement should not be made near drafts caused by heating, ventilating and air conditioning vents, doors, fans, and windows. Locations near excessive heat, such as fireplaces or in direct sunlight, and areas of high humidity should be avoided.

- The measurement location should not be within 90 centimeters (3 feet) of windows or other potential openings in the exterior wall. If there are no potential openings (e.g., windows) in the exterior wall, then the measurement location should not be within 30 centimeters (1 foot) of the exterior walls of the building.

- The detector should be at least 50 centimeters (20 inches) from the floor, and at least 10 centimeters (4 inches) from other objects. For those detectors that may be suspended, an optimal height for placement is in the general breathing zone, such as 2 to 2.5 meters (about 6 to 8 feet) from the floor.

- In general, measurements should not be made in kitchens, laundry rooms, closets, or bathrooms.

1.2.4 Documentation

The operator of the measurement device must record enough information about the measurement in a permanent log so that data interpretation and comparison can be made.

The results of radon decay product measurements should be reported in Working Levels (WL). If the WL value is converted to a radon concentration which is also reported to a homeowner, it should be stated that this approximate conversion is based on a 50 percent equilibrium ratio. In addition, the report should indicate that this ratio is typical of the home environment, but any indoor environment (especially in schools and workplaces) may have a different and varying relationship between radon and decay products.

The following list may be applied to each of the measurement methods discussed in Sections 2 and 3. However, there may be method-specific documentation requirements that will be mentioned in the applicable protocol.

- The start and stop times and dates of the measurement;
- Whether the standardized measurement conditions, as discussed in Section 1.2.2, are satisfied;
- The exact location of the device, on a diagram of the room and building if possible;
- Other easily obtained information that may be useful, such as the type of building and heating system, the existence of a crawl space or basement, the occupants' smoking habits, and the operation of humidifiers, air filters, electrostatic precipitators, and clothes dryers;
- The serial number and manufacturer of the detector, along with the code number or description which uniquely identifies customer, building, room, and sampling position; and
- The condition (open or closed) of any crawl space vents.

1.3 QUALITY ASSURANCE

The objective of quality assurance is to ensure that data are scientifically sound and of known precision and accuracy. This section discusses the four general categories of quality control measurements; specific guidance is provided for each method in the relevant section.

Anyone providing measurement services using radon and radon decay product measurement devices should establish and maintain quality assurance programs. 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. The EPA offers general guidance on preparing quality assurance plans (U.S. EPA 1980); a draft standard prepared by a radon industry group is also available (AARST 1991b). The quality assurance program should include the maintenance of control charts and related statistical data, as described by Goldin (Goldin 1984) and by the EPA (U.S. EPA 1984).

1.3.1 Calibration Measurements

Calibration measurements are samples collected or 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.

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. Providers of passive measurement devices should conduct spiked measurements at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Providers of measurements with active devices are required to recalibrate their instruments at least once every 12 months. Participation in the EPA National RMP Program will not satisfy the need for annual calibration, as this Program is a performance test, not a calibration procedure.

1.3.2 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 act as a check on instrument operation.

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 and is discussed in the section for each method.

1.3.3 Duplicate (Collocated) 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 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 should be side-by-side measurements made in at least 10 percent of the total number of measurement locations, or 50 each month, whichever is smaller. The locations selected for duplication should be distributed systematically throughout the entire population of samples. Groups selling measurements to homeowners can do this by providing two measurements, instead of one, to a random selection of purchasers, with the measurements made side-by-side. As with spiked samples introduced into the system as blind measurements, the precision of duplicate measurements should be monitored and recorded in the quality assurance records. The analysis of data from duplicates should follow the methodology described by Goldin in section 5.3 of his report and plotted on range control charts (Goldin 1984, U.S. EPA 1984). 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.

1.3.4 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, battery, or electronics) should be checked regularly and the results noted in a log. Each user should develop methods for regularly monitoring (preferably daily) their measurement system, and for recording and reviewing results.

The EPA established the National RMP Program to enable participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. One condition of successful participation in this Program is that the total error of any individual device (including both errors in precision and accuracy) be within ±25 percent of the "true" radon or radon decay product concentration at or above 4 pCi/L. For further information, please contact:

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

Section 2: INDOOR RADON MEASUREMENT DEVICE PROTOCOLS

2.1 PROTOCOL FOR USING CONTINUOUS RADON MONITORS (CR) TO MEASURE INDOOR RADON CONCENTRATIONS

2.1.1 Purpose

This protocol provides guidance for using continuous radon monitors (CR) to measure indoor radon concentrations accurately and to obtain reproducible results. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid comparison of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.1.2 Scope

This protocol covers, in general terms, the sample collection and analysis method, the equipment needed, and the quality control objectives of measurements made with CRs. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency, Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street S.W., Washington, D.C. 20460.

2.1.3 Method

There are three general types of CR monitors covered by this protocol. In the first type, ambient air is sampled for radon in a scintillation cell after passing through a filter that removes radon decay products and dust. As the radon in the cell decays, the radon decay products plate out on the interior surface of the scintillation cell. Alpha particles produced by subsequent decays, or by the initial radon decay, strike the zinc sulfide coating on the inside of the scintillation cell, thereby producing scintillations. The scintillations are detected by a photomultiplier tube in the detector which generates electrical pulses. These pulses are processed by the detector electronics and the data are usually stored in the memory of the monitor where results are available for recall or transmission to a data logger or printer.

This type of CR monitor uses either a flow-through cell or a periodic-fill cell. In the flow-through cell, air is drawn continuously through the cell by a small pump. In the periodic-fill cell, air is drawn into the cell once during each pre-selected time interval; then the scintillations are counted and the cycle repeated. A third variation operates by radon diffusion through a filter area with the radon concentration in the cell varying with the radon concentration in the ambient air, after a small diffusion time lag. The concentrations measured by all three variations of cells lag the ambient radon concentrations because of the inherent delay in the radon decay product disintegration process.

A second type of CR monitor operates as an ionization chamber. Radon in the ambient air diffuses into the chamber through a filtered area so that the radon concentration in the chamber follows the radon concentration in the ambient air with some small time lag. Within the chamber, alpha particles emitted during the decay of radon atoms produce bursts of ions which are recorded as individual electrical pulses for each disintegration. These pulses are processed by the monitor electronics; the number of pulses counted is displayed usually on the monitor, and the data are available usually for processing by an optional data logger/printer.

A third type of CR monitor functions by allowing ambient air to diffuse through a filter into a detection chamber. As the radon decays, the alpha particles are counted using a solid-state silicon detector. The measured radon concentration in the chamber follows the radon concentration in the ambient air by a small time lag.

2.1.4 Equipment

Equipment required depends on the type and model of CR monitor used. Aged air or nitrogen must be available for introduction into the CR monitor to measure the background count rate during calibration. For scintillation cell-type CRs, sealed scintillation cells with a measured low background should be available as spare cells.

2.1.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The CR measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

2.1.5.1 Pre-Sampling Testing. Before and after each measurement, the CR monitor should be tested carefully according to manufacturer's directions to:

- Verify that the correct input parameters and the unit's clock or timer are set properly; and
- Verify the operation of the pump. Flow rates within the range of the manufacturer's specifications are satisfactory.

After every 1,000 hours of operation of scintillation cell-type CRs, the background count rate should be checked by purging the unit with clean, aged air or nitrogen in accordance with the procedures identified in the operating manual for the instrument. In addition, the background count rate of all CR types should be monitored more frequently by operating the instrument in a low radon environment.

Participation in a laboratory intercomparison program should be conducted initially and at least once every 12 months thereafter, and after equipment repair, to verify that the conversion factor used by the CR monitor is accurate. This is done by comparing the unit's response to a known radon concentration. At this time, the correct operation of the pump should be verified. Participation in the EPA National Radon Measurement Proficiency (RMP) Program does not satisfy the need for annual calibration, as this Program is a performance test rather than an internal calibration.

2.1.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

2.1.7 Deployment and Operation

2.1.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

2.1.7.2 Operation. The CR monitor should be programmed to run continuously, recording periodically the radon concentration for at least 48 hours. Longer measurements may be required, depending on the CR type and radon level being measured. An increase in operating time decreases the uncertainty associated with using the measurement result to represent a longer-term average concentration.

Care should be taken to account for data that are produced before equilibrium conditions have been established in a flow-through cell. Generally, conditions stabilize after the first four hours. Measurements made prior to this time are low and should either be discarded or used to estimate radon concentrations using pre-established system constants (Busigin et al. 1979, Thomas 1972). If the first four hours of data from a 48-hour measurement are discarded, the remaining hours of data can be averaged and are sufficient to represent a two-day measurement.

2.1.8 Retrieval of Monitors

When the measurement is terminated, the operator should document the stop-date and -time and whether the closed-building conditions are still in effect.

2.1.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented.

The serial numbers of the CR monitor, scintillation cells, and other equipment must also be recorded.

2.1.10 Results

2.1.10.1 Sensitivity. Most CR monitors are capable of a lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) of 1.0 picoCurie per liter (pCi/L) or less.

2.1.10.2 Precision. Most CR monitors can achieve a coefficient of variation of less than 10 percent at 4 pCi/L or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored continuously over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.1.11 Quality Assurance

The quality assurance program for CR measurements includes four parts: (1) calibration, (2) background measurements, (3) duplicate measurements, and (4) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

2.1.11.1 Calibration. Every CR monitor should be calibrated in a radon calibration chamber before being put into service, and after any repairs or modifications. (Note that an inherent element in the calibration process is a thorough determination of the background count rate using clean, aged air or nitrogen.) Subsequent recalibrations and background checks should be done at least once every 12 months, with cross-checks to a recently calibrated instrument at least semiannually. All cells need individual calibration factors.

2.1.11.2 Background Measurements. After every 1,000 hours of operation of scintillation cell-type CRs (about every 20th 48-hour measurement), and whenever any type of CR is calibrated, the background should be checked by purging the monitor with clean, aged air or nitrogen. In addition, the background count rate should be monitored more frequently by operating the instrument in a low radon environment. Cells which develop a high background after prolonged use should be reconditioned by the manufacturer.

2.1.11.3 Duplicate Measurements. When two or more CR monitors of the same type (e.g., scintillation cell, ionization chamber, or silicon detector types) are available, the precision of the measurements can be estimated by operating the monitors side-by-side. The analysis of duplicate results should follow the methodology described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.1.11.4 Routine Instrument Checks. Proper operation of all radiation counting instruments requires that their response to a reference source be constant to within established limits. Therefore, counting equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check cell (for scintillation cell-type CRs) prior to beginning each measurement. The count rate of the check source should be high enough to yield good counting statistics in a short time (for example, 1,000 to 10,000 counts per minute).

If a check source is unavailable or incompatible with the type of CR monitor being used, an informal intercomparison with another measurement method that has proven reliability (for example in the EPA National RMP Program) should be conducted at least every tenth measurement. In addition, it is important to check regularly all components of the equipment that affect the result, including battery and electronics, and to document these checks.

Pumps and flow meters should be checked routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

2.2 PROTOCOL FOR USING ALPHA TRACK DETECTORS (AT or ATD) TO MEASURE INDOOR RADON CONCENTRATIONS

2.2.1 Purpose

This protocol provides guidance for using alpha track detectors (AT or ATD) to obtain accurate and reproducible measurements of indoor radon concentrations. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.2.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be addressed to the U.S. Environmental Protection Agency, Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C., 20460.

2.2.3 Method

An AT consists of a small piece of plastic or film enclosed in a container with a filter-covered opening or similar design for excluding radon decay products. Radon diffuses into the container and alpha particles emitted by the radon and its decay products strike the detector and produce submicroscopic damage tracks. At the end of the measurement period, the detectors are returned to a laboratory. Plastic detectors are placed in a caustic solution that accentuates the damage tracks so they can be counted using a microscope or an automated counting system. The number of tracks per unit area is correlated to the radon concentration in air, using a conversion factor derived from data generated at a calibration facility. The number of tracks per unit of analyzed detector area produced per unit of time (minus the background) is proportional to the radon concentration. AT detectors function as true integrators and measure the average concentration over the exposure period.

Many factors contribute to the variability of AT results, including differences in the detector response within and between batches of plastic, non-uniform plate-out of decay products inside the detector holder, differences in the number of background tracks, and variations in etching conditions. Since the variability in AT results decreases with the number of net tracks counted, counting more tracks over a larger area of the detector, particularly at low exposures, will reduce the uncertainty of the result.

2.2.4 Equipment

ATs are available from commercial suppliers. These suppliers offer contract services in which they provide the detector and subsequent analysis and reporting for a fixed price. Establishing an in-house capability to provide packaged detectors, a calibration program, and an analysis program would probably not be practical or economically advantageous for most users. Therefore, details for establishing the analytical aspects of an AT program are omitted from this protocol. Additional details concerning AT programs have been reviewed elsewhere (Fleischer et al. 1965, Lovett 1969).

Assuming ATs are obtained from a commercial supplier, the following equipment is needed to initiate a measurement:

- An AT in an individual, sealed container (such as an aluminized plastic bag) to prevent extraneous exposure before deployment;
- A means to attach the AT to its measurement location, if it is to be hung from the wall or ceiling;
- An instruction sheet for the occupant, a sample log sheet, and a shipping container (along with a prepaid mailing label, if appropriate);
- Manufacturer instructions for resealing the detector at the time of retrieval and prior to returning it to the supplier for analysis; and
- A data collection log, if appropriate.

2.2.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The AT measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The AT should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

2.2.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

A 12-month AT measurement provides information about radon concentrations in a building during an entire year, so the closed-building conditions do not have to be satisfied to perform a valid year-long measurement.

2.2.7 Deployment

2.2.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

If the detector is installed during a site visit, the final site selected should be shown to the building occupant to be certain it is acceptable for the duration of the measurement period.

2.2.7.2 Timely Deployment. A group of ATs should be deployed into houses as soon as possible after delivery from the supplier. In order to minimize chances of high background exposures, users should not order more ATs than they can reasonably expect to install within the following few months. If the storage time exceeds more than a few months, the background exposures from a sample of the stored detectors should be assessed to determine if they are different from the background of detectors that are not stored for long periods. The supplier's instructions regarding storage and background determination should be followed. This background assessment of detectors stored for long periods is not necessary if the analysis laboratory measures routinely the background of stored detectors, and if the stored detectors remain tightly sealed.

The sampling period begins when the protective cover or bag is removed. The edge of the bag must be cut carefully, or the cover removed, so that it can be reused to reseal the detector at the end of the exposure period. The detector and the radon-proof container should be inspected to make sure that they are intact and have not been physically damaged in shipment or handling.

2.2.8 Retrieval of Detectors

At the end of the measurement period (usually 90 days for short-term tests and one year for long-term measurements), the detector should be inspected for damage or deviation from the conditions entered in the log book at the time of deployment. Any changes should be noted in the log book. The time and date of removal should be entered on the data form for the detector and in the log book, if used. The detector should then be resealed following the instructions provided by the supplier. After retrieval, the detectors should be stored in a low radon environment and returned as soon as possible to the analytical laboratory for processing. In many cases, attempts at resealing ATs have not been totally successful, resulting in some continued exposure of the detectors beyond the deployment period. This extra exposure could bias the results high if the detectors are held for a significant length of time prior to analysis.

2.2.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that should be documented.

2.2.10 Analysis Requirements

2.2.10.1 Sensitivity. The lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) is dependent upon the stability of the number of background tracks. Depending upon the system used, the background may be less variable if a greater area is analyzed. With present ATs, routine counting can achieve an LLD of 1 pCi/L-month, and an LLD of 0.2 pCi/L-month may be achieved by counting additional area.

2.2.10.2 Precision. The precision should be monitored using the results of the duplicate detectors described in Section 2.2.11.3 of this protocol, rather than a precision quoted by the manufacturer. The precision of an AT system is dependent upon the total number of tracks counted on the flank and test detector, and therefore the area of the detector that is analyzed. If few net tracks are counted, poor precision is obtained. Thus, it is important that the organization performing the measurement with an AT arranges for counting an adequate area or number of net tracks.

2.2.11 Quality Assurance

The quality assurance program for AT measurements involves five separate parts: (1) calibration, (2) known exposure measurements, (3) duplicate (collocated) detectors, (4) control detectors, and (5) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

2.2.11.1 Calibration. Every AT laboratory system should be calibrated in a radon calibration chamber at least once every 12 months. Determination of a calibration factor requires exposure of ATs to a known radon concentration in a radon exposure chamber. These calibration exposures are to be used to obtain or verify the conversion factor between net tracks per unit area and radon concentration. Participation in the EPA National Radon Measurement Proficiency Program does not satisfy the need for annual calibration, as this Program is a proficiency test rather than an internal calibration. The following guidance is provided to manufacturers and suppliers of AT services as minimum requirements in determining the calibration factor.

- ATs should be exposed in a radon chamber at several different radon concentrations or exposure levels similar to those found in the tested buildings (a minimum of three different concentrations).

- A minimum of 10 detectors should be exposed at each level.

- A calibration factor should be determined for each batch or sheet of detector material received from the material supplier. Alternatively, calibration factors may be established from several sheets, and these factors extended to detectors from sheets exhibiting similar sensitivities (within pre-established tolerance limits).

2.2.11.2 Known Exposure Measurements. Anyone providing measurement services with AT devices should submit ATs with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure (spiked) detectors should be labeled in the same manner as field detectors to ensure identical processing. The results of the spiked detector analyses should be monitored and recorded. Any significant deviation from the known concentration to which they were exposed should be investigated.

2.2.11.3 Duplicate (Collocated) Detectors. Anyone providing measurement services with AT devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. The pair of detectors should be treated identically in every respect. They should be shipped, stored, opened, installed, removed, and processed together, and not identified as duplicates to the processing laboratory. The samples selected for duplication should be distributed systematically throughout the entire population of measurements. Groups selling measurements to homeowners can accomplish this by providing two detectors instead of one to a random selection of purchasers, with instructions to place the detectors side-by-side. Consideration should be given to providing some means to ensure that the duplicate devices are not separated during the measurement period. Data from duplicate detectors should be evaluated using the procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.2.11.4 Control Detectors

2.2.11.4.1 Laboratory Control Detectors. The laboratory background level for each batch of ATs should be established by each laboratory or supplier.

Suppliers should measure the background of a statistically significant number of unexposed ATs that have been processed according to their standard operating procedures. Normally, the analysis laboratory or supplier calculates the net readings (which are used to calculate the reported sample radon concentrations) by subtracting the laboratory blank values from the results obtained from the field detectors.

2.2.11.4.2 Field Control Detectors. Field control detectors must be a component of any AT measurement program. Field control ATs (field blanks) should consist of a minimum of five percent of the devices that are deployed every month or 25, whichever is smaller. Users should set these aside from each shipment, keep them sealed and in a low radon (less than 0.2 pCi/L) environment, label them in the same manner as the field ATs to assure identical processing, and send them back to the supplier with the field ATs for analysis. These control devices are necessary to measure the background exposure that accumulates during shipment and storage. The results should be monitored and recorded. If one or a few field blanks have concentrations significantly greater than the LLD established by the supplier, it may indicate defective packaging or handling. If the average value from the field control devices (field blanks) is significantly greater than the LLD established by the supplier, this average value should be subtracted from the individual values reported for the other devices in the exposure group.

It may be advisable to use three sets of detectors (pre-exposure, field, and post-exposure background) in order to allow the most thorough and complete evaluation of radon levels. For example, one group of detectors (pre-exposure detectors) may be earmarked for background measurement, and returned for processing immediately after the other detectors are deployed. The results from these detectors determine if the number of tracks acquired before deployment is significant and should be subtracted from the gross result. The second set of background detectors (post-exposure background detectors) are obtained just before the field monitors are to be collected, and are opened and kept in the same location as the returning field monitors for the same duration, and returned with them. Finally, this "post-exposure background" is subtracted from the field results, if found to be significant. In general, a value of 1 pCi/L or greater for any blank AT indicates a significant level that should be investigated, and potentially subtracted from the field AT results.

2.2.11.5 Routine Instrument Checks. Proper functioning of the analysis instruments and proper response by their operators require that the equipment be subject to routine checks. Daily or more frequent monitoring of equipment and operators is vital to ensuring consistently accurate results.

2.3 PROTOCOL FOR USING ELECTRET ION CHAMBER RADON DETECTORS (EC or ES, EL) TO MEASURE INDOOR RADON CONCENTRATIONS

2.3.1 Purpose

This protocol provides guidance for using electret ion chamber radon detectors (EC) to obtain accurate and reproducible measurements of indoor radon concentrations. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol can produce either short-term or long-term measurements, depending upon the type of EC employed. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.3.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be addressed to the U.S. Environmental Protection Agency, Office of Radiation Programs, Radon Division, Problem Assessment Branch (ANR-464), 401 M Street, S.W., Washington, D.C., 20460.

2.3.3 Method

Short-term (ES) and long-term (EL) ECs have been described elsewhere (Kotrappa et al. 1988, 1990). They require no power, and function as true integrating detectors, measuring the average concentration during the measurement period.

The EC contains a charged electret (an electrostatically-charged disk of Teflon^{R}) which collects ions formed in the chamber by radiation emitted from radon and radon decay products. When the device is exposed, radon diffuses into the chamber through filtered openings. Ions which are generated continuously by the decay of radon and radon decay products are drawn to the surface of the electret and reduce its surface voltage. The amount of voltage reduction is related directly to the average radon concentration and the duration of the exposure period. ECs can be deployed for exposure periods of two days (one day for research purposes) to 12 months, depending upon the thickness of the electret and the volume of the ion chamber chosen for use. These deployment periods are flexible, and valid measurements can be made with other deployment periods depending on the application.

The electret must be removed from the EC chamber and the electret voltage measured with a special surface voltmeter both before and after exposure. To determine the average radon concentration during the exposure period, the difference between the initial and final voltages is divided first by a calibration factor and then by the number of exposure days. A background radon concentration equivalent of ambient gamma radiation is subtracted to compute radon concentration. Electret voltage measurements can be made in a laboratory or in the field.

2.3.4 Equipment

The following equipment is required to measure radon using the EC detection method:

- An EC of the type recommended for the anticipated exposure period and radon concentration (ES or EL);
- An instruction sheet for the user and a shipping container with a label for returning the detector(s) to the laboratory, if appropriate;
- A specially-built surface voltmeter for measuring electret voltages before and after exposure; and
- A data collection log.

2.3.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The ES or EL measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The ES or EL should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

The ES or EL should be inspected prior to deployment to see that it has not been damaged during handling and shipping.

2.3.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

A 12-month EL measurement provides information about radon concentrations during an entire year, so the closed-building conditions do not have to be satisfied to perform a valid year-long measurement.

2.3.7 Deployment

2.3.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

2.3.7.2 Timely Deployment. Both ESs and ELs should be deployed as soon as possible after their initial voltage is measured. Until an ES or EL is deployed, an electret cover should remain in place over the electret to minimize voltage loss due to background radon and gamma radiation.

2.3.8 Retrieval of Detectors

The recommended deployment period for the very short-term ESs is two days (one day for research or special circumstances), two to seven days for the short-term ESs, and for the long-term ELs one to 12 months. If the occupant is terminating the sampling, the instructions should inform the occupant of when and how to terminate the sampling period. EC units integrate the radon (ion) signal permanently, so variations from these recommended measurement periods are acceptable to accommodate special circumstances as long as the final electret voltage for any measurement remains above 150 volts. In addition, the occupant also should be instructed to send the ES or EL to the laboratory as soon as possible, preferably within a few days following exposure termination.

At the end of the monitoring period, the ES or EL should be inspected for any deviation from the conditions described in the log book at the time of deployment. Any changes should be noted. The electret should be covered again using the mechanism provided.

2.3.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented.

In addition, the serial number, type, and supplier of the chamber and electret, along with a code number or description which uniquely identifies customer, building, room, and sampling position, must be documented. If the temperature of the room in which the EC is analyzed after exposure is significantly different (more than 10°F) from the temperature of the room in which the EC was analyzed prior to exposure, those temperatures need to be recorded.

2.3.10 Analysis Requirements

In general, all ESs or ELs should be analyzed in the field or in the laboratory as soon as possible following removal from buildings. A background correction must be made to the radon concentration value obtained because electret ion chambers have a small response to background gamma radiation. If the temperature at the time of analysis is significantly different (more than 10°F) than at the time when the pre-exposure voltage was determined, a temperature correction factor may be necessary (consult the manufacturer). It is therefore advisable to measure voltages after the temperatures of the reader and detector have stabilized to a room temperature in which both pre- and post-exposure voltages have been measured.

2.3.10.1 Sensitivity. For a seven-day exposure period using an ES, the lower level of detection (LLD), as defined by Thomas (Thomas 1971) as the concentration that can be measured with a 50 percent error, is about 0.2 pCi/L. For an EL, the LLD is about 0.3 pCi/L or less for a three-month measurement. Note that this definition of LLD is different from that for radiation counting instruments, as defined for other methods by Altshuler and Pasternack (Altshuler and Pasternack 1963).

2.3.10.2 Precision. Precision should be monitored by using the results of duplicate detector analyses described in Section 2.3.11.3 of this protocol. This method can produce duplicate measurements with a coefficient of variation of 10 percent or less at 4 pCi/L or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored continuously over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.3.11 Quality Assurance

The quality assurance program for measurements with ES or EL detectors includes five parts: (1) calibration, (2) known exposure detectors, (3) duplicate (collocated) detectors, (4) control detectors, and (5) routine instrument checks. The purpose of a quality assurance program is to assure and document the accuracy and precision of the measurements and that the measurements are not influenced by exposure from sources outside the environment to be measured.

2.3.11.1 Calibration. Every ES or EL detector system (detectors plus reader) should be calibrated in a radon calibration chamber at least once every 12 months. Initial calibration for the system is provided by the manufacturer. Determination of calibration factors for ES or EL detectors requires exposure of detectors to known concentrations of radon-222 in a radon exposure chamber. Since ESs and ELs are also sensitive to exposure to gamma radiation (see Section 2.3.11.4), a gamma exposure rate measurement in the test chamber is also required.

The following guidance is provided to manufacturers and suppliers of EC services as minimum requirements in determining the calibration factor:

- Detectors should be exposed in a radon chamber at several different radon concentrations or exposure levels similar to those found in the tested buildings (a minimum of three different concentrations).
- A minimum of 10 detectors should be exposed at each level.
- The period of exposure should be sufficient to allow the detector to achieve equilibrium with the chamber atmosphere.

2.3.11.2 Known Exposure Detectors. Anyone providing measurement services with ES or EL detectors should subject detectors with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Blind calibration detectors should be labeled in the same manner as the field detectors to ensure identical processing. The results of the spiked detector analysis should be monitored and recorded and any significant deviation from the known concentration to which they were exposed should be investigated.

2.3.11.3 Duplicate (Collocated) Detectors. Anyone providing measurement services with EC devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. The duplicate devices should be shipped, stored, exposed, and analyzed under the same conditions, and not identified as duplicates to the processing laboratory. The samples selected for duplication should be distributed systematically throughout the entire population of samples. Groups selling measurement services to homeowners can accomplish this by providing two detectors instead of one to a random selection of purchasers, with instructions to place the detectors side-by-side. Consideration should be given to providing some means to ensure that the duplicate devices are not separated during the measurement period. The analysis of duplicate data should follow the methodology described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.3.11.4 Control Detectors for Background Gamma Exposure and Electret Stability Monitoring. Electrets should exhibit very little loss in surface voltage due to internal electrical instabilities. Anyone providing measurement services with ES or EL detectors should set aside a minimum of five percent of the electrets or 10, whichever number is smaller, from each shipment and evaluate them for voltage drift. They should be kept covered with protective caps in a low radon environment and analyzed for voltage drift over a time period similar to the time period used for those deployed in homes. Any voltage loss found in the control electrets of more than one volt per week over a three-week test period for ESs, or one volt per month over a three-month period for ELs, should be investigated.

ECs are sensitive to background gamma radiation. The equivalent radon signal in picoCuries per liter (pCi/L) per unit background radiation in microroentgens per hour (μR/hr) is determined by the manufacturer for three different types of EC chambers currently available. This is specific to the chamber and not to the electret used in the chamber. These parameters are 0.07, 0.087, and 0.12 for H, S, and L chambers, respectively. Depending upon the type of chamber employed in EC, one of these values must be multiplied by the gamma radiation level at the site (in μR/hr) and the product (in equivalent pCi/L) subtracted from the apparent radon concentration. The gamma radiation at the measurement site is usually taken from the EPA list of average background by State, as provided by the manufacturer. However, it can also be measured with an EC unit that is sealed in a radon-proof bag available from the manufacturer, or measured directly using appropriate radiation detection instruments. The latter step is necessary for accurate radon measurements at very low levels such as those encountered in the outdoor environment.

2.3.11.5 Routine Instrument Checks. Proper operation of the surface voltmeter should be monitored following the manufacturer's procedures for (1) zeroing the voltmeter, and (2) analyzing a reference electret. These checks should be conducted at least once a week while the voltmeter is in use.

2.4 PROTOCOL FOR USING ACTIVATED CHARCOAL ADSORPTION DEVICES (AC) TO MEASURE INDOOR RADON CONCENTRATIONS

2.4.1 Purpose

This protocol provides guidance for using activated charcoal adsorption devices (AC) to obtain accurate and reproducible measurements of indoor radon concentrations. As referred to in this document, ACs are those charcoal adsorption devices that are analyzed by gamma scintillation (including open-faced canisters, diffusion barrier canisters, and diffusion bags). Charcoal detectors analyzed by liquid scintillation are covered under a separate protocol (see Section 2.5). Adherence to this protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.4.2 Scope

This protocol covers, in general terms, the sample collection and analysis method, the equipment needed, and the quality control objectives of measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency, Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C., 20460.

2.4.3 Method

ACs are passive devices requiring no power to function. The passive nature of the activated charcoal allows continual adsorption and desorption of radon. During the measurement period (typically two to seven days), the adsorbed radon undergoes radioactive decay. Therefore, the technique does not integrate uniformly radon concentrations during the exposure period. As with all devices that store radon, the average concentration calculated using the mid-exposure time is subject to error if the ambient radon concentration varies substantially during the measurement period.

The AC technique is described in detail elsewhere (Cohen and Cohen 1983, George 1984, George and Weber 1990). A device used commonly by several groups consists of a circular, six- to 10-centimeter (cm) diameter container that is approximately 2.5 cm deep and filled with 25 to 100 grams of activated charcoal. One side of the container is fitted with a screen that keeps the charcoal in but allows air to diffuse into the charcoal.

In some cases, the charcoal container has a diffusion barrier over the opening. For longer exposures, this barrier improves the uniformity of response to variations of radon concentration with time. Desiccant is also incorporated in some containers to reduce interference from moisture adsorption during longer exposures. Another variation of the charcoal container has charcoal packaged inside a sealed bag, allowing the radon to diffuse through the bag. All ACs are sealed with a radon-proof cover or outer container after preparation.

The measurement is initiated by removing the cover to allow radon-laden air to diffuse into the charcoal bed where the radon is adsorbed onto the charcoal. At the end of a measurement period, the device is resealed securely and returned to a laboratory for analysis.

At the laboratory, the ACs are analyzed for radon decay products by placing the charcoal, still in its container, directly on a gamma detector. Corrections may be needed to account for the reduced sensitivity of the charcoal due to adsorbed water. This correction may be done by weighing each detector when it is prepared and then reweighing it when it is returned to the laboratory for analysis. Any weight increase is attributed to water adsorbed on the charcoal. The weight of water gained is correlated to a correction factor, which is derived empirically by using a method discussed elsewhere (George 1984). This correction factor is used to correct the analytical results.

This correction is not needed if the configuration of the AC is modified to reduce significantly the adsorption of water and if the user has demonstrated experimentally that, over a wide range of humidities, there is a negligible change in the collection efficiency of the charcoal within the specified exposure period.

AC measurement systems are calibrated by analyzing detectors exposed to known concentrations of radon in a calibration facility.

2.4.4 Equipment

ACs made specifically for ambient radon-monitoring can be obtained from suppliers or can be manufactured using readily available components. Some charcoal canisters designed for use in respirators or in active air sampling may be adapted for use in ambient radon monitoring, as described elsewhere (Cohen and Cohen 1983, George 1984).

The following equipment is required to measure radon using ACs:

- A charcoal container(s) sealed with a protective cover;
- An instruction sheet and sampling data sheet for the occupant, and a shipping container (along with a prepaid mailing label, appropriate; and
- A data collection log.

Laboratory analysis of the exposed devices is performed using a sodium iodide gamma scintillation detector to count the gamma rays emitted by the radon decay products on the charcoal. The detector may be used in conjunction with a multi-channel gamma spectrometer or with a single-channel analyzer with the window set to include the appropriate gamma energy window. The detector system and detector geometry must be the same used to derive the calibration factors for the device.

2.4.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The AC measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The devices should not be deployed if the occupant's schedule prohibits terminating the measurement at the time selected for sealing the device and returning it to the laboratory.

2.4.6 Measurement Criteria

The reader should refer to Section 1.2.2 for general conditions that must be adhered to in order to ensure standardization of measurement conditions.

2.4.7 Deployment

2.4.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria to use when choosing a measurement device location.

2.4.7.2 Timely Deployment. ACs should be deployed within the shelf life specified by the supplier. Until ACs are deployed, they should remain tightly sealed to maintain maximum sensitivity and low background.

For charcoal canisters, the sealing tape and protective cover should be removed from the canister to begin the sampling period. The cover and tape must be saved to reseal the canister at the end of the measurement. For diffusion bags, there is a radon-proof mailing container that is sealed at the end of the deployment period. This container may be separate from the radon-proof packaging. The device should be inspected to see that it has not been damaged during handling and shipping. It should be intact, with no charcoal leakage. For canisters, the device should be placed with the open side up toward the air. Nothing, apart from the device, should impede air flow around it.

2.4.8 Retrieval of Detectors

The detectors should be deployed for a two- to seven-day measurement period as specified in the supplier's instructions. If the occupant is terminating the sampling, the instructions should inform the occupant of when to terminate the sampling period and should indicate that a deviation from the schedule may be acceptable if the time of termination is documented on the device. In addition, the occupant should also be instructed to send the device to the laboratory as soon as possible, preferably the day of termination. The analysis laboratory should be calibrated to permit accurate analysis of devices deployed for some reasonable time beyond the recommended sampling period. For example, a detector deployed for 24 hours beyond the recommended sampling time may not present an analysis problem to the measurement laboratory.

At the end of the monitoring period, the detector should be inspected for any deviation from the conditions described in the log book at the time of deployment. Any changes should be noted. The detector should be resealed using the original protective cover.

After the device is retrieved, it must be returned to the laboratory as soon as possible for analysis. The detector should be analyzed at least three hours after the end of sampling to allow for ingrowth of decay products.

2.4.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

In addition, the test location temperature may need to be recorded, depending on the device configuration.

2.4.10 Analysis Requirements

ACs should be analyzed in the laboratory as soon as possible following removal from the houses. The maximum allowable delay time between the end of sampling and analysis will vary with the radon concentration and background experienced in each laboratory and should be evaluated, especially if sensitivity is of prime consideration. Corrections for the radon-222 decay during sampling, during the interval between sampling and counting, and during counting should be made. If the device does not have a moisture barrier, the detector should be weighed, and, if necessary, a correction should be applied for the increase in weight due to moisture adsorbed. A description of the procedure used to derive the moisture correction factor is provided elsewhere (George 1984).

2.4.10.1 Sensitivity. For a two- to seven-day exposure period, the lower level of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) should be 0.5 pCi/L or less. This LLD can normally be achieved with a counting time of up to 30 minutes. The LLD should be calculated using the results of the laboratory background determination that is described in Section 2.4.11.4.1 of this protocol.

2.4.10.2 Precision. Precision should be monitored using the results of the duplicate detector analyses described in this protocol (Section 2.4.11.3). This method can produce measurements with a coefficient of variation of 10 percent or less at 4 pCi/L or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored frequently over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.4.11 Quality Assurance

The quality assurance program for ACs includes five parts: (1) calibration, (2) known exposure detectors, (3) duplicate (collocated) detectors, (4) control detectors, and (5) routine instrument checks. The purpose of this program is to identify the accuracy and precision of the measurements and to assure that the measurements are not influenced by extraneous exposures. The quality assurance program should include the maintenance of control charts (section 5.3 of Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

2.4.11.1 Calibration. Every AC system should be calibrated in a radon calibration chamber at least once every 12 months. Determination of calibration factors for ACs requires exposure of the detectors to known concentrations of radon-222 in a radon exposure chamber. The calibration factors depend on the exposure time and may also depend on the amount of water adsorbed by the charcoal container during exposure. These calibration factors should be determined using the procedures described previously (George 1984). Calibration factors should be determined for each AC measurement system (container type, amount of charcoal, gamma detector type, etc.).

2.4.11.2 Known Exposure Detectors. Anyone providing measurement services with AC detectors should submit charcoal detectors with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure (spiked) detectors should be labeled in the same manner as the field detectors to assure identical processing. The results of the spiked detector analysis should be monitored and recorded and any significant deviation from the known concentration to which they were exposed should be investigated.

2.4.11.3 Duplicate (Collocated) Detectors. Anyone providing measurement services with AC devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. The duplicate detectors should be shipped, stored, exposed, and analyzed under the same conditions, and not identified as duplicates to the processing laboratory. The locations selected to receive duplicates should be distributed systematically throughout the entire population of samples. Groups selling measurement services to homeowners can do this by providing two detectors instead of one to a random selection of purchasers, with instructions to place them side-by-side. Consideration should be given to providing some means to ensure that the duplicate detectors are not separated during the measurement period. Data from duplicate detectors should be evaluated using the procedures described by Goldin (Section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.4.11.4 Control Detectors

2.4.11.4.1 Laboratory Control Detectors. The laboratory background level for each batch of ACs should be established by each laboratory or supplier. Suppliers should measure the background of a statistically significant number of unexposed detectors that have been processed according to their standard operating procedures (laboratory blanks). Normally, the analysis laboratory or supplier calculates the net readings (which are used to calculate the reported sample radon concentrations) by subtracting the laboratory blank values from the results obtained from the field detectors.

2.4.11.4.2 Field Control Detectors. Field control detectors (field blanks) should consist of a minimum of five percent of the devices that are deployed every month or 25, whichever is smaller. Large users of ACs should set these aside from each shipment, keep them sealed and in a low radon (less than 0.2 pCi/L) environment, label them in the same manner as the field detectors to ensure identical processing, and send them back to the supplier with one shipment each month for analysis. These control devices measure the background exposure that may accumulate during shipment or storage, and results should be monitored and recorded. If one or a few of the field control detectors have concentrations significantly greater than the LLD established by the supplier it may indicate defective devices or poor procedures. If most of the controls have concentrations significantly greater than the LLD, the average value of the field controls should be subtracted from the reported field detector concentrations and the supplier notified of a possible problem.

2.4.11.5 Routine Instrument Checks. Proper operation of all radiation counting instruments requires that their response to a reference source be constant to within established limits. Therefore, counting equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check source at least once per day. The characteristics of the check source (i.e., geometry, type of radiation emitted, etc.) should, if possible, be similar to the samples to be analyzed. The count rate of the check source should be high enough to yield good counting statistics in a short time (for example, 1,000 to 10,000 counts per minute).

2.5 PROTOCOL FOR USING CHARCOAL LIQUID SCINTILLATION (LS) DEVICES TO MEASURE INDOOR RADON CONCENTRATIONS

2.5.1 Purpose

This protocol provides guidance for using charcoal liquid scintillation (LS) devices to obtain accurate and reproducible measurements of indoor radon concentrations. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.5.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency, Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C., 20460.

2.5.3 Method

LS devices are passive detectors requiring no power to function. The passive nature of the activated charcoal allows continual adsorption and desorption of radon, and the adsorbed radon undergoes radioactive decay during the measurement period. Therefore, the technique does not integrate uniformly radon concentrations during the exposure period. As with all devices that store radon, the calculated average concentration is subject to error if the ambient radon concentration adsorbed during the first half of the sampling period is substantially higher or lower than the average over the period.

The LS technique is described elsewhere (Prichard and Marien 1985). Several companies now provide a type of LS device that is a capped, 20-ml liquid scintillation vial that is approximately 25 mm in diameter by 60 mm and contains one to three grams of charcoal (other designs are also feasible). In some cases, the vial contains a diffusion barrier over the charcoal which improves the uniformity of response of the device to variations of radon concentration with time, particularly for longer exposures. Some LS devices include a few grams of desiccant which reduces interference from moisture adsorption by the charcoal (Perlman 1989). All LS devices are sealed with a radon-proof closure after preparation.

A measurement with the LS device is initiated by removing the radon-proof closure to allow radon-laden air to diffuse into the charcoal where the radon is adsorbed. At the end of the exposure (typically two to seven days), the device is resealed securely and returned to the laboratory for analysis.

At the laboratory, the devices are prepared for analysis by radon desorption techniques. This technique transfers reproducibly a major fraction of the radon adsorbed on the charcoal into a vial of liquid scintillation fluid. The vials of liquid scintillation fluid containing the dissolved radon are placed in a liquid scintillation counter and counted for a specified number of minutes (e.g., 10 minutes) or until the standard deviation of the count is acceptable (e.g., less than 10 percent).

2.5.4 Equipment

LS devices made specifically for ambient radon monitoring are supplied and analyzed by several laboratories.

The following equipment is required to measure radon with an LS device:

- LS devices properly sealed by the supplier;
- An instruction sheet for the occupant, and a shipping container (along with a prepaid mailing label, if appropriate; and
- A data collection log.

2.5.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The LS measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The LS device should not be deployed if the occupant's schedule prohibits terminating the measurement at the time selected for closing the device and returning it to the laboratory.

2.5.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

2.5.7 Deployment

2.5.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

2.5.7.2 Timely Deployment. LS devices should be deployed into buildings within the shelf life specified by the supplier. Until they are deployed, they should remain tightly sealed to maintain low background.

The protective cap should be removed from the device to begin the sampling period. The cap must be saved to reseal the device at the end of the measurement. The device should be inspected to assure that it has not been damaged during handling and shipping. It should be intact, with no charcoal leakage. The device should also be placed with the open vial mouth up. Nothing should impede air flow around the device.

2.5.8 Retrieval of Devices

The device should be deployed for the measurement period (usually between two days and one week) specified in the instructions supplied by the analytical laboratory. If the occupant is terminating the sampling, the instructions should inform the occupant of when to terminate the sampling period and should indicate that the actual time of termination must be documented on the device. In addition, the occupant also should be instructed to send the device to the laboratory as soon as possible, preferably the day of sample termination. The analysis laboratory should be calibrated to permit accurate analysis of devices deployed for some reasonable time beyond the recommended sampling period. For example, a detector deployed for 24 hours beyond the recommended sampling time may not present an analysis problem to the measurement laboratory.

At the end of the monitoring period, the device should be inspected for any deviation from the conditions described in the log book at the time of deployment. Any changes should be noted. The device should be resealed using the original protective cap.

2.5.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

2.5.10 Analysis Requirements

LS devices should be returned to the supplier's analysis laboratory as soon as possible following removal from the houses. The maximum allowable delay time between the end of sampling and analysis should not exceed the time specified by the supplier's instructions, especially if the radon concentration measured was expected to be low. Corrections for radon-222 decay during sampling, during the interval between sampling and counting, and during counting, will be made by the analysis laboratory. The procedures followed by an individual supplier's analysis laboratory may include a correction for moisture as measured by weight gain if this is significant for their device configuration. Other correction or calibration factors applied by the analysis laboratory must include factors accounting for the transfer of radon from the charcoal to the scintillation fluid under rigorously controlled conditions, and for the counting efficiency achieved with the specified scintillation mixture and liquid scintillation counting system.

2.5.10.1 Sensitivity. The lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) should be specified by individual suppliers for LS devices exposed and shipped according to their directions. It is estimated that LLDs of a few tenths of a picoCurie per liter (pCi/L) are achievable for some LS devices (Cohen 1988, Grodzins 1988, Perlman 1988, Prichard 1988). The LLD should be calculated using the results of the laboratory control devices discussed in Section 2.5.11.4.1 of this protocol.

2.5.10.2 Precision. Precision should be monitored and recorded periodically using the results of the duplicate device analyses described in Section 2.5.11.3 of this protocol. Measurements made with this method can produce duplicate results with a coefficient of variation of 10 percent or less at 4 pCi/L or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored frequently over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.5.11 Quality Assurance

The quality assurance program for an LS system includes five parts: (1) calibration, (2) known exposure devices, (3) duplicate (collocated) devices, (4) control devices, and (5) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

2.5.11.1 Calibration. Every LS laboratory system should be calibrated in a radon calibration chamber at least once every 12 months. Determination of calibration factors for LS devices requires exposure of calibration devices to known concentrations of radon-222 in a radon exposure chamber at carefully measured radon concentrations. The calibration factors depend on the exposure time and may also depend on the amount of water adsorbed by the device during exposure. Calibration factors should be determined for a range of different exposure times and, if appropriate, humidities.

2.5.11.2 Known Exposure Devices. Anyone providing measurement services with LS devices should submit devices with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure (spiked) devices should be labeled in the same manner as the field devices to ensure identical processing. The results of the spiked device analysis should be monitored and recorded, and any significant deviation from the known concentration to which they were exposed should be investigated.

2.5.11.3 Duplicate (Collocated) Devices. Anyone providing measurement services with LS devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. Each pair of duplicate devices should be shipped, stored, exposed, and analyzed under the same conditions. The samples for duplication should be distributed systematically throughout the entire population of samples. Groups selling measurement services to homeowners can do this by providing two detectors instead of one to a random selection of purchasers with instructions to place them side-by-side. Consideration should be given to providing some means to ensure that the duplicate devices are not separated during the measurement period. Data from duplicate devices should be evaluated using procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.5.11.4 Control Devices

2.5.11.4.1 Laboratory Control Devices. The laboratory background level for each batch of LS devices should be established by each laboratory or supplier. Suppliers should measure the background of a statistically significant number of unexposed LS devices that have been processed according to their standard operating procedures (laboratory blanks). Normally, the analysis laboratory or supplier calculates the net readings (which are used to calculate the reported sample radon concentrations) by subtracting the laboratory blank values from the results obtained from the field detectors.

2.5.11.4.2 Field Control Devices. Field control devices (field blanks) should consist of a minimum of five percent of the devices that are deployed every month or 25, whichever is smaller. Large users of LS detectors should set these aside from each shipment, keep them sealed and in a low radon (less than 0.2 pCi/L) environment, label them in the same manner as the field devices, and send them back to the supplier with one shipment each month for analysis. These control devices measure the background exposure that may accumulate during shipment or storage, and the results should be monitored and recorded. If one or a few of the field control detectors have concentrations significantly greater than the LLD established by the supplier, it may indicate defective devices or procedures. If most of the controls have concentrations significantly greater than the LLD, the average value at the field controls should be subtracted from the reported field device concentration and the supplier notified of a possible problem.

2.5.11.5 Routine Instrument Checks. Proper operation of all radiation counting instruments requires that their response to a reference source be constant to within established limits. Therefore, counting equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check source at least once per day. The characteristics of the check source (i.e., type of radiation emitted) should, if possible, be similar to the samples to be analyzed. The count rate of the check source should be high enough to yield good counting statistics in a short time (for example, 1,000 to 10,000 counts per minute).

2.6 PROTOCOL FOR USING GRAB RADON SAMPLING (GB, GC, GS), PUMP/COLLAPSIBLE BAG DEVICES (PB), AND THREE-DAY INTEGRATING EVACUATED SCINTILLATION CELLS (SC) TO MEASURE INDOOR RADON CONCENTRATIONS

2.6.1 Purpose

This protocol provides guidance for three similar methods that measure indoor radon air concentrations: grab radon sampling techniques (GB, GC, GS), pumps with collapsible bags as devices (PB), and three-day integrating evacuated scintillation cells (SC). Adherence to this protocol will help obtain accurate and reproducible measurements, ensure uniformity among measurement programs, and allow valid comparisons of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled.

Results of grab sampling are influenced greatly by conditions that exist in the building during and for up to 12 hours prior to the measurement. It is therefore especially important when making grab measurements to conform to closed-building conditions for 12 hours before the measurement. Grab sampling techniques are not recommended for measurements made to determine the need for remedial action. The reader should also refer to the EPA guidance document entitled, "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.6.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency, Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C. 20460.

2.6.3 Methods

2.6.3.1 Grab Radon Sampling Techniques. There are three grab radon sampling methods covered by this protocol. In the first method, known as grab radon/scintillation cell (GS), a sample of air is drawn into and sealed in a flask or cell that has a zinc sulfide phosphor coating on its interior surfaces. One surface of the cell is fitted with a clear window that is put in contact with a photomultiplier tube to count light pulses (scintillations) resulting from alpha disintegrations from the air sample interacting with the zinc sulfide coating. The number of pulses is proportional to the radon concentration in the cell. The cell is counted about four hours after filling to allow the short-lived radon decay products to reach equilibrium with the radon. After the cells are placed in the counters, the counting system should be allowed to dark-adapt for two minutes. Correction factors (see Section 2.6.13, Exhibit 2-1) are applied to the counting results to compensate for decay during the time between collection and counting and for decay during counting if the counting time is long (> one hour). Supplementary information on this technique is provided in Section 2.6.13. In a variation of this method, used in some portable instruments, air is pumped continuously through a flow-through-type scintillation cell for just a few minutes. Alpha particles resulting from the decay of radon gas and decay products are counted as the gas is swept through.

A second grab method covered by this protocol, known as grab radon/activated charcoal (GC), uses air pumped through activated charcoal to collect the sample. A charcoal-filled cartridge is placed into a sampler and air is pumped through the carbon cartridge. The pump with a charcoal cartridge is not flow-dependent but must remain operational at the sampling location until the charcoal collects enough radon to be in equilibrium with the radon at the sampling location. A sampling duration of one hour has been found to be optimal for most systems. The cartridge must be weighed prior to and after sampling in order to correct for the reduced sensitivity of the charcoal due to adsorbed water. The cartridges are analyzed by placing them on a sodium iodide gamma scintillation system or a germanium gamma detector. The GC system must be calibrated by analyzing cartridges pumped with known concentrations of radon in a qualified facility.

The third grab method, known as grab radon pump/collapsible bag (GB), uses the same technology described in Section 2.6.3.2 for pump/collapsible bag devices (PB). The GB method covered in this section differs only in that the bag is filled over a much shorter collection period than in the PB method described below.

2.6.3.2 Pump/Collapsible Bag Devices (PB). One of the older and simpler methods of making an integrated measurement of the concentration of radon over a period of time is to collect a sample of ambient air in a radon-proof container over the desired sampling time period and measure the resulting radon concentration in the container.

One practical method is to use a small pump with a very low and uniform flow rate to pump ambient air into an inflatable and collapsible radon-proof bag (Sill 1977). After the desired sampling period (typically 24 hours), the concentration of radon in the bag can be analyzed by any of the standard methods such as the GS protocol (Section 2.6.3.1) using the appropriate radon decay correction factors (Section 2.6.13, Exhibit 2-1). For this method, the counting system should be allowed to dark-adapt for two minutes after the cells are placed in the counters. The main purpose of the collapsible bag is to avoid variation in pump flow rate due to build up of back pressure in a container. Bags that have been measured to have a very low loss of radon by diffusion through the bag have been made of laminated Mylar, aluminized laminated Mylar, and Tedlar^R. The pump flow rate is not critical as long as it is suitable for the size of the bag and the sample duration, but variation of the flow rate over the collection time period of the sample will affect the accuracy of the measurement. A number of suitable battery- and/or charger-operated pumps with controlled flow rates are available commercially.

Although this PB method accumulates radon over a period of time for subsequent analysis, it should not be considered a true integrating method. Radon peaks occurring early in the sampling period will leave less radon for analysis than the same size peak occurring toward the end of the sampling period.

2.6.3.3 Three-Day Integrating Evacuated Scintillation Cells (SC). This method typically uses Lucas-type scintillation cells that have been outfitted with a restricter valve attached to the main valve. Samples are collected by opening the valve on an evacuated cell. The restricter valve is set so that the cell fills from a 30-inch mercury (Hg) vacuum to about 80 percent of its capacity over a three-day period. At the end of the measurement period, the valve is closed and returned to the analysis laboratory. Since the volume of the cell is known, the exact volume of filtered air collected over the three-day measurement period can be calculated from the vacuum gauge reading at the end of the sampling period.

The sample is analyzed on an alpha scintillation counter. Prior to counting, the pressure in the cell is brought to one atmosphere by adding radon-free (aged) air so that the sample is analyzed under the same conditions that prevailed during calibration of the cell. To allow radon and radon decay products to grow into equilibrium and to allow any radon decay products that may have been collected to decay, the sample should be counted no sooner than four hours after the end of the measurement period. After the cells are placed in the counters, the counting system should be allowed to dark-adapt for two minutes.

During the three-day sampling period, some of the radon that has been collected decays. The midpoint of the sampling period cannot be used for the decay correction factor because the airflow into the cell is greater during the initial time of sampling. The fraction of radon that decays must therefore be calculated from the shape of a plot of percent fill versus time. This must be measured for each cell. This factor should be applied as a correction during data reduction.

Since this method accumulates radon over a period of time for subsequent analysis, it is not a true integrating method. Radon peaks occurring early in the sampling period will leave less radon for analysis than the same size peak occurring toward the end of the sampling period.

2.6.4 Equipment

2.6.4.1 Grab Radon Sampling Techniques

2.6.4.1.1 Grab Radon/Scintillation Cell Method (GS). The equipment needed for this method includes the following:

- A scintillation cell (flask) or cells to be filled at the site;
- A pump to flow air through the cell or to evacuate the cell (depending on the valve arrangement on the cell);
- A clock to measure time from collection to counting;
- A filter and filter holder to attach to the air inlet valve of the cell; and
- A data collection log.

The equipment required for analyzing the air sample includes the following:

- A photomultiplier tube and high-voltage assembly in a light-tight chamber;
- A scaler-timer for registering pulses from the photomultiplier tube assembly and timing the counting interval;
- A National Institute of Standards and Technology (NIST)-traceable alpha check source and scintillation disc;
- A calibration flask or cell;
- A vacuum pump and cell flushing apparatus; and
- Aged air or nitrogen for flushing counting cells.

2.6.4.1.2 Grab Radon/Activated Charcoal (GC). The equipment needed for this method includes the following:

- A charcoal cartridge with both apertures sealed with protective metallic or other impermeable covers;
- A pump to pull air through the cartridge;
- A data collection log;

- A sodium iodide gamma scintillation detector and analyzer; and
- An analytic scale capable of weighing small differences in weight (up to several grams) due to water adsorbed by the charcoal.

Laboratory analysis of the saturated charcoal cartridge is performed using a sodium iodide gamma scintillation detector to count the gamma rays emitted by the radon decay products adsorbed on the carbon. The detectors may be used in conjunction with a multi-channel gamma spectrometer or with a single-channel analyzer calibrated to include the appropriate gamma energies.

2.6.4.1.3 Grab Radon Pump/Collapsible Bag Sampling (GB). The equipment requirements for this method is similar to those for the PB method of Section 2.6.4.2.

2.6.4.2 Pump/Collapsible Bag Devices (PB). The following equipment is required to conduct measurements using the PB method:

- A pump with a suitable uniform flow rate. The materials of the pump should not absorb or off-gas any substantial amount of radon;
- A collapsible bag of tested, low radon-loss material; and
- A data collection log.

2.6.4.3 Three-Day Integrating Evacuated Scintillation Cells (SC). The following equipment is required to measure radon with an evacuated cell:

- An evacuated cell with the restricter valve and vacuum gauge prepared by the supplier;
- An instruction sheet and a shipping container (along with a prepaid mailing label, if appropriate; and
- A data collection log.

2.6.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The measurement devices should not be deployed if the occupant's schedule prohibits terminating the measurement at the time selected.

Prior to collection of the grab radon sample, proper operation of the counting equipment must be verified, and counter efficiency and background must be determined. In addition, a background for each cartridge or cell should be determined prior to sampling. This may be done using the procedures described in Section 2.6.13 for flask counting.

For highly accurate cell measurements, it is necessary to standardize cell pressure prior to counting because the path lengths of alpha particles are a function of air density. For example, a cell calibrated at sea level and used to count a sample collected at Grand Junction, Colorado (1,370 meters above sea level) would overestimate the radon activity of the sample by about nine percent (George 1983). This error probably approaches the maximum that would be encountered; therefore, it may not be necessary to make this correction if this error can be tolerated. Correction procedures are given elsewhere (George 1983).

2.6.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

2.6.7 Deployment

2.6.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

2.6.7.2 Sampling with GB, GC, and GS. All air samples drawn into scintillation cells or flasks must be filtered to remove radon decay products and other airborne radioactive particulates. The sampling hose should be short so as to draw room air (not hose air) into the cell. Filters may be reused many times as long as they remain undamaged and functional.

For collection of a sample using a single-valve cell (Lucas-type), the cell is evacuated to at least 25 inches of mercury, the filter is attached to the cell, and the valve is opened allowing the cell to fill with air. At least 10 seconds should be allowed for the cell to fill completely. To ensure a good vacuum at the time of sampling, the cell may be evacuated using a small hand-operated pump in the room being sampled. It is good practice to evacuate the cell at least five times, allowing it to fill completely with room air each time. The air to be sampled must flow through the filter each time. If it can be demonstrated that the cells and valves do not leak, it is acceptable to evacuate the cells in the laboratory and simply attach the filter and open the valve in the building to collect a sample.

To sample using the double-valve, flow-through type cell, the filter should be attached to the inlet valve and a suitable vacuum pump should be attached to the other valve. The pump may be motor-driven or hand-operated. To begin sampling, both valves should be opened and the pump operated to flow at least 10 complete air exchanges through the cell. The pump is then stopped and both valves are closed.

Sampling using the GC or GB method is accomplished by opening and attaching a prepared sealed cartridge or collapsible bag to the sampling pump. For charcoal cartridges, the pump should draw air through the cartridge at approximately the same rate as that used in calibrating the system. Sampling should continue until the charcoal collects enough radon to be in equilibrium with the radon at the sampling site. A one-hour sampling period is typical for most GC systems. For the GB method, the pump should have a known uniform flow rate and the system should be leak-proof.

2.6.7.3 Timely Deployment of SCs. SC devices should be deployed within the period specified by the supplier. Until they are deployed, they should remain tightly sealed to maintain maximum sensitivity and accuracy.

To deploy the SC device, the reading of the attached vacuum gauge must be recorded on the log sheet along with the start-date and -time for the sample. The sample collection is started by opening the main valve according to the supplier's instructions.

2.6.8 Retrieval of Devices

2.6.8.1 Grab Radon Sampling Techniques. All pertinent sampling information (discussed in Sections 1.2.4 and 2.6.7) should be recorded after completing the measurement. The detectors should be packaged carefully for return to the counting location so that the samples will not be lost due to breakage, valves being opened, or loss of cartridge integrity.

2.6.8.2 Three-Day Integrating Evacuated Scintillation Cells (SC). The SC device should be deployed for the measurement period specified in the instructions supplied by the analytical laboratory (typically three days). If the occupant is terminating the sampling, the instructions should inform the occupant of when and how to terminate the sampling period and should indicate that the actual time of termination must be documented on the data form. In addition, the vacuum gauge reading must be recorded on the data form after the sampling valve is closed. The occupant should also be instructed to send the device to the laboratory as soon as possible, preferably on the day of sample termination.

At the end of the monitoring period, the device should be inspected for any deviation from the conditions described in the log book at the time of deployment. Any changes should be noted.

2.6.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made. In addition to this list, the following are method-specific details of documentation requirements.

- For GBs, GCs, and GSs, the serial numbers of cells, cartridges, bags, pumps, and counting equipment should also be recorded.
- For PBs, the serial numbers of bags, pumps, and equipment used for analysis of the radon concentration should also be recorded.
- For SCs, the start-time and stop-time vacuum gauge readings should also be recorded, along with the serial numbers of the cells and counting equipment.

2.6.10 Counting and Calculations

2.6.10.1 Grab Radon Sampling Techniques

2.6.10.1.1 Grab Radon/Scintillation Cell Sampling (GS). Cells should not be counted for at least four hours following the time of collection. Background and check sources should be counted as described in Section 2.6.13. The cell to be counted is placed on the photomultiplier tube, the cover placed over the cell, and the system allowed to dark-adapt. The cell may then be counted for a sufficient period to collect an adequate number of counts for good counting statistics in relation to the system background counts.

2.6.10.1.2 Grab Radon/Activated Charcoal Sampling (GC). Cartridges should not be analyzed for at least four hours after the end of sampling to allow for ingrowth of the radon decay products. Cartridges should then be analyzed in a laboratory following removal from the sampling location. The cartridge should be weighed, and if necessary, a correction should be applied for the increase in weight due to moisture adsorption. The maximum allowable delay time between the end of sampling and analysis will vary with the background experienced in each laboratory and should be evaluated, especially if sensitivity is of prime consideration. The cartridge should be analyzed on a calibrated sodium iodide gamma scintillation system or a germanium gamma detector.

2.6.10.1.3 Grab Radon Pump/Collapsible Bag Sampling (GB). After a four-hour waiting period, the concentration of radon in the bag can be analyzed by any of the standard methods including the GS method described above (Section 2.6.10.1.1).

2.6.10.1.4 Cell Flushing and Storage. After the cells have been counted and data are satisfactorily recorded, the cells must be flushed with aged air or nitrogen to remove the sample. Flow-through cells are flushed with at least 10 volume exchanges at a flow of about two liters per minute. Cells with single valves are evacuated and refilled with aged air or nitrogen at least five times. The cells are left filled with aged air or nitrogen and allowed to sit overnight before being counted for background. If an acceptable background is obtained, the cell is ready for reuse.

2.6.10.2 Pump/Collapsible Bag Devices (PB). If the radon concentration in the collapsible bag is to be analyzed on site, the appropriate grab radon sampling protocol (Section 2.6.10.1) should be followed.

If the radon concentration is to be measured by an analysis laboratory, the bag should be delivered to the laboratory as soon as possible following completion of sampling, especially if low concentrations are being measured.

2.6.10.3 Three-Day Integrating Evacuated Scintillation Cells (SC). SC devices should be returned to the supplier's analysis laboratory as soon as possible following removal from the buildings. The maximum allowable delay time between the end of sampling and analysis should not exceed the time specified by the supplier's instructions, especially if sensitivity is an important consideration. Corrections for the radon-222 decay during sampling, during the interval between sampling and counting, and during counting, will be made by the analysis laboratory.

2.6.11 Analysis Requirements

2.6.11.1 Sensitivity.

2.6.11.1.1 Grab Radon Sampling Techniques. The sensitivity of the GS method is dependent on the volume of the cell being used. However, sensitivities of 0.1 picoCuries per liter (pCi/L) are achievable (George 1980, George 1983). For the GC method, the lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) should be 1.0 pCi/L or less. This can be achieved normally with a counting time of up to 30 minutes. The sensitivity of the GB method depends on the analysis method used.

2.6.11.1.2 Pump/Collapsible Bag Devices (PB). The LLD for a PB will depend on the method used to analyze the contents of the bag. If a GS method is used, an LLD of a few tenths of a pCi/L should be possible.

2.6.11.1.3 Three-Day Integrating Evacuated Scintillation Cells (SC). The LLD should be specified by individual suppliers for SC devices exposed and shipped according to their directions. It is estimated that LLDs of a few tenths of a pCi/L are achievable with these devices.

2.6.11.2 Precision. The results of duplicates (collocated measurements) should be monitored and recorded using the results of the duplicate device analyses described in Section 2.6.12.3 of this protocol. These methods can produce duplicate measurements with a coefficient of variation of 10 percent or less at 4 pCi/L or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored frequently over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.6.12 Quality Assurance

The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the intended structure. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

This section describes five parts of a quality assurance program: (1) calibration of the system, (2) known exposure measurements, (3) duplicate (collocated) devices, (4) background measurements/control devices, and (5) routine instrument checks. Each type of method (GB, GC, GS, PB, and SC) requires some variation of all parts of the program.

2.6.12.1 Calibration

Every device should be calibrated in a radon calibration chamber before being put into service, and after any repairs or modifications. Subsequent recalibrations should be done once every 12 months, with cross-checks to a recently calibrated instrument at least semiannually.

2.6.12.1.1 Calibration Factors. Determination of calibration factors requires exposure of calibration devices to known concentrations of radon-222 in a radon exposure chamber at carefully measured radon concentrations. Since the cells are subject to shipping and handling, they should be recalibrated periodically at radon levels similar to those found in tested buildings. Scintillation counting systems used to count exposed cells should be either the system used to calibrate the cell or one calibrated against that system.

2.6.12.1.2 <u>Cell Calibration</u>. If a GS method of measuring the radon concentrations is used in the PB or GB methods, the following procedure on calibration should be followed.

The cell counting system consisting of the scaler, detector, and high-voltage supply must be calibrated. The correct high voltage is determined by increasing the high voltage by increments and plotting the resultant counts. This procedure is described elsewhere (George 1983). Each counting system should be calibrated in a radon calibration chamber before being put into service, and after any repairs or modifications. Subsequent recalibrations should be done once every 12 months, with cross-checks to a recently calibrated instrument at least semiannually. Also, a check source or calibration cell should be counted in each analysis system each day to demonstrate proper operation prior to counting any samples.

A separate calibration factor must be obtained for each cell in the counting system. This is done by filling each cell with radon of a known concentration and counting the cell to determine the conversion factor (in counts per minute per pCi). The known concentration of radon may be obtained from a radon calibration chamber or estimated from a bubbler tube containing a known concentration of radium. These calibration procedures are discussed in more detail elsewhere (Beckman 1975, George 1976, Lucas 1957).

2.6.12.1.3 <u>Grab-Radon/Activated Charcoal (GC) Method Calibration</u>. This method must be calibrated in a radon calibration chamber to establish a calibration factor for a specific cartridge model. Samples should be taken at different humidities and temperatures to establish correction factors. Calibration should be carried out at several flow rates and exposure times to verify the acceptable limits. Calibration factors must be established with the identical gamma counting system and counting geometry used in sampling.

2.6.12.2 <u>Known Exposure Measurements</u>. Anyone providing measurement services using these methods should submit devices with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure (spiked) devices should be labeled in the same manner as the field devices to assure identical processing. The results of the known exposure analyses should be monitored and recorded, and any significant deviation from the known concentration to which they were exposed should be investigated.

2.6.12.3 <u>Duplicate (Collocated) Devices</u>. Anyone providing measurement services with these methods should place duplicate devices in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller.

To the greatest extent possible, care should be taken to ensure that the samples are duplicates, are taken in close proximity, and are away from drafts. The samples selected for duplication should be distributed systematically throughout the entire population of samples. The duplicate devices should be shipped, stored, exposed, and analyzed under the same conditions, and not identified as duplicates to the processing laboratory. Groups selling measurement services to homeowners can accomplish this by making two side-by-side measurements in a random selection of homes. Data from duplicate devices should be evaluated using the procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.6.12.4 Background Measurements/Control Devices

2.6.12.4.1 Background Measurements. A background count for each type of system is determined prior to measurement. When the GC method is used, the background of the charcoal should also be assessed routinely.

2.6.12.4.2 Laboratory Control Devices. The background level for each device should be established by each supplier. Suppliers should measure the background of each device before each use or periodically, with a frequency based on experience. In order to calculate the radon concentrations of the sample, the background should be subtracted from the field readings taken with that cell.

2.6.12.4.3 Field Control Devices. Field control devices (field blanks) should consist of a minimum of five percent of the devices that are deployed every month or 25, whichever is smaller. Users should set these aside from each shipment, keep them sealed and in a low radon (less than 0.2 pCi/L) environment, label them in the same manner as the field devices, and send them back to the supplier with one shipment each month for analyses. It may be clear to the analysis laboratory that these are blanks, however it is still important to conduct the analysis. For the SC method, careful initial and final readings of the vacuum gauges on the control cells and the cell background counts on analysis will be of some use in detecting an occasional leaking cell, but any background detected in a leaking cell is not relevant to the measured field sample concentrations.

2.6.12.5 Routine Instrument Checks. Proper operation of all radiation counting instruments requires that their response to a reference source be constant to within established limits. Therefore, counting equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check source at least once per day. The characteristics of the check source (i.e., geometry, type of radiation emitted, etc.) should, if possible, be similar to the samples to be analyzed. The count rate of the check source should be high enough to yield good counting statistics in a short time (for example, 1,000 to 10,000 counts per minute).

Pumps and flow meters should be checked routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

2.6.13 Supplementary Information for the Grab Radon Sampling/ Scintillation Cell (GS) Method

2.6.13.1 Procedure. The procedure described below is that used by the EPA Office of Radiation Program in its field measurement programs. It is designed for measurements made using specific cell counters and their associated cells. Equipment is available from several suppliers, and it may be necessary to modify the procedure slightly to accommodate these differences. For example, the correct cell volume must be used in calculating the activity in the cell. The following is a general procedure for equipment used by the EPA:

(1) The cells to be used are flushed with aged air or nitrogen to remove traces of the previous sample. It may be necessary to store cells for 24 hours prior to reuse if the cell had contained a high activity sample. Each cell is placed in the counter, and allowed two minutes for the system to become dark-adapted. The background of the cell is then counted for ten minutes. Background data are recorded for each cell.

(2) At the survey site, the sample is collected by flowing air into the longer tube in the top of the double-valve cell for a period sufficient to allow 10 air exchanges. For the single-valve cells, it is only necessary to open the valve on the evacuated cells and allow 10 to 15 seconds for complete filling. Cells must be filled with air forced through a filter to prevent entry of airborne particulates.

(3) The filled cells must be allowed to equilibrate for four hours prior to counting. The cells should not be exposed to bright light prior to counting.

(4) The cells are placed in the counters, and the systems are allowed to dark-adapt for two minutes. The cells are then counted. Counting time will vary based on the activity in the cell; however, at least 1,000 counts is desirable to provide good statistics.

(5) The activity in the sample is calculated and corrected for ingrowth and decay as described below.

2.6.13.2 Calculation of Results. The radon concentration in pCi/L is determined using the following formula:

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

Where:

cpm(s) = Counts per minute for the sample

cpm(bkg) = Counts per minute for background

E = Efficiency of the system determined for each cell. For the cells used by the EPA, the factor is typically 4-5 cpm/pCi.

C = Radon correction factor for decay during counting (from Exhibit 2-1)

A = Radon correction factor for decay of radon from time of collection to start of counting (from Exhibit 2-1)

V = Volume of counting cell in liters (L).

2.6.13.3 Sample Calculation. The following sample calculation demonstrates the procedure for calculating results:

- Background count for system = 10 counts in 10 minutes, or 1 cpm
- Sample count for 120 minutes = 1200 counts, or 10 cpm
- System efficiency (E) from cell calibration = 4.62 cpm/pCi
- Count time correction (C) for 120 minutes = 1.00757
- Delay time correction (A) for 4 hours = 0.97026
- Volume correction (V) for cell = 0.170 L

$$pCi/L = \frac{10\ cpm - 1\ cpm}{4.62\ cpm/pCi} \times \frac{1.00757}{0.97026} \times \frac{1}{0.170\ L} = 11.9$$

Exhibit 2-1

Radon Correction Factors

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

	A			C
Time	Minutes	Hours	Days	Hours
0	1.00000	1.00000	1.00000	1.00000
1	0.99987	0.99248	0.83431	1.00378
2	0.99975	0.98502	0.69607	1.00757
3	0.99962	0.97761	0.58074	1.01136
4	0.99950	0.97026	0.48451	1.01517
5	0.99937	0.96296	0.40423	1.01899
6	0.99925	0.95572	0.33726	1.02281
7	0.99912	0.94854	0.26138	1.02665
8	0.99899	0.94140	0.23475	1.03050
9	0.99887	0.93432	0.19586	1.03435
10	0.99874	0.92730	0.16341	1.03821
11	0.99862	0.92033	0.13633	1.04209
12	0.99849	0.91340	0.11374	1.04597
13	0.99837	0.90654	0.09490	1.04986
14	0.99824	0.89972	0.07917	1.05377
15	0.99811	0.89295	0.06605	1.05768
16	0.99799	0.88624	0.05511	1.06160
17	0.99786	0.87958	0.04598	1.06553
18	0.99774	0.87296	0.03836	1.06947
19	0.99761	0.86640	0.03200	1.07342
20	0.99749	0.85988	0.02670	1.07738
21	0.99736	0.85342	0.02228	1.08135
22	0.99724	0.84700	0.01859	1.08532
23	0.99711	0.84063	0.01551	1.08931
24	0.99699	0.83431	0.01294	1.09331
25	0.99686	0.82803	0.01079	1.09732

Exhibit 2-1 (continued)

Radon Correction Factors

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

	A			C
Time	Minutes	Hours	Days	Hours
26	0.99673	0.82181	0.00901	1.10133
27	0.99661	0.81563	0.00751	1.10536
28	0.99648	0.80950	0.00627	1.10939
29	0.99636	0.80341	0.00523	1.11344
30	0.99623	0.79737	0.00436	1.11749
31	0.99611	0.79137	0.00364	1.12155
32	0.99598	0.78542	0.00304	1.12562
33	0.99586	0.77951	0.00253	1.12971
34	0.99573	0.77365	0.00211	1.13380
35	0.99561	0.76784	0.00176	1.13790
36	0.99548	0.76206	0.00147	1.14201
37	0.99536	0.75633	0.00123	1.14613
38	0.99523	0.75064	0.00102	1.15026
39	0.99511	0.74500	0.00085	1.15440
40	0.99498	0.73940	0.00071	1.15854
41	0.99486	0.73384	0.00059	1.16270
42	0.99473	0.72832	0.00050	1.16687
43	0.99461	0.72284	0.00041	1.17105
44	0.99448	0.71741	0.00035	1.17523
45	0.99435	0.71201	0.00029	1.17943
46	0.99423	0.70666	0.00024	1.18363
47	0.99410	0.70134	0.00020	1.18784
48	0.99398	0.69607	0.00017	1.19207
49	0.99385	0.69084	0.00014	1.19630
50	0.99373	0.68564	0.00012	1.20054

Exhibit 2-1 (continued)

Radon Correction Factors

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

	A			C
Time	Minutes	Hours	Days	Hours
51	0.99360	0.68049	0.00010	1.20479
52	0.99348	0.67537	0.00008	1.20905
53	0.99335	0.67029	0.00007	1.21332
54	0.99323	0.66525	0.00006	1.21760
55	0.99310	0.66025	0.00005	1.22189
56	0.99298	0.65528	0.00004	1.22619
57	0.99286	0.65036	0.00003	1.23050
58	0.99273	0.64547	0.00003	1.23481
59	0.99261	0.64061	0.00002	1.23914
60	0.99248	0.63579	0.00002	1.24347

2.7 INTERIM PROTOCOL FOR USING UNFILTERED TRACK DETECTION (UT) TO MEASURE INDOOR RADON CONCENTRATIONS

2.7.1 Purpose

This interim protocol provides guidance for using unfiltered track detection (UT) to obtain accurate and reproducible measurements of indoor radon concentrations. The Agency has not conducted large-scale field tests using the UT technique, and this interim protocol has been prepared with the assistance of researchers who have field experience with this method. As the EPA and others acquire more experience with this interim technique, the guidelines may be revised. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.7.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be addressed to the U.S. Environmental Protection Agency, Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C., 20460.

2.7.3 Method

A UT detector consists of a piece of cellulose nitrate film packaged in a shielded container. Alpha particles emitted by radon and its decay products in air strike the detector and produce submicroscopic damage tracks. Cellulose nitrate is sensitive to alpha energies between about 1.5 MeV and 4.8 MeV (Damkjaer 1986, Jonsson 1987). It is not sensitive to radon decay products that plate out on the detector since their energies are above 5 MeV. Because the device detects (with different sensitivities) both radon and radon decay products, the equilibrium ratio (calculated as [working level X 100] per pCi/L of radon) between radon decay products and radon can affect the device's ability to measure accurately the concentration of radon gas. While the effect may not be pronounced at values found typically in homes (estimated usually in the range from 20 to 60 percent [Nazaroff and Nero 1988]), the error becomes significant when extreme values are encountered. Based on the EPA specifications, devices of this type (which are produced by several manufacturers) can be operated over an equilibrium range of about 40 percent, with the midpoint value available from the manufacturer.

At the end of the measurement period, the detectors are returned to a laboratory for processing and analysis. Detectors are placed in a caustic solution that accentuates the damage tracks so they can be counted using a microscope or an automatic spark counter. The detector may be exposed on one or both sides. The number of tracks per unit area is correlated to the radon concentration in air, using a conversion factor derived from data generated at a calibration facility. This conversion factor may vary for different ranges of equilibrium ratio because of the contribution from radon or radon decay products. Within a predetermined range, the number of tracks produced per unit of analyzed detector area per unit of time is proportional to the radon concentration.

Several factors contribute to the variability of the UT measurement results, including equilibrium ratio, differences in the detector response within and between batches of film, detector placement, differences in the number of background tracks, variations in etching conditions, and type of readout mechanism. Since the variability in UT measurement results decreases as the number of net tracks counted increases, counting more tracks over a larger area of the detector will reduce the uncertainty of the result. Whereas a counting area of a few square millimeters is typical with the filtered alpha track detector, it is more common to count one or more square centimeters with the UT detector.

2.7.4 Equipment

UT detectors are available from commercial suppliers. These suppliers offer contract services in which they provide the detector and subsequent analysis and reporting for a unit price. Establishing an in-house capability to provide packaged detectors, a calibration program, and a readout program would probably not be practical or economically advantageous for most users. Therefore, details for establishing the analytical aspects of a UT program are omitted from this protocol.

Assuming that UT detectors are obtained from a commercial supplier, the following equipment is needed to initiate monitoring in a house:

- The UT detector packaged in an individual, shielded container to prevent extraneous exposure before deployment;

- An instruction sheet for the occupant, a sample log sheet, and a shipping container (along with a mailing label, if appropriate;

- At the time of retrieval, some means for sealing the detector prior to returning it to the supplier for analysis; and

- A data collection log, if appropriate.

2.7.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The UT measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The UT detector should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

2.7.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

2.7.7 Deployment

2.7.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

If the detector is installed during a site visit, the final site selected should be shown to the building occupant to be certain it is acceptable for the duration of the measurement period.

2.7.7.2 Timely Deployment. A batch of UT detectors should be deployed into buildings as soon as possible after delivery from the supplier. To minimize chances of high background exposures, groups should not order more detectors than they can reasonably expect to install within the following few months. If the storage time exceeds more than a few months, the background exposures from a sample of the stored detectors should be assessed to determine if they are different from the background of detectors that are not stored for long periods. The supplier's instructions regarding storage and background determination should be followed. This background assessment of detectors stored for long periods is not necessary if the analysis laboratory measures routinely the background of stored detectors, and if the stored detectors remain tightly sealed.

The sampling period is initiated when the cellulose nitrate film is exposed. The detector should be inspected to ensure that it is intact and has not been physically damaged in shipment or handling.

2.7.8 Retrieval of Detectors

The device should be deployed for the measurement period specified in the instructions supplied by the analytical laboratory. If the occupant is terminating the sampling, the instructions should inform the occupant of when to terminate the sampling period and should indicate that the actual time of termination must be documented on the device. In addition, the occupant also should be instructed to send the device to the laboratory as soon as possible, preferably the day of sample termination. The analysis system should be calibrated to permit accurate analysis of devices deployed for some reasonable time beyond the recommended sampling period.

At the end of the measurement period, the detector should be inspected for damage or deviation from the conditions entered in the log book at the time of deployment. Any changes should be noted in the log book. The date of removal is entered on the data form for the detector and in the log book. The detector is then resealed according to instructions supplied by the manufacturer. After retrieval, the detectors should be returned as soon as possible to the analytical laboratory for processing.

2.7.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

2.7.10 Analysis Requirements

2.7.10.1 Sensitivity. The UT method permits analysis of large counting areas and thus can achieve high sensitivity. The lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) and the precision of a UT system are, in part, dependent upon the total number of tracks counted. The number of tracks counted is dependent on the total area analyzed, the number of film emulsion sides exposed (one or two), the length of time of deployment, and the radon concentration being measured.

2.7.10.2 Precision. The precision should be monitored using the results of the duplicate detectors described in Section 2.7.11.3 of this protocol, rather than a precision quoted by the manufacturer. It is important that precision be monitored continuously over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.7.11 Quality Assurance

The quality assurance program for a UT system includes five parts: (1) calibration, (2) known exposure measurements, (3) duplicate (collocated) detectors, (4) control detectors, and (5) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

2.7.11.1 Calibration. Every UT laboratory system should be calibrated in a radon calibration chamber at least once every 12 months. Determination of a calibration factor requires exposure of UT detectors to a known radon and decay product concentration in a radon exposure chamber. These calibration exposures are to be used to obtain or verify the conversion factor between net tracks per unit area and radon concentration. The following guidance is provided to manufacturers and suppliers of this device as minimum requirements in determining the calibration factor:

- UT detectors should be exposed in a radon chamber at several different radon and decay product concentrations similar to those expected in the tested buildings (a minimum of three different concentrations). Concentrations of radon decay products must be known in order to be included in the calculation of the calibration factor.

- A minimum of 10 detectors should be exposed at each level.

- A calibration factor should be determined for each batch of detector material received from the material supplier. Alternatively, calibration factors may be established from several sheets, and these factors extended to detectors from sheets exhibiting similar sensitivities (within pre-established tolerance limits).

- Altitude of the radon chamber must be known if located at more than 600 feet (200 meters) above sea level so that a correction can be included in the calculation of the calibration factor.

2.7.11.2 Known Exposure Measurements. Anyone providing measurement services with UT detectors should submit detectors with known radon and decay product exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure (spiked) detectors should be labeled in the same manner as field detectors to ensure identical processing. The results of the spiked detector analyses should be monitored and recorded. Any significant deviation from the known concentrations to which they were exposed should be investigated.

2.7.11.3 Duplicate (Collocated) Detectors. Anyone providing measurement services with UT devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. The pair of detectors should be treated identically in every respect. They should be shipped, stored, opened, installed, removed, and processed together, and not identified as duplicates to the processing laboratory. The samples selected for duplication should be distributed systematically throughout the entire population of measurements. Groups selling measurements to homeowners can do this by providing two detectors (instead of one) to a random selection of purchasers, with instructions to place the detectors side-by-side. Consideration should be given to providing some means to ensure that the duplicate devices are not separated during the measurement period. Data from duplicate detectors should be evaluated using the procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.7.11.4 Control Detectors

2.7.11.4.1 Laboratory Control Detectors. The laboratory background level for each batch of UT detectors should be established by each supplier. Suppliers should measure the background of a statistically significant number of unexposed detectors that have been processed according to their standard operating procedures. Normally, the analysis laboratory or supplier calculates the net readings (which are used to calculate the reported sample radon concentrations) by subtracting the laboratory blank values from the results obtained from the field detectors.

2.7.11.4.2 Field Control Detectors. Field control UT detectors (field blanks) should consist of a minimum of five percent of the devices that are deployed every month or 25, whichever is smaller. Users should set these aside from each shipment, keep them sealed and in a low radon (less than 0.2 pCi/L) environment, label them in the same manner as the field UT detectors to assure identical processing, and send them back to the supplier with the field UT detectors for analysis. These control devices are necessary to measure the background exposure that accumulates during shipment and storage. The results should be monitored and recorded. If one or a few field blanks have concentrations significantly greater than the LLD established by the supplier, it may indicate defective packaging or handling. If the average value from the field control devices (field blanks) is significantly greater than the LLD established by the supplier, this average value should be subtracted from the individual values reported for the other devices in the exposure group.

2.7.11.5 Routine Instrument Checks. Proper functioning of the analysis instruments and proper response by their operators require that the equipment be subject to routine checks. Daily or more frequent monitoring of equipment and operators is vital to ensuring consistently accurate results.

Section 3: INDOOR RADON DECAY PRODUCT MEASUREMENT DEVICE PROTOCOLS

3.1 PROTOCOL FOR USING CONTINUOUS WORKING LEVEL MONITORS (CW) TO MEASURE INDOOR RADON DECAY PRODUCT CONCENTRATIONS

3.1.1 Purpose

This protocol provides guidance for using continuous working level monitors (CW) to obtain accurate and reproducible measurements of indoor radon decay product concentrations. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

3.1.2 Scope

This protocol covers, in general terms, the sample collection and analysis method, the equipment needed, and the quality control objectives of measurements made with CW. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency, Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch 401 M Street, S.W., Washington, D.C., 20460.

3.1.3 Method

The CW method samples the ambient air by filtering airborne particles as the air is drawn through a filter cartridge at a low flow rate of about 0.1 to one liter per minute. An alpha detector such as a diffused-junction or surface-barrier detector counts the alpha particles produced by the radon decay products as they decay on the filter. The detector is set normally to detect alpha particles with energies between two and eight MeV. The alpha particles emitted from the radon decay products radium A (Po-218) and radium C' (Po-214) are the significant contributors to the events that are measured by the detector. All CW detectors are capable of measuring individual radon and thoron decay products, while some can be adapted to measure the percentage of thoron decay products. The event count is directly proportional to the number of alpha particles emitted by the radon decay products on the filter. The unit contains typically a microprocessor that stores the number of counts and elapsed time. The CW detector can be set to record the total counts registered over specified time periods. The unit must be calibrated in a calibration facility to convert count rate to Working Level (WL) values. This may be done initially by the manufacturer, and should be done periodically thereafter by the operator.

3.1.4 Equipment

In addition to the CW detector, equipment needed includes replacement filters, a readout or programming device (if not part of the detector), an alpha-emitting check source, and an air flow rate meter.

3.1.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The CW measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The CW detector should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

3.1.5.1 Pre-Sampling Testing. The CW detector should be tested carefully before and after each measurement in order to:

- Verify that a new filter has been installed and the input parameters and clock are set properly;
- Measure the detector's efficiency with a check source such as Am-241 or Th-230 and ascertain that it compares well with the technical specifications for the unit; and
- Verify the operation of the pump.

When feasible, the unit should be checked after every fourth 48-hour measurement or week of operation to measure the background count rate using the procedures that are in the operating manual for the instrument.

In addition, participation in a laboratory intercomparison program should be conducted initially and at least once every 12 months thereafter, and after equipment repair, to verify that the conversion factor used by the microprocessor is accurate. This is done by comparing the unit's response to a known radon decay product concentration. At this time, the correct operation of the pump also should be verified by measuring the flow rate.

3.1.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

3.1.7 Deployment and Operation

3.1.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

3.1.7.2 Operation. The CW detector should be programmed to run continuously, recording the periodic integrated WL and, when possible, the total integrated average WL. The sampling period should be 48 hours, with a grace period of two hours (i.e., a sampling period of 46 hours is acceptable if conditions prohibit terminating sampling after exactly 48 hours). The longer the operating time, the smaller the uncertainty associated with using the measurement result to estimate a longer-term average concentration. The integrated average WL over the measurement period should be reported as the measurement result. If results are also reported in pCi/L, it should be stated that this approximate conversion is based on a 50 percent equilibrium ratio, which is typical of the home environment, and any individual environment may have a different relationship between radon and decay products.

3.1.8 Retrieval of Detectors

When the measurement is terminated, the operator should note the stop-date and -time and whether the standardized conditions are still in effect.

3.1.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

In addition, the serial number of the CW detector and calibration factor used should be recorded.

3.1.10 Analysis Requirements

3.1.10.1 Sensitivity. All known commercially available CW detectors are capable of a lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) of 0.01 WL or less.

3.1.10.2. Precision. Precision should be monitored and recorded using the results of side-by-side measurements described in Section 3.1.11.3 of this protocol. This method can produce duplicate measurements with a coefficient of variation of 10 percent or less at 0.02 WL or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored frequently over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

3.1.11 Quality Assurance

The quality assurance program for a CW system includes four parts: (1) calibration and known exposures, (2) background measurements, (3) duplicate measurements, and (4) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

3.1.11.1 Calibration and Known Exposures. Every CW detector should be calibrated in a radon calibration chamber before being put into service, and after any repairs or modifications. Subsequent recalibrations should be done once every 12 months, with cross-checks to a recently calibrated instrument at least semiannually.

3.1.11.2 Background Measurements. Background count rate checks must be conducted after at least every 168 hours (fourth 48-hour measurement) of operation and whenever the unit is calibrated. The CW should be purged with clean, aged air or nitrogen in accordance with the procedures given in the instrument's operating manual. In addition, the background count rate may be monitored more frequently by operating the CW in a low radon environment.

3.1.11.3 Duplicate Measurements. When two or more CW detectors are available, the precision of the measurements can be estimated by operating the detectors side-by-side. The analysis of duplicate results should follow the methodology described by Goldin (section 5.3 in Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

3.1.11.4 Routine Instrument Checks. Checks using an Am-241 or similar-energy alpha check source must be performed before and after each measurement. In addition, it is important to check regularly all components of the equipment that affect the result.

Pump and flow meters should be checked routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

3.2 PROTOCOL FOR USING RADON PROGENY INTEGRATING SAMPLING UNITS (RPISU *or* RP) TO MEASURE INDOOR RADON DECAY PRODUCT CONCENTRATIONS

3.2.1 Purpose

This protocol provides guidance for using radon progeny integrating sampling units (RPISU or RP) to produce accurate and reproducible measurements of indoor radon decay product concentrations. Adherence to this procedure will help ensure uniformity in measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

3.2.2 Scope

This protocol covers, in general terms, the equipment, procedures, analysis, and quality control objectives for measurements made with RPs. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency, Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C., 20460.

3.2.3 Method

3.2.3.1 Thermoluminescent Dosimeter (TLD) RP. There are three types of RPs. The TLD type contains an air sampling pump that draws a continuous, uniform flow of air through a detector assembly. The detector assembly includes a filter and at least two TLDs. One TLD measures the radiation emitted from radon decay products collected on the filter, and the other TLD is used for a background gamma correction. This RP is intended for a sampling period of 48 hours to a few weeks.

Analysis of the detector TLDs is performed in a laboratory using a TLD reader. Interpretation of the results of this measurement requires a calibration for the detector and the analysis system based on exposures to known concentrations of radon decay products.

3.2.3.2 Alpha Track Detector (ATD) RP. A second type of RP consists of an air sampling pump and an ATD assembly. The air sampling pump draws a continuous, uniform flow of air through a filter in the detector assembly where the radon decay products are deposited. Opposite to the side of the filter where the radon decay products are deposited is a cylinder with three collimating cylindrical holes. Alpha particles emitted from the radon decay products on the filter pass through the collimating holes and through different thicknesses of energy-absorbing film before impinging on a disc of alpha track detecting plastic film (LR-115 or CR-39). Analysis of the number of alpha particle tracks in each of the three sectors of the film allows the determination of the number of alpha particles derived from radium A (Po-218) and radium C' (Po-214). This feature allows the determination of the equilibrium factor for the radon decay products. This type of RP is intended for a sampling period of about 48 hours to a few weeks.

Etching and counting of the alpha track assembly is carried out by mailing the detector film to the analysis laboratory. Interpretation of the results of this measurement requires a calibration for the detector and the analysis system based on exposure to known concentrations of radon decay products.

3.2.3.3 Electret RP. The electret RP is similar in operation to the TLD-type RP, except that the TLD is replaced with an electret. The current model of this device contains a one-liter-per-minute constant air flow pump and collects the decay products on a 11.4 cm^2 filter. As the radon decay products that are collected on the filter decay, negatively charged ions generated by alpha particle radiation are collected on a positively-charged electret, thereby reducing its surface voltage. This reduction has been demonstrated to be proportional to the radon decay product concentration. For more general information on electrets, the reader should refer to Section 2.3.

RPs are true integrating instruments if the pump flow rate is uniform throughout the sampling period. The electret must be removed from the chamber and the electret voltage measured with a special surface voltmeter both before and after exposure. To determine the average radon concentration during the exposure period, the difference between the initial and final voltages is divided first by a calibration factor and then by the number of exposure days. A background radon concentration equivalent of ambient gamma radiation is subtracted to compute radon concentration. Electret voltage measurements can be made in a laboratory or in the field.

3.2.4 Equipment

The three types of RP sampling systems include a sampling pump and the detector assembly. Sampling with the TLD-type RP requires either a fresh detector assembly or fresh TLD chips to be inserted in the detector assembly. Using the electret-type RP requires a sufficient charge on the electret. Sampling with the ATD-type RP requires a fresh detector disc (LR-115 or CR-39). An air flow rate meter should be available for checking flow rates with the RP, and spare filters should be available as replacements as needed.

3.2.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The RP measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The RPISU should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

Prior to installation in the building, the pump should be checked to ensure that it is operable and capable of maintaining a uniform flow through the detector assembly. Extra pump assemblies should be available during deployment in case a problem is encountered.

Arrangements should be made with the occupant of the building to ensure that entry into the building is possible at the time of installation, and to determine availability of a suitable electrical outlet near the sampling area in the selected room.

3.2.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

3.2.7 Deployment and Operation

3.2.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

In addition, the air intake (sampling head) should be placed at least 50 centimeters (20 inches) above the floor and at least 10 centimeters (four inches) from surfaces that may obstruct flow.

3.2.7.2 Operation. The RP should be installed and, if possible, the air flow rate checked with a calibrated flow meter. The location, date, starting time, running-time meter reading, and flow rate should be recorded on the detector assembly envelope and in a log. The RP should be observed for a few minutes after initiating measurements to ensure continued operation. The occupants should also be informed about the RP and requested that they report any problems or pump shut-down. The occupants should be aware of the length of time the RP will be operated, and an appointment should be arranged to retrieve the unit. The criteria for the standardized measurement conditions (Section 1.2.2) should also be told to the occupants.

The sampling period should be at least 48 hours, and may need to be longer, depending on the type of RP head. A longer operating time decreases the uncertainty associated with the measurement result.

3.2.8 Retrieval of Devices

Prior to pump shut-down, the flow rate should be measured with a calibrated flow meter (if possible) and the unit should be observed briefly to ensure that it is operating properly. The detector assembly or detector film should be removed for processing and the date, time, running-time meter reading, and flow rate should be recorded both on the envelope and in a log book. The filter should be checked for holes or dust loading and any other observed conditions that might affect the measurement. If TLDs or film discs are to be removed from the detector assembly, removal should be delayed for at least three hours after sampling is completed to allow for decay and registration of radon decay products on the filter.

3.2.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

In addition, the serial numbers of the RPs, TLDs, film discs, or electrets must be recorded.

3.2.10 Analysis Requirements

Analysis of the film from the ATD-type RPs requires an analysis laboratory equipped to etch and count alpha track film.

Analysis of TLD-type RPs requires a TLD reader. The TLD reader is an instrument that heats the TLDs at a uniform and reproducible rate and measures simultaneously the light emitted by the thermoluminescent material. The readout process is controlled carefully, with the detector purged with nitrogen to prevent spurious emissions. Prior to analyzing the RPISU dosimeters, the TLD reader should be tested periodically using dosimeters exposed to a known level of alpha or gamma radiation. TLDs are prepared for reuse by cleaning and annealing at the prescribed temperature in an oven.

Analysis of the electret-type RPs requires a specially-built surface voltmeter for measuring electret voltages before and after exposure. For more information on analysis requirements, the reader should refer to Section 2.3.10 (Electret Ion Chamber Radon Detectors) of the Radon Measurement Device Protocols.

3.2.10.1 Sensitivity. The lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) should be specified by individual suppliers for RP detectors exposed according to their directions. The LLD will depend upon the length of the exposure and the background of the detector for materials used. The LLD should be calculated using the results of the laboratory control devices.

3.2.10.2 Precision. Precision should be monitored and recorded using the results of the duplicate detector analyses described in Section 3.2.11.3. This method may achieve a coefficient of variation of 10 percent at radon decay product concentrations of 0.02 WL or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored continuously over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

3.2.11 Quality Assurance

The quality assurance program for an RP system includes five parts: (1) calibration, (2) known exposure detectors, (3) duplicate (collocated) detectors, (4) control detectors, and (5) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

Users of electret-type RPs should follow the quality assurance guidance given for electret ion chamber devices in Section 2.3 of this document.

3.2.11.1 Calibration. Every RP should be calibrated in a radon calibration chamber before being put into service, and after any repairs or modifications. Subsequent recalibrations should be done once every 12 months, with cross-checks to a recently calibrated instrument at least semiannually. Calibration of RPs requires exposure in a controlled radon-exposure chamber where the radon decay product concentration is known during the exposure period. The detector must be exposed in the chamber using the normal operating flow rate for the RP sampling pumps. Calibration should include exposure of a minimum of four detectors exposed at different radon decay product concentrations representative of the range found in routine measurements. The relationship of TLD reader units or etched track reader units to working level (WL) for a given sample volume and the standard error associated with this measurement should be determined. Calibration of the RPs also includes testing to ensure accuracy of the flow rate measurement.

3.2.11.2 Known Exposure Devices. Anyone providing measurement services with RP devices should submit detectors with known decay product exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure detectors should be labeled in the same manner as the field detectors to assure blind processing. The results of the known exposure detector analysis should be monitored and recorded, and any significant deviation from the known concentration to which they were exposed should be investigated.

3.2.11.3 Duplicate (Collocated) Detectors. Anyone providing measurement services with RP devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. The duplicate detectors should be shipped, stored, exposed, and analyzed under the same conditions. The samples selected for duplication should be distributed systematically throughout the entire population of samples. Groups selling measurement services to homeowners can do this by making two side-by-side measurements in a random selection of homes. Data from duplicate detectors should be evaluated using the procedures described by Goldin (section 5.3 in Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

3.2.11.4 Control Detectors. TLD-type RPs use a TLD that is shielded from the gamma radiation emitted by the material on the filter. This TLD is incorporated in the detector assembly to measure the environmental gamma exposure of the sampling detector. The two TLDs are processed identically and the environmental gamma exposure is subtracted from the sample reading. Electret-type RPs also require an environmental gamma background correction.

3.2.11.4.1 Laboratory Control Detectors. The laboratory background level for each batch of assembled TLDs should be established by each supplier. Suppliers should measure the background of a statistically significant number of unexposed thermoluminescent assemblies that have been processed according to their standard operating procedures. To calculate the net readings used to calculate the reported sample radon concentrations, the analysis laboratory subtracts this laboratory blank value from the results obtained from the field detectors.

Similarly, the laboratory background level for each batch of ATD-type RPs should be established by each supplier of these detectors. Suppliers should measure the background of a statistically significant number of unexposed detector films that have been processed according to their standard operating procedures. The analysis laboratory will subtract this laboratory blank value from the results obtained from the field detectors before calculating the final result.

Users of electret-type RPs should follow similar control detector procedures discussed in section 2.3.11.1.

3.2.11.4.2 Field Control Detectors (Blanks). Field control detectors (field blanks) should consist of a minimum of five percent of the detectors deployed each month or 25, whichever is smaller. Users should set these aside from each shipment, keep them sealed, label them in the same manner as the field detectors, and, where applicable, send them back to the analysis laboratory as blind controls with one shipment each month. These field blank detectors measure the background exposure that may accumulate during shipment or storage. The results should be monitored and recorded. If one or a few of the field blanks have concentrations significantly greater than the LLD established by the supplier, it may indicate defective material or procedures. If the average value from the background control detectors (field blanks) is significantly greater than the LLD established by the supplier, this average value should be subtracted from the individual values reported for the other detectors in the exposure group. The cause for the elevated field blank readings should then be investigated.

3.2.11.5 Routine Instrument Checks. Proper operation of all analysis equipment requires that their response to a reference source be constant to within established limits. Therefore, analysis equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check source at least once per day during operation.

Pumps and flow meters should be checked routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

3.3 PROTOCOL FOR USING GRAB SAMPLING-WORKING LEVEL (GW) TO MEASURE INDOOR RADON DECAY PRODUCT CONCENTRATIONS

3.3.1 Purpose

This protocol provides guidance for using the grab sampling-working level (GW) technique to provide accurate and reproducible measurements of indoor radon decay product concentrations. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this procedure will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled.

The results of the GW method are influenced greatly by conditions that exist in the building during and for up to 12 hours prior to the measurement. It is therefore especially important when making grab measurements to conform to the closed-building conditions for 12 hours before the measurement. Grab sampling techniques are not recommended for measurements made to determine the need for remedial action. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

3.3.2 Scope

This procedure covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency, Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C., 20460.

3.3.3 Method

Grab sampling measurements of radon decay product concentrations in air are performed by collecting the decay products from a known volume of air on a filter and by counting the activity on the filter during or following collection. Several methods for performing such measurements have been developed and have been described previously (George 1980). Comparable results may be obtained using all these methods. This procedure, however, will describe two methods that have been used most widely with good results. These are the Kusnetz procedure and the modified Tsivoglou procedure.

The Kusnetz procedure (ANSI 1973, Kusnetz 1956) may be used to obtain results in working levels (WL) when the concentration of individual decay products is unimportant. Decay products from up to 100 liters of air are collected on a filter in a five-minute sampling period. The total alpha activity on the filter is counted at any time between 40 and 90 minutes after the end of sampling. Counting can be done using a scintillation-type counter to obtain gross alpha counts for the selected period. Counts from the filter are converted to disintegrations using the appropriate counter efficiency. The disintegrations from the decay products collected from the known volume of air may be converted into WLs using the appropriate "Kusnetz factor" (see Section 3.4.11, Exhibit 3-1) for the counting time used.

The Tsivoglou procedure (Tsivoglou et al. 1953), as modified by Thomas (Thomas 1972), may be used to determine WL and the concentration of the individual radon decay products. Sampling is the same as that used for the Kusnetz procedure; however, the filter is counted three separate times following collection. The filter is counted between the interval of two to five minutes, six to 20 minutes, and 21 to 30 minutes, following completion of sampling. Count results are used in a series of equations to calculate concentrations of the three radon decay products and WL. These equations and an example calculation appear in Section 3.4.11.

3.3.4 Equipment

Equipment required for radon decay product concentration determination by GW consists of the following items:

- An air sampling pump capable of maintaining a flow rate of two to 25 liters per minute through the selected filter. The flow rate should not vary significantly during the sampling period;
- A filter holder (with adapters for attachment) to accept a 25- or 47-mm diameter, 0.8-micron membrane or glass fiber filter;
- A calibrated air flow measurement device to determine the air flow through the filter during sampling;
- A stopwatch or timer for accurate timing of sampling and counting;
- A scintillation counter and a zinc sulfide scintillation disc;
- A National Institute of Standards and Technology (NIST)-traceable alpha calibration source to determine counter efficiency; and
- A data collection log.

3.3.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The GW measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The GW device should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

3.3.5.1 Premeasurement Testing

Prior to collection of the sample, proper operation of the equipment must be verified, and the counter efficiency and background must be determined. This is especially critical for the Tsivoglou procedure, in which the sample counting must begin two minutes following the end of sampling.

The air pump, filter assembly, and flow meter must be tested to ensure that there are no leaks in the system. The scintillation counter must be operated with the scintillation tray (where applicable) and scintillation disc in place to determine background for the counting system. Also, the counter must be operated with an NIST-traceable alpha calibration source in place of a filter in the counting location to determine system counting efficiency. Both the system background and system efficiency are used in the calculation of results from the actual sample.

3.3.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

3.3.7 Deployment

3.3.7.1 Location in Room. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

3.3.7.2 Sampling. A new filter should be placed in the filter holder prior to entering the building. Care should be taken to avoid puncturing the filter and to avoid leakage. The sampling is initiated by starting the pump and the clock simultaneously. The air flow rate should be noted and recorded in a log book. The time the sampling was begun should also be recorded. The sampling period should be five minutes, and the time from the beginning of sampling to the time of counting must be recorded precisely.

3.3.8 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

3.3.9 Analysis Requirements

Analysis may be done using the Kusnetz procedure (ANSI 1973, Kusnetz 1956), the modified Tsivoglou procedure (Thomas 1972, Tsivoglou et al. 1953), or other procedures described elsewhere (George 1980). If the Tsivoglou procedure is used, the counting must be started two minutes following the end of sampling. Analysis using the Kusnetz procedure must be performed between 40 and 90 minutes following the end of sampling. A counting time of 10 minutes during this period is usually used. The reader should refer to Sections 3.3.3 and 3.3.11 for more information.

The filter from the holder must be removed using forceps, and placed carefully facing the scintillation phosphor. The side of the filter on which the decay products were collected must face the phosphor disc. The chamber containing the filter and disc should be closed and allowed to dark-adapt prior to starting counting. For the Tsivoglou method, this procedure of placing the filter in the counting position must be done quickly, since the first of the three counts must begin two minutes following the end of sampling. If the counter used has been shown to be slow to dark-adapt, the counting should be done in a darkened environment. Additional details on the procedure and calculations are available (Kusnetz 1956, Thomas 1972, Tsivoglou et al. 1953).

3.3.9.1 Sensitivity. For a five-minute sampling period (10 to 20 liters of air) on a 25-mm filter, the lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) using the Kusnetz or modified Tsivoglou counting procedure can be approximately 0.0005 WL (George 1980).

3.3.9.2 Precision. Precision should be monitored using the results of duplicate measurements (refer to Section 3.4.10.2). Sources of error in the procedure may result from inaccuracies in measuring the volume of air sampled, characteristics of the filter used, and measurement of the amount of radioactivity on the filter. The method can produce duplicate measurements with a coefficient of variation of 10 percent or less at 0.02 WL or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored continuously over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

3.3.10 Quality Assurance

The quality assurance program for a GW system includes three parts: (1) calibration of the system, (2) duplicate measurements, and (3) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

3.3.10.1 Calibration. Pumps and flow meters used to sample air must be calibrated routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

Every GW device should be calibrated in a radon (decay product) calibration chamber before being put into service, and after any repairs or modifications. Subsequent recalibrations should be done once every 12 months, with cross-checks to a recently calibrated instrument at least semiannually. Grab measurements should be made in a calibration chamber with known radon decay product concentrations to verify the calibration factor. These measurements should also be used to test the collection efficiency and self-absorption of the filter material being used for sampling. A change in the filter material being used requires that the new material be checked for collection efficiency in a calibration chamber.

3.3.10.2 Duplicate Measurements. Anyone providing measurement services with GW devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. To the greatest extent possible, care should be taken to ensure that the samples are duplicates. The filter heads should be relatively close to each other and away from drafts. Care should also be taken to ensure that one filter is not in the discharge air stream of the other sampler. The measurements selected for duplication should be distributed systematically throughout the entire population of measurements. Data from duplicate samples should be evaluated using the procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

3.3.10.3 Routine Instrument Checks. Proper operation of all radiation counting instruments requires that their response to a reference source be constant to within established limits. Therefore, counting equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check source at least once per day. The characteristics of the check source (i.e., geometry, type of radiation emitted, etc.) should, if possible, be similar to the samples to be analyzed. The count rate of the check source should be high enough to yield good counting statistics in a short time (for example, 1,000 to 10,000 counts per minute).

The radiological counters should have calibration checks run daily to determine counter efficiency. This is particularly important for portable counters taken into the field that may be subject to rugged use and temperature extremes. These checks are made using an NIST-traceable alpha calibration source such as Am-241. In addition, the system background count rate should be assessed regularly.

Pumps and flow meters should be checked routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

3.3.11 Supplementary Information for the Grab Sampling-Working Level (GW) Method

3.3.11.1 Sample Collection. Two commonly used methods are described below. There are several other methods reported in the literature. Sampling using these methods requires collection of radon decay products on a filter, and measuring the alpha activity of the sample with a calibrated detector at time intervals that are specific for each method.

The filter is installed in the filter holder assembly and attached to the pump. The pump is then operated for exactly five minutes, pulling air through the filter. Starting time and air flow rate should be recorded. The pump is stopped at the end of the five-minute sampling time. At this time, the stopwatch should be started or reset.

3.3.11.2 Sample Counting. Sample counting for two different techniques is described below.

3.3.11.2.1 Modified Tsivoglou Technique (Thomas 1972, Tsivoglou et al. 1953). The filter is transferred carefully from the filter holder assembly to the detector. The collection side of the filter is oriented toward the face of the detector.

The counter is operated for the following time intervals (after sampling has stopped): two to five minutes, six to 20 minutes, and 21 to 30 minutes. The total counts for each time period are then recorded.

3.3.11.2.2 Kusnetz Technique (Kusnetz 1956). The filter is transferred carefully from the filter holder assembly to the detector. The collection side of the filter is oriented toward the face of the detector.

The counter is operated over any 10-minute time interval between 40 minutes and 90 minutes after sampling starts. The total counts for the sample and the time (in minutes after sampling) at the midpoint of the 10-minute time interval are then recorded.

3.3.11.3 Data Analysis. Data analysis for the two different techniques is described below.

3.3.11.3.1 Modified Tsivoglou Technique. The concentration, in picoCuries per liter (pCi/L), of each of the radon decay products (Po-218, Pb-214, and Po-214) can be determined by using the following calculations:

$$C_2 = \frac{1}{FE} (0.16921\ G_1 - 0.08213\ G_2 + 0.07765\ G_3 - 0.5608\ R)$$

$$C_3 = \frac{1}{FE} (0.001108\ G_1 - 0.02052\ G_2 + 0.04904\ G_3 - 0.1577\ R)$$

$$C_4 = \frac{1}{FE} (-0.02236\ G_1 + 0.03310\ G_2 - 0.03766\ G_3 - 0.05720\ R)$$

It is important to note that the constants in these equations are based on a 3.04-minute half-life of Po-218. The working level (WL) associated with these concentrations can then be calculated using the following relationship:

$$WL = (1.028 \times 10^{-3} \times C_2 + 5.07 \times 10^{-3} \times C_3 + 3.728 \times 10^{-3} \times C_4)$$

Where:

C_2 = concentration of Po-218 (RaA) in pCi/L;

C_3 = concentration of Pb-214 (RaB) in pCi/L;

C_4 = concentration of Po-214 (RaC') in pCi/L;

F = sampling flow rate in liters per minute (Lpm);

E = counter efficiency in counts per minute/disintegrations per minute (cpm/dpm);

G_1 = gross alpha counts for the time interval of two to five minutes;

G_2 = gross alpha counts for the time interval of six to 20 minutes;

G_3 = gross alpha counts for the time interval of 21 to 30 minutes; and

R = background counting rate in cpm.

Reference: (Thomas 1972).

3.3.11.3.2 Kusnetz Technique. WL is calculated as follows:

$$WL = \frac{C}{K_t VE}$$

Where:

C = sample cpm - background cpm;
K_t = factor determined from Exhibit 3-1 (PHS 1957) for time from end of collection to midpoint of counting;
V = total sample air volume in liters [calculated as flow rate (L/m) x sample time (m)]; and
E = counter efficiency in cpm/dpm.

Exhibit 3-1

Kusnetz Factors
(Public Health Service 1957)

Time	K_t
40	150
42	146
44	142
46	138
48	134
50	130
52	126
54	122
56	118
58	114
60	110
62	106
64	102
66	98
68	94
70	90
72	87
74	84
76	82
78	78
80	75
82	73
84	69
86	66
88	63
90	60

3.3.11.4 Sample Problems

3.3.11.4.1 Sample Problem for the Modified Tsivoglou Technique

Given:

F = sampling flow rate = 3.5 Lpm
E = counting efficiency = 0.47 cpm/dpm
G_1 = 880
G_2 = 2660
G_3 = 1460
R = 0.5

Calculate:

$$C_2 = \frac{1}{3.5 \times 0.47} (0.16921 \times 880 - 0.08213 \times 2660 + 0.07765 \times 1460 - 0.05608 \times 0.5)$$

$C_2 = 26.8$ pCi/L

$$C_3 = \frac{1}{3.5 \times 0.47} (0.001108 \times 880 - 0.02052 \times 2660 + 0.04904 \times 1460 - 0.1577 \times 0.5)$$

$C_3 = 10.9$ pCi/L

$$C_4 = \frac{1}{3.5 \times 0.47} (-0.02236 \times 880 + 0.03310 \times 2660 - 0.03766 \times 1460 - 0.05720 \times 0.5)$$

$C_4 = 8.1$ pCi/L

$$WL = (1.028 \times 10^{-3} \times 26.8 + 5.07 \times 10^{-3} \times 10.9 + 3.728 \times 10^{-3} \times 8.1)$$

$WL = 0.11$

3.3.11.4.2 Sample Problem for the Kusnetz Technique

Background count = 3 counts in 5 minutes, or 0.6 cpm

Standard count = 5,985 counts in 5 minutes, or 1,197 cpm

$$\text{Efficiency} = \frac{1197\ \text{cpm} - 0.6\ \text{cpm}}{2430\ \text{dpm}} = 0.49\ \text{(known source of 2439 dpm)}$$

Sample volume = 4.4 liter/minute x 5 minutes = 22 liters

Sample count at 45 minutes (time from end of sampling period to start of counting period) = 560 counts in 10 minutes, or 56 cpm

K_t at 50 minutes (from Exhibit 3-1) = 130

$$\text{WL} = \frac{56\ \text{cpm} - 0.6\ \text{cpm}}{130 \times 22\ \text{L} \times 0.49}$$

WL = 0.04

GLOSSARY

Accuracy: The degree of agreement of a measurement (X) with an accepted reference or true value (T); usually expressed as the difference 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 measurement 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 count rate: The counting rate obtained on a given instrument with a background counting sample. Typical reference background counting samples are:

- Empty planchet: for G-M detectors, internal proportional counters, low background beta counters, alpha spectrometers.
- Scintillation vial containing scintillant and sample known to contain no radioactivity: for liquid scintillation counters.
- Container filled with distilled water: for gamma spectrometers.

Background measurements: Measurements made with either active instruments exposed to a radon-free gas, such as aged air or nitrogen, or for passive detectors by analyzing unexposed detectors. Results 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 from radioactive material other than that under consideration. Background radiation due to cosmic rays and natural radioactivity is always present; background radiation may also be due to the presence of radioactive substances in building materials.

Bias: A systematic (consistent) error in test results. Bias can exist between test results and the true value (absolute bias, or lack of accuracy), or between results from different sources (relative bias). For example, if different laboratories analyze a homogeneous and stable blind sample, the relative biases among the laboratories would be measured by the differences existing among the results from the different laboratories. However, if the true value of the blind sample were known, the absolute bias or lack of accuracy from the true value would be known for each laboratory. See **Systematic error.**

Blank sample: A control sample in which the detector is unexposed and submitted for analysis. Often used to determine detector background values.

Blind spikes: Detectors exposed to known radon or decay product concentrations and submitted for analysis without being labelled as such. Used to evaluate the accuracy of the measurement.

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 satisfactory operation of an instrument.

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

$$\text{COV} = \text{RSD} = \frac{s}{X_{ave}} \times 100 \text{ for a sample,}$$

or

$$COV' = RSD' = \frac{\sigma}{\mu} \times 100 \text{ for a population.}$$

See **Relative percent difference.**

Curie (Ci): A standard measurement for radioactivity, specifically the rate of decay for a gram of radium - 37 billion decays per second. A unit of radioactivity equal to 3.7×10^{10} disintegrations per second.

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

Electron: An elementary constituent of an atom that orbits the nucleus and has a negative charge. Beta decay is radioactive decay in which an electron is emitted from a nucleus.

Electron volt (eV): One eV is equivalent to the energy gained by an electron in passing through a potential difference of one volt. One unit of energy = 1.6×10^{-12} ergs = 1.6×10^{-19} joules; 1 MeV = 10^6 eV.

Equilibrium, radioactive: A state in which the formation of atoms by decay of a parent radioactive isotope is equal to its rate of disintegration by radioactive decay.

Equilibrium ratio, radioactive: The total concentration of radon decay products (RDPs) present divided by the concentration that would exist if the RDPs were in radioactive equilibrium with the radon gas concentration which is present. At 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 RDPs never reach equilibrium in a house environment. A commonly assumed equilibrium ratio is 0.5 (i.e., the progeny are halfway toward equilibrium), in which case 1 WL corresponds to 200 pCi/L. However, equilibrium ratios vary with time and location, and ratios of 0.3 to 0.7 are commonly observed. Large buildings, including schools, often contain equilibrium ratios less than 0.5.

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 energies between 10 keV to 9 MeV.

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

Ion: An electrically charged atom in which the number of electrons does not equal the number of protons.

Ionization: The process whereby a neutral atom or molecule becomes negatively or positively charged by acquiring or losing an electron.

Ionizing radiation: Any type of radiation capable of producing ionization in materials it contacts; includes high-energy charged particles such as alpha and beta rays, and nonparticulate radiation such as gamma rays and X-rays. In contrast to wave radiation (e.g., visible light and radio waves) in which waves do not ionize adjacent atoms as they move.

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]).

Passive radon/radon decay product measurement device: A radon or radon decay product 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 does not include continuous radon/radon decay product monitors, or grab radon/radon decay product measurement systems.

PicoCurie (pCi): One pCi is one trillionth 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 one decay every 27 seconds in a volume of one liter, or 0.037 decays per second in every liter of air.

Pooled estimate of variance: An estimate of precision derived from different sets of duplicates, calculated as follows:

$$S_{dp}^2 = \frac{S_{d1}^2 (n_1 - 1) + S_{d2}^2 (n_2 - 1)}{(n_1 - 1) + (n_2 - 1)}$$

where:

S^2dp = pooled variance;
S^2d1 = variance observed with the first group of detectors or equipment;
S^2d2 = variance observed with the second group of detectors or equipment;
n_1 = sample size of the first group of detectors or equipment; and
n_2 = sample size of the second group of detectors or equipment.

Precision: A measure of mutual agreement among individual measurements of the same property, usually under prescribed and similar conditions. Most desirably expressed in terms of the standard deviation, but can be expressed in terms of the variance, pooled estimate of variance, range, relative percent difference, 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, interlaboratory 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 almost exclusively 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.

Random error: Variations of repeated measurements that are random in nature and not predictable individually. The causes of random error are assumed to be indeterminate or nonassignable. The distribution of random errors is assumed generally to be normal (Gaussian).

Range: The difference between the maximum and minimum values of a set of values. When the number of values is small (i.e., eight or less), the range is a relatively sensitive (efficient) measure of variability. As the number of values increases above eight, the efficiency of the range (as an estimator of the variability) decreases rapidly. The range, or difference between two paired values, is of particular importance in air pollution measurement, since in many situations duplicate measurements are performed as part of the quality assurance program.

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

$$R_{d\%} = \frac{|X_1 - X_2|}{X_{ave}} \times 100$$

where:

X_1 = concentration observed with the first detector or equipment;
X_2 = concentration observed with the second detector, equipment, or absolute value; 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

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

Relative standard deviation: See Coefficient of variation.

Spiked measurements, or known exposure measurements: Quality control measurements in which the detector .or instrument is exposed to a known concentration 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:

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

For a finite population, the standard deviation (s) 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.

Systematic error: The condition of a consistent deviation of the results of a measurement process from the reference or known level. The cause for the deviation, or bias, may be known or unknown, but is considered "assignable" (i.e., if the cause is unknown, it should be possible to determine the cause). See **Bias**.

Time integrated sampling: Sampling 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).

Variance: Mathematically, the sample variance is the sum of squares of the differences between the individual values of a set and the arithmetic average of the set, divided by one less than the number of values:

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

For a finite population, the variance σ^2 is the sum of squares of deviations from the arithmetic mean, divided by the number of values in the population:

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

where μ is the true arithmetic mean of the population.

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 x 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).

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