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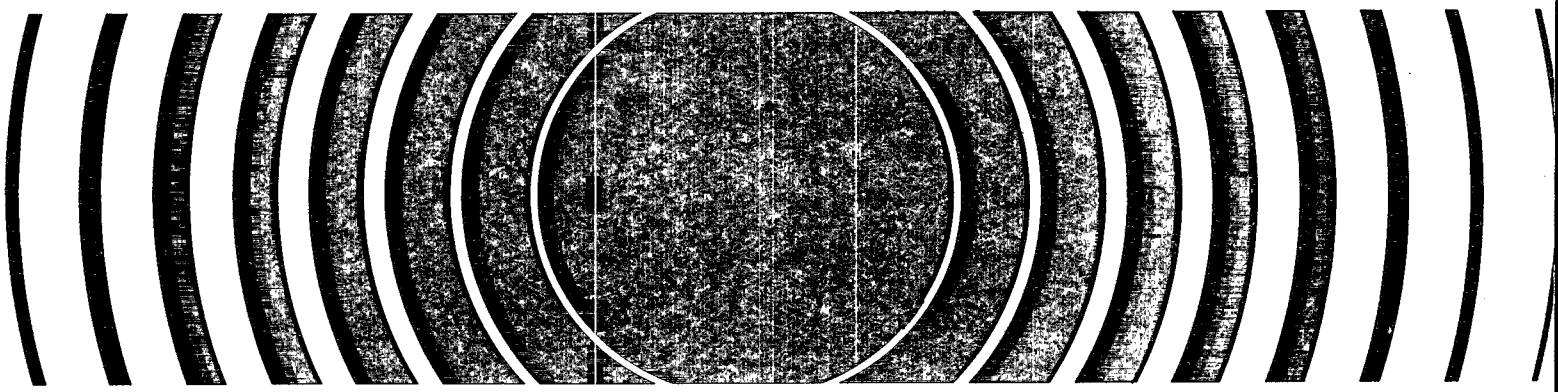
Indoor Radon and Radon Decay Product Measurement Protocols



INDOOR RADON AND RADON DECAY PRODUCT MEASUREMENT PROTOCOLS

U.S. Environmental Protection Agency
Office of Radiation Programs

Problem Assessment Branch
Radon Division

Eastern Environmental
Radiation Facility

Las Vegas Facility

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DISCLAIMER

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

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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 growing concern to State and Federal health officials. There is increased awareness that indoor radon concentrations may be greater than had once been estimated, 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 to locate houses with the potential for causing high exposure. However, in spite of the urgency to locate houses with high concentrations, 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.

This document updates the interim EPA Radon Measurement Protocols by providing guidance for using a total of 11 measurement techniques. EPA has extensive laboratory and field experience with seven of the methods: continuous working level and radon monitors, alpha-track detectors, charcoal canisters, RPISUs, and grab techniques. The remaining four methods are interim; EPA has evaluated these techniques in the laboratory and found them to be satisfactory. However, the Agency has not conducted large-scale field tests using the interim techniques, and the interim protocols have been prepared with the assistance of respected researchers who have field experience with the methods. As EPA and others acquire more experience with these interim techniques, these guidelines may be revised.

These protocols provide instrument-specific technological guidance that can be used as the basis for standard operating procedures. The Agency also has issued a report titled "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 1987), that outlines the recommended strategy for assessing indoor radon levels and provides guidance for interpreting measurement results. This strategy is summarized in the following section.

1.2 RECOMMENDED TWO-STEP STRATEGY

The EPA recognizes that radon concentrations in homes may vary greatly over time (Gesell 1983; Hess et al. 1985; Stranden et al. 1979; Fleischer and Turner 1984; Wilkening and Wicke 1986; Nyberg and Bernhardt 1983). Furthermore, concentrations at different locations in the same house often vary by a factor of two or more (George et. al. 1984; Hess et. al. 1985; Keller, et. al. 1984). Because of these temporal and spatial variations, the EPA does not know of a way to use the result of a single measurement to provide an accurate estimate of health risks or make a well-informed decision on the need for remedial action. What the EPA recommends, therefore, is a two-step strategy for making the fewest measurements possible, while ensuring that radon concentrations are not seriously underestimated.

The first step is a screening measurement, which is used to quickly and inexpensively estimate the highest concentrations to which occupants may be exposed, and to decide whether and what type of additional measurements are needed. Another use of screening measurements is in multiple-home surveys designed to efficiently identify homes that contain high concentrations. Screening measurements should be inexpensive and simple, so that time or money is not wasted in houses that do not pose a health threat. The screening measurement alone, however, does not provide sufficient information to decide on the need for remedial action.

The second step of making follow-up measurements is recommended when the screening measurement exceeds 4 pCi/L (.02 WL). Follow-up measurements make a conservative estimate of the annual average concentration in living areas. This document describes the house conditions under which screening measurements should be made. The procedures for making follow-up measurements, if required, are presented in "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 1987). The EPA recommends that any decision on permanent corrective action to reduce indoor radon concentrations be made only after the completion of follow-up measurements.

1.3 SCREENING MEASUREMENTS

The EPA recommends that screening measurements be made under the following conditions:

a. Screening measurements should be made in the lowest area in the house that residents now use or could adapt for use as a living area. In many houses, the lowest livable area will be a basement that could be converted to a den, playroom, or bedroom without major structural changes. The highest concentrations of radon are usually found in areas of the house closest to the underlying soil,* as shown by a growing body of data (Gesell 1983, George et. al. 1984) which indicate that basement concentrations tend to be a factor of two to three times higher than concentrations in rooms above the basement.

b. Screening measurements should be made under "closed-house" conditions (Section 1.3.1); that is, in a closed building with a minimum level of ventilation. Radon concentrations under these conditions are likely to be as reproducible as feasible during occupied conditions (Ronca-Battista and Magno 1988), and are also higher than the average concentrations in almost all cases.

Screening measurements estimate the highest potential concentration to which an occupant may be exposed. Therefore, if the result of a screening measurement is very low, there is a high probability that the long-term average concentration in the rooms used as living areas are even lower, and the need for further measurements can be eliminated with confidence. Adherence to these procedures for screening measurements will decrease the number of false negatives, or homes that contain concentrations high enough to warrant remedial action (EPA and CDC 1986), but that are not identified as such because of a low measurement result. The outcome of such a false negative is no further measurements, so potentially high concentrations may never be identified. A false positive measurement result is less serious because it would result in further measurements, which would reveal that the concentrations in the house are low. In the interest of reducing radon exposures, the EPA believes that false positives are preferable to false negatives.

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* The guidance presented here assumes the source of radon to be the underlying soil, rather than building materials or water. If sources other than soil are suspected, radon in water or radon flux measurements should be made.

1.3.1 Closed-House Conditions

All short-term (that is, less than three months in duration) screening measurements should be made during periods of the year when windows are normally kept closed. For most climates in this country, this will be from late fall to early spring. The occupants should be instructed to keep windows and doors closed during the measurement period. Doors should be opened only for a few minutes to get in and out of the house. In addition, external-internal air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operating. For measurement periods of four days or less, closed-house conditions should exist for 12 hours prior to the beginning of the measurement. It may be difficult to verify these conditions or to implement them for an extended period, but they should be adhered to as closely as is reasonable.

There are two reasons why measurements in northern climates should be made during the winter season. First, during the winter, closed-house conditions exist as normal living conditions. Thus, there is a greater assurance in the winter that proper conditions exist prior to and during the measurement period. Second, information on factors that influence indoor radon concentrations indicate that concentrations during the winter are generally higher than during the summer, thus maximizing the probability of finding those houses with elevated radon concentrations.

If, however, it is necessary to make measurements during the summer, when closed-house conditions are not the normal living conditions, it will be necessary to establish a means of providing reasonable assurance that closed-house conditions exist prior to and during the measurements.

Organizations performing measurements in southern areas that do not experience extended periods of cold weather should evaluate seasonable variations in living conditions and identify if there are time periods when closed-house conditions normally exist. If such periods exist, it is during those periods that measurements should be conducted. Air-conditioning systems that recycle interior air can be operated during screening measurements.

Additional data are needed to better address measurements made during summer months in cold climates and at any time in warm climates. The interim data taken under these conditions need to be interpreted in the light of present knowledge of seasonal variability.

Measurements of four days or less should not be conducted if severe storms with high winds are expected. Severe weather can affect the measurement results in the following ways. First, a

high wind can increase the variability of radon concentrations because of wind-induced differences in air pressure between the house interior and exterior. Also, rapid changes in barometric pressure increase the chance of a large difference between the interior and exterior air pressure, thus, changing the rate of radon influx. Weather predictions available on local news stations may provide sufficient information to determine if this criterion is satisfied.

1.3.2 Duration of Screening Measurements

The duration of screening measurements can range from one day to three months depending upon the method used. Because of the variability of radon concentrations with time (Section 1.1), screening measurements with longer sampling periods should be less variable than short-period samples (Ronca-Battista and Magno 1988). If a sampling period of one to several days is used, the sampling period should be a multiple of 24 hours in order to avoid a possible bias introduced by sampling only a portion of the diurnal cycle of radon concentration. Grab samples (five minutes) are not recommended for screening measurements, except for quick screening of homes located near sites of known high concentrations; however, the average of several grab measurements made in a 24-hour period can be substituted for a one-day integrated screening measurement. When screening measurements of four days or less are made, particular care should be taken to ensure that closed-house conditions are implemented at least 12 hours before the beginning of the measurement, and that the caution about weather conditions is observed.

1.3.3 Location Selection

The location of the measurement within a room should be decided with the objective of measuring the most stable concentrations. The following criteria should be applied, in order of importance, when selecting a measurement location within a room.

a. The measurement should not be made near drafts caused by heating, ventilation, air conditioning vents, doors, windows, and fireplaces. Especially for measurements using charcoal absorption, locations near heat, in strong sunlight, and in areas of high humidity should be avoided. In general, measurements should not be made in kitchens and bathrooms.

b. The measurements should be made away from exterior house walls to reduce the effect of ventilation through cracks in the walls. Sampling locations should be at least ten centimeters (four inches) from other objects.

c. The passive device or the air intake of an instrument

should be placed at least 75 centimeters (30 inches) above the floor to reduce possible effects of drafts near the floor.

1.4 QUALITY ASSURANCE

The objective of quality assurance is to ensure that data are scientifically sound and of known precision and accuracy.

Manufacturers, suppliers, radon analysis laboratories, and commercial users of 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 quality assurance program should include the maintenance of control charts and related statistical data, as described by Goldin (Goldin 1984).

1.4.1 Calibration Measurements

Calibration measurements are samples collected or measurements made in a known radon environment, such as a calibration chamber. Detectors requiring laboratory readout, such as charcoal canisters, alpha-track detectors, EICs, and RPISU samplers are exposed in a calibration chamber and then analyzed. Instruments providing immediate results, such as continuous working-level monitors and continuous 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 normally determined 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 supplier or 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, suppliers, and analysis laboratories.

Known exposure measurements or spiked samples consist of detectors with known exposures in radon calibration chambers that 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. Commercial users of more than a small number of detectors should arrange for the introduction of blind spiked samples in their routine shipments and monitor the results in their quality assurance programs.

1.4.2 Background Measurements

Background measurements are required both for continuous monitors and for detectors requiring laboratory analysis. Sufficient instrument background measurements should be made to establish a reliable instrument background and to act as a check on instrument operation.

Detectors or devices requiring laboratory analysis require two types of background measurements made in both the laboratory and the field. Suppliers and analysis laboratories routinely should measure 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 routinely subtracted by the laboratory from the results reported to the user for field samples, and should be made available to commercial users of detectors 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 & Pasternack 1963). This LLD is based on the system's background and can restrict the ability of some measurement systems to measure low concentrations.

Commercial users of more than a few detectors should provide 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.

1.4.3 Duplicate (Colocated) 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 or coefficient of variation. Provision of sufficient replicate measurements to establish the relative measurement error of the measurement system is the responsibility of the manufacturer or the analysis laboratory.

Commercial users of more than a few detectors should provide duplicates for side-by-side measurements for at least ten percent of their samples, or 50 each month, whichever is smaller. The

samples selected for duplication should be systematically distributed 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. If passive devices are used, consideration should be given to providing some means to ensure that the duplicate devices are not separated during the measurement period. 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 (Goldin 1984). If the precision estimated by the commercial user is not within the precision expected of the measurement method, the problem should be reported to the analysis laboratory and the cause investigated.

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

Section 2: RADON MEASUREMENT PROTOCOLS

2.1 PROTOCOL FOR USING CONTINUOUS RADON MONITORS TO MEASURE INDOOR RADON CONCENTRATIONS

2.1.1 Purpose

This protocol provides guidance for using a continuous radon monitor (CRM) to measure indoor radon concentrations accurately and to obtain reproducible results. Following the protocol will help ensure uniformity among measurement programs and allow valid comparison of results. Measurements made in accordance with this protocol will produce screening measurements of radon concentrations representative of closed-house conditions. Such screening measurements of closed-house concentrations have a smaller variability and are more reproducible than measurements made when the house conditions are not controlled.

If measurements with CRMs are for a purpose other than a screening measurement, the investigator should follow guidance provided by EPA in "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 520/1-86-014-1, 1987).

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 a CRM. It is not meant to replace an instrument manual, but rather provides guidelines to be incorporated into standard operating procedures. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency (EPA), 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 two general types of continuous radon monitors covered by this protocol. In the first type of CRM, 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 sulphide coating on the inside of the scintillation cell producing scintillations. The scintillations are detected by a photo-multiplier tube in the detector which generates electrical pulses. These pulses are processed by the detector electronics and the data usually are stored in the memory of the CRM where results are available for recall or transmission to a data logger or printer.

This type of CRM uses either a flow-through cell or a periodic-fill cell. In the flow-through cell, air is continuously drawn through the cell by a small suction pump. In the periodic-fill cell, air is drawn into the cell once each preselected time interval; then the scintillations are counted and the cycle repeated. A third type of cell 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 types of cells lag the ambient radon concentrations by a small amount because of the inherent delay in the radon decay product disintegration process.

A second type of continuous radon 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 usually displayed on the monitor, and the data are usually available for processing by an optional data logger/printer.

A third type of continuous radon 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.

2.1.4 Equipment

Equipment required depends on the type and model of CRM used. Aged air, or nitrogen, should be available for introduction into the CRM to measure the background count rate. (Outdoor air can be used if necessary.) Sealed scintillation cells with measured low background should be available as spare cells.

2.1.5 Pre-Sampling Testing

The CRM should be carefully tested according to manufacturer's directions before and after each measurement 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 1000 hours of operation the unit should be examined to check the background count rate by purging 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 should be monitored more frequently by operating the instrument in an outdoor or other low radon environment.
Participation in a laboratory intercomparison program should be conducted at least semiannually to verify that the conversion factor used by the CRM 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.

2.1.6 Measurement Criteria

The following conditions should exist prior to and during a measurement to standardize the measurement conditions as much as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows 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 and other reasons discussed in section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operated during the measurement and for at least 12 hours before the measurement is initiated. Air conditioning systems that recycle interior air may be operated.

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

- Short-term measurements should not be conducted if severe storms with high winds or rapidly changing barometric pressure are predicted during the measurement period. Weather predictions available on local news stations may provide sufficient information to determine if this condition is satisfied.

2.1.7 Deployment and Operation

2.1.7.1 Location Selection. The following criteria should be applied to select the location of the CRM within a room.

- The measurement should not be made near drafts caused by heating, ventilating and air conditioning (HVAC) vents, doors, and windows.
- The measurement location should not be close to the outside walls of the house.
- The unit should be placed on a table or stool so that the air intake is at least 75 centimeters (30 inches) from the floor and at least 10 centimeters (4 inches) from other objects.
- In general, measurements should not be made in kitchens or bathrooms.

2.1.7.2 Operation. The CRM should be programmed to run continuously, periodically (usually hourly) recording the radon concentration. The sampling period should generally not be less than 24 hours. An increase in operating time decreases the uncertainty associated with the measurement result.

Care should be taken to eliminate data that are produced before equilibrium conditions have been established in a flow-through cell. Generally, conditions stabilize after the first four hours. Measurements taken prior to this are low and should be discarded. After this four hour period, the periodic readings can be averaged to obtain an integrated measurement result (e.g. a 24-hour average concentration).

2.1.7.3 Documentation. It is important that the operator of the CRM records enough information about the measurement in a permanent log so that data interpretations and comparisons can be made. This information includes the following:

- Start and stop times and date of the measurement;
- Information about how the standardized conditions, as previously specified, were satisfied;
- Exact location of the instrument, on a diagram of the room and house, if possible;
- Other easily obtained information that may be useful, such as the type of house, type of heating system, or the existence of a crawl space;

- Serial numbers of the CRM, scintillation cells, and other equipment.

2.1.8 Results

2.1.8.1 Lower Limit of Detection. Most CRMs are capable of an LLD of 0.5 pCi/L or less (Altshuler and Pastenack 1963). Special cells are available for some CRMs which have LLDs of 0.1 pCi/L.

2.1.8.2 Precision. Most CRMs can achieve a coefficient of variation of less than 10% (1 sigma) at 4 pCi/L or greater.

2.1.9 Quality Assurance

The elements of a quality assurance program for CRM measurements are (1) calibration, (2) background checks, and (3) duplicate samples. The quality assurance program should include the maintenance of control charts, as described by Goldin (Goldin 1984).

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

2.1.9.1 Calibration. CRMs should be calibrated in a radon calibration chamber before being put in service, after any repairs, and at least every six months. Spare cells should have individual calibration factors determined. Where design of the CRM permits, a calibration check source or cell should be counted to demonstrate proper operation prior to beginning sampling.

2.1.9.2 Background. After every 1000 hours of operation the CRM background should be checked by purging with clean aged air or nitrogen in accordance with the procedures given in the instrument operating manual. In addition, the background count rate should be monitored frequently by operating the instrument in an outdoor or other low radon environment. Cells which develop a high background after prolonged use should be reconditioned by the manufacturer.

2.1.9.3 Duplicate Samples. When two or more CRMs are available, the coefficient of variation of the measurements can be estimated by operating the CRMs side by side. The analysis of duplicate results should follow the methodology described by Goldin in section 5.3 of his report (Goldin 1984).

2.2 PROTOCOL FOR USING ALPHA-TRACK DETECTORS TO MEASURE INDOOR RADON CONCENTRATIONS

2.2.1 Purpose

This protocol provides guidance for using alpha-track detectors (ATD) to obtain accurate and reproducible measurements of indoor radon concentrations. Following the protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce screening measurements of radon concentration representative of closed-house conditions. Such screening measurements with closed-house concentrations have a smaller variability and are more reproducible than measurements made when the house conditions are not controlled.

If measurements with ATDs are for a purpose other than screening measurement, the investigator should follow guidance provided by EPA in "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 520/1-86-014-1, 1987).

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 provides guidelines to be adopted into standard operating procedures. 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 alpha-track detector (ATD) consists of a small piece of plastic or film enclosed in a container with a filter-covered opening. Radon diffuses through the filter 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 produced per unit of time is proportional to the radon concentration, so an ATD functions as a true integrating detector and measures the average concentration over the measurement period.

Many factors contribute to the variability of the ATD results including differences in the detector response within and between

batches of plastic, non-uniform plateout of decay products inside the detector holder, differences in the number of background tracks and variations in etching conditions. Since the variability in ATD results decreases with the number of net tracks counted, particularly at low exposures, counting more tracks over a larger area of the detector will reduce the uncertainty of the result.

2.2.4 Equipment

Alpha-track detectors are available from commercial suppliers. These suppliers offer contract services in which they provide the detector and subsequent data readout and reporting for a fixed 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 an ATD program are omitted from this protocol. If additional details are desired, they have been reviewed by Fleischer and Lovett (Fleischer 1965; Lovett 1969).

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

- The alpha track detector in an individual, sealed container, such as an aluminized plastic bag to prevent extraneous exposure before deployment;
- A means to attach the ATD to its measurement location, if it is to be hung from the wall or ceiling;
- Instruction sheet for the occupant, a sample log sheet, a shipping container and, if it is to be mailed, a prepaid mailing label for returning the detector to the laboratory;
- At the time of retrieval, some means (such as tape) for resealing the detector prior to returning it to the supplier for analysis;
- Data collection log.

2.2.5 Predeployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The ATD measurement should not be made if the occupant knows he will be moving during the period. Deployment should be delayed until the new occupant is settled in the house. Likewise, the measurement should be delayed if the occupant is planning remodeling, changes in the

heating, ventilating and air conditioning (HVAC) systems, or other modifications that may influence the radon concentration during the period.

2.2.6 Measurement Criteria

The following conditions should exist during the measurement period to standardize the measurement conditions as much as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows and external doors should be closed (except for normal entrance and exit) during the measurement period. Normal entrance and exit includes opening and closing of a door, but an external door should not be left open for extended periods. These conditions are expected to exist as normal living conditions during the winter in northern climates. For this reason and other reasons discussed in Section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operated during the measurement. Air conditioning systems that recycle interior air may be operated.

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

A 12-month ATD measurement provides information about radon concentrations in a house during an entire year, so the closed-house conditions do not have to be satisfied to measure the annual average concentration over 12 months.

2.2.7 Deployment

2.2.7.1 Timely Deployment. A group of ATDs should be deployed into houses as soon as possible after delivery from the supplier. Groups should not order more ATDs than they reasonably can expect to install within the following few months to minimize chances of high background exposures. If the storage time exceeds more than a few months, the background exposures from a sample of the stored detectors should be assessed. Consult the manufacturer's instructions regarding storage and background determination.

2.2.7.2 Location Selection. The following criteria should be applied to select the location of the detector within a room.

- A position should be selected where the ATD will not be disturbed during the measurement period.
- The detector should not be placed near drafts caused by HVAC vents, windows, doors, etc.
- The detectors should be located at least 75 centimeters (30 inches) from the floor and at least 10 centimeters (4 inches) from other objects.
- The detector should not be placed close to the outside walls of the house.
- In general, detectors should not be placed in kitchens or bathrooms.

It is often convenient to suspend the detector from the ceiling. The detector should be positioned at least 20 centimeters (8 inches) below the ceiling. If the detector is installed during a site visit, the final site selected should be shown to the home occupant to be certain it is acceptable for the duration of the measurement period.

The sampling period is begun when the protective cover or bag is removed. Cut the edge of the bag or remove the cover so that it can be reused to reseal the detector at the end of the exposure period. Inspect the detector and the radon proof container to make sure they are intact and have not been physically damaged in shipment or handling.

Fill in the information called for with the detector. Also, record the detector serial number in a log book along with a description of the location in the house in which the detector was placed. If during the exposure period it is necessary to relocate the detector, make certain it is noted in the log book, along with the date it was relocated.

2.2.8 Retrieval of Detectors

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 using the protective cover or bag with the correct serial number for that detector or the cover originally provided. If a bag is used, the open edge of the bag is folded several times and resealed with tape. If the bag or cover has been destroyed or misplaced, the detector should be wrapped in several

layers of aluminum foil and taped shut. After retrieval, the detectors should be returned as soon as possible to the analytical laboratory for processing.

2.2.9 Documentation

It is important that enough information about the measurement is recorded in a permanent log so that data interpretations and comparisons can be made. Information that should be recorded is shown below.

- The start and stop dates of the measurement.
- Whether standardized conditions, as previously specified, are satisfied.
- Exact location of the detector, on a diagram of the room and house if possible.
- Serial number and manufacturer of the detector along with code number or description which uniquely identifies customer, building, room, and sampling position.
- Other easily gathered information that may be useful, such as the type of house, type of heating system, or the existence of a basement or crawl space.

2.2.10 Analysis Requirements

2.2.10.1 Sensitivity. The lower limit of detection (LLD) (Altshuler and Pasternack 1963) and the precision of an ATD system is dependent upon the total number of tracks counted, and therefore the area of the detector that is analyzed. With present ATDs, routine counting achieves an LLD of 1 pCi/L-month, and an LLD of 0.2 pCi/L-month is achieved by counting additional area. Table 2-1 illustrates the dependence of precision on the number of net tracks counted. As can be seen from Table 2-1, if few net tracks are counted, poor precision is obtained. Thus, it is important that the organization performing the measurements with an ATD arranges for counting an adequate area or number of net tracks.

2.2.10.2 Precision. The coefficient of variation 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 coefficient of variation should not exceed 20 percent (1 sigma) at radon concentrations of 4 pCi/L or greater.

Table 2-1

Dependence of Precision on Number of Net Tracks Counted

Number of Net Tracks Counted	2 Sigma Error (%) (a)
4	100
6	82
10	63
15	52
20	45
50	28
75	23
100	20

(a) This is the minimum error for the number of net tracks indicated based only on counting statistics. Additional error may be introduced during processing.

2.2.11 Quality Assurance

The quality assurance program for measurements with ATDs involves four separate parts: (1) calibration detectors, (2) known exposure (spiked) detectors, (3) duplicate detectors as a test of the precision, and (4) control (blank) detectors to check for exposure during shipment or storage. The quality assurance program should include the maintenance of control charts as described by Goldin (Goldin 1984).

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

2.2.11.1 Calibration Factors. Determination of a calibration factor requires exposure of ATDs 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. The following guidance is provided to manufacturers and suppliers of alpha-track services as minimum requirements in determining the calibration factor.

- ATDs should be exposed in a radon chamber at several different radon concentrations or exposure levels similar to those found in the tested houses (a minimum of three different concentrations).
- A minimum of ten detectors should be exposed at each level.
- The period of exposure should be sufficient to allow the ATD to achieve equilibrium with the chamber atmosphere.
- A calibration factor should be determined for each batch or sheet of detector material received from the material supplier.

2.2.11.2 Known Exposure Measurements. Both suppliers of alpha-track services and large users of these services should submit ATDs with known radon exposures (spiked samples) for analysis on a regular schedule. Known exposure (spiked) detectors should be labeled in the same manner as field detectors to ensure identical processing. The number of spiked detectors submitted for analysis should be a few percent of the total number of detectors analyzed. 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 (Colocated) Detectors. The organization performing the measurements 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 systematically distributed 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 in section 5.3 of his report (Goldin 1984). The method should achieve a coefficient of variation of 20 percent (1 sigma) or less at radon concentrations of 4 pCi/L or greater. Consistent failure in duplicate agreement may indicate a problem in the measurement process that 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 ATDs should be established by each supplier. Suppliers should measure the background of a statistically significant number of unexposed ATDs that have been processed according to their standard operating procedures. This laboratory blank value normally is subtracted by the analysis laboratory or supplier from the results obtained from the field detectors to arrive at the net readings used to calculate the reported sample radon concentrations.

2.2.11.4.2 Field Control Detectors. Field control ATDs (field blanks) should consist of a minimum of 5 percent of the devices that are deployed every month or 25, whichever is smaller. Commercial users should set these aside from each shipment, keep them sealed and in a low radon (less than 0.5 pCi/L) environment, label them in the same manner as the field ATDs to assure identical processing, and send them back to the supplier with the field ATDs 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 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.

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 reading of the blanks is significantly greater than the LLD, it should be subtracted from the individual concentrations reported for the field samples.

2.3 INTERIM PROTOCOL FOR USING ELECTRET ION CHAMBER RADON DETECTORS (EICs) TO MEASURE INDOOR RADON CONCENTRATIONS

2.3.1 Purpose

This protocol provides guidance for using electret ion chamber radon detectors (EICs) to obtain accurate and reproducible measurements of indoor radon concentrations. Following the protocol will help ensure uniformity among measurement programs and allow valid intercomparision of results. Measurements made in accordance with this protocol will produce screening measurements of radon concentration representative of closed-house conditions. Such screening measurements of closed-house concentrations have a smaller variability and are more reproducible than measurements made when the house conditions are not controlled.

If measurements with EICs are for a purpose other than a screening measurement, the investigator should follow guidance provided by EPA in "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 520/1-86-014-1, 1987).

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 adopted into standard operating procedures. 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

Electret ion chamber radon detectors (EICs) have been described by Kotrappa et. al. (Kotrappa 1988). They require no power and function as true integrating detectors, measuring the average concentration during the measurement period.

EICs contain a permanently charged electret[1] which collects ions formed in the chamber by radiation emitted from 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 directly related to

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[1] An electrostatically charged disk of Teflon^{R}.

the average radon concentration present during the exposure period. There are both short-term (2 to 7 day) and long-term (1 to 12 month) EICs that are currently marketed. The thickness of the electret affects the usable measurement period.

The electret must be removed from the canister and the electret voltage must be measured with a special surface voltmeter both before and after exposure. The difference between the initial and final voltage is divided first by a calibration factor and then by the number of exposure days to determine the average radon concentration during the exposure period. 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 an EIC:

- A short-term or long-term EIC;
- An instruction sheet for the user and a shipping container with a label for returning the EIC(s) to the laboratory;
- A specially built surface voltmeter for measuring electret voltages before and after exposure;
- A data collection log.

2.3.5 Predeployment Considerations

The measurement should not be made if the occupant is planning remodeling, changes in the heating, ventilating and air conditioning system, or other modifications that may influence the radon concentration during the measurement period.

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

2.3.6 Measurement Criteria

The following conditions should exist prior to and during a measurement to ensure that the conditions are as standardized as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows 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 of 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 and others discussed in Section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operated during the measurement and for at least 12 hours before the measurement is initiated. Air conditioning systems that recycle interior air may be operated.

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

- Short-term measurements should not be conducted if severe storms with high winds or rapidly changing barometric pressures are predicted during the measurement period. Weather predictions available on local news stations may provide sufficient information to determine if this condition is satisfied.

A 12-month EIC measurement provides information about radon concentrations in a house during an entire year, so the closed-house conditions do not have to be satisfied to measure the annual average concentration over 12 months.

2.3.7 Deployment

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

2.3.7.1 Timely Deployment. Both long and short-term EICs should be deployed as soon as possible after their initial voltage is measured. Until an EIC is deployed, an electret cover should remain in place over the electret to minimize background loss of voltage.

2.3.7.2 Location Selection. The following criteria should be applied to select the location of an EIC within a room.

- A position should be selected where the detector will not be disturbed during the measurement period.

- The detector should not be placed near drafts caused by HVAC vents, windows, and doors.

- The detector should be placed at least 75 centimeters (30 inches) above the floor level and at least 10 centimeters (4 inches) from other objects.

- The detector should not be placed close to the exterior walls of the house.

- In general, detectors should not be placed in kitchens or bathrooms.

2.3.8 Retrieval of Detectors

Short-term EICs may be deployed for a two to seven day measurement period, and long-term EICs for one to twelve months. If the occupant is terminating the sampling, the instructions given to the occupant should tell the occupant when and how to terminate the sampling period. A deviation from the schedule by up to few days is acceptable for short-term EICs and up to three weeks for long-term EICs, if the time of termination is documented on the EIC information form. In addition, the occupant also should be instructed to send the EIC to the laboratory as soon as possible, preferably within a few days following exposure termination.

At the end of the monitoring period, the EIC 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 EIC electret should be covered again using the mechanism provided.

2.3.9 Documentation

It is important that enough information about the measurement be recorded in a permanent log so that data interpretations and comparisons can be made. The information includes the following:

- The dates and start and stop times of the measurement;

- Whether standardized conditions, as previously specified, are satisfied;

- Exact location of the detector, on a diagram of the room and house, if possible;

- Other easily gathered information that may be useful, such as the type of house, type of heating system, and the existence of a crawl space;

- Serial number and supplier of detector along with a code number or description which uniquely identifies customer, building, room, and sampling position.

2.3.10 Analysis Requirements

In general, all EICs should be analyzed in the field or in the laboratory as soon as possible following removal from houses. A background correction must be made to the radon concentration value obtained because EICs have a small response to background gamma radiation.

2.3.10.1 Sensitivity. For a 7-day exposure period using a short-term EIC the lower level of detection (LLD) (Altshuler and Pasternak 1963) is about 0.3 pCi/L. For a long-term EIC, the LLD is also about 0.3 pCi/L.

2.3.10.2 Precision. The coefficient of variation should not exceed 10 percent (1 sigma) at radon concentrations of 4 pCi/L or greater. This precision should be monitored by using the results of duplicate detector analyses described in Section 2.3.11.3 of this protocol.

2.3.11 Quality Assurance

The quality assurance (QA) program for measurements with EIC detectors includes four parts: (1) calibration detectors, (2) known exposure (spiked) detectors, (3) duplicate detectors as a test of the precision and (4) control (blank) detectors to check for exposure during shipment or storage. The purpose of a QA program is to identify the accuracy and precision of the measurements and to assure that the measurements are not influenced by exposure from sources outside the environment to be measured.

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

2.3.11.1 Calibration Factors. Determination of calibration factors for EIC detectors requires exposure of detectors to known concentrations of radon-222 in a radon exposure chamber. Since EICs are also sensitive to exposure to gamma radiation (see Section 2.3.11.4), a gamma background measurement is also required.

The following guidance is provided to manufacturers and suppliers of EIC 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 houses (a minimum of three different concentrations).

- A minimum of ten 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. Both suppliers of EIC detector services and large users of these services should submit detectors with known radon exposures (spiked samples) for analysis on a regular schedule. Blind calibration detectors should be labeled in the same manner as the field detectors to ensure identical processing. The number of devices submitted for analysis should be a few percent of the total number of detectors analyzed. 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 (Colocated) Detectors. Duplicate EICs should be placed in enough houses to monitor the precision of the measurement. This will usually be approximately 10 percent of the houses to be tested 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 systematically distributed throughout the entire population of samples. 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. The analysis of duplicate data should follow the methodology described by Goldin in section 5.3 of his report (Goldin 1984). The method should achieve a coefficient of variation of 10 percent (1 sigma) or less at radon concentrations of 4 pCi/L or greater. Consistent failure in duplicate agreement indicates an error in the measurement process that should be investigated.

2.3.11.4 Control EICs for Background Gamma Exposure and Electret Stability Monitoring. Electrets should exhibit very little drift in surface voltage due to internal electrical instabilities.

Neither the short-term or the long-term electrets should show voltage reductions of more than that which they exhibit when exposed to 0.3 pCi/L. A minimum of 5 percent of the electrets, or 10, whichever is smaller, should be set aside from each shipment and evaluated 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 drift found in the control electrets of more than 2 volts per week for short-term electrets or 1 volt per month for long-term electrets should be investigated.

EICs also are sensitive to background gamma radiation. The electret voltage drop due to the background gamma radiation needs to be assessed so that an appropriate correction can be made to the measured concentration value. This background voltage drop should be subtracted from the total voltage drop exhibited by the electret, to produce a net voltage difference due only to the exposure to the ions produced by the decay of radon in the EIC chamber. A background correction of 0.8 pCi/L is routinely subtracted from both long and short-term EIC readings to correct for an average background value of 10 uR/hr. This background correction is made by the analysis laboratory or by the user if the detector is read in the field. In cases where higher than normal background radiation is suspected or known to exist, a gamma background measurement should be made (preferably with an energy-compensated scintillometer), and an additional correction of 0.08 pCi/L for each additional uR/hr should be made.

2.4 PROTOCOL FOR USING CHARCOAL CANISTERS TO MEASURE INDOOR RADON CONCENTRATIONS

2.4.1 Purpose

This protocol provides guidance for using a charcoal canister to obtain accurate and reproducible measurements of indoor radon concentrations. Following the protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce screening measurements of radon concentrations representative of closed-house conditions. Such screening measurements have a smaller variability and are more reproducible than measurements made when the house conditions are not controlled.

If measurements with charcoal canisters are for a purpose other than a screening measurement, the investigator should follow guidance provided by EPA in "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 520/1-86-014-1, 1987).

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 adopted into standard operating procedures. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency (EPA), Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C., 20460.

2.4.3 Method

Charcoal canisters 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 the adsorbed radon undergoes radioactive decay. Therefore, the technique does not uniformly integrate 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 adsorbed during the first half of the sampling period is substantially higher or lower than the average over the period.

The charcoal canister measurement technique is described in detail by Cohen and by George (Cohen 1983 and George 1984). The charcoal canister now used by several groups consists of a circular, 6-to-10 centimeter diameter container approximately 2.5

centimeters deep 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 canister contains a diffusion barrier over the canister opening which improves the uniformity of response to variations of radon concentration with time for longer exposures. Desiccant also is incorporated in some canisters to reduce interference from moisture adsorption during longer exposures. All charcoal canisters are sealed with a radon proof cover or closure after preparation.

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

At the laboratory, the canisters are analyzed for radon decay products by placing the charcoal, still in its container, directly on a gamma detector. If it is necessary to make a correction to account for the reduced sensitivity of the charcoal due to adsorbed water, this may be done by weighing each canister 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 that should be empirically derived using a method discussed by George (George 1984). This correction factor is used to correct the analytical results.

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

Charcoal canister systems are calibrated by analyzing canisters exposed to known concentrations of radon in a calibration facility.

2.4.4 Equipment

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

The following equipment will be required to measure radon with charcoal canisters.

- Charcoal canister(s) sealed with protective cover;
- Instruction sheet and sampling data sheet for the occupant, a shipping container and, if sent by mail, a prepaid mailing label for returning canister(s) to the analytical laboratory;
- Data collection log.

Laboratory analysis of the exposed canisters 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 multichannel gamma spectrometer or with a single-channel analyzer with the window set to cover the appropriate gamma energy window. The detector system and detector geometry must be identical with the system used to derive the canister calibration factors.

2.4.5 Predeployment Considerations

The measurement should not be made if the occupant is planning remodeling, changes in the heating, ventilating and air conditioning (HVAC) system, or other modifications that may influence the radon concentration during the measurement period.

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

2.4.6 Measurement Criteria

The following conditions should exist prior to and during a measurement to ensure that the conditions are as standardized as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows 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 of 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 and others discussed in Section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operated during the measurement and for at least 12 hours before the measurement is initiated. Air conditioning systems that recycle interior air may be operated.

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

- Short-term measurements should not be conducted if severe storms with high winds or rapidly changing barometric pressure are predicted during the measurement period. Weather predictions available on local news stations may provide sufficient information to determine if this condition is satisfied.

2.4.7 Deployment

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

2.4.7.2 Location Selection. The following criteria should be applied to select the location of a canister within a room.

- A position should be selected where the canister will not be disturbed during the measurement period.

- The canister should not be placed near drafts caused by HVAC vents, windows, and doors. Avoid locations near excessive heat, such as fireplaces or in direct, strong sunlight, and areas of high humidity.

- The canister should be placed at least 75 centimeters (30 inches) above the floor and at least 10 centimeters (4 inches) from other objects.

- The canister should not be placed close to the outside walls of the house.

- Canisters should not be placed in kitchens or bathrooms.

The protective cover and sealing tape 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. Inspect the canister to see that it has not been damaged during handling and shipping. It should be intact, with no charcoal leaking. Place the canister with the open side up toward the air. Nothing should impede air flow around the canister.

2.4.8 Retrieval of Detectors

The canisters should be deployed for a two- to seven-day measurement period as specified in the suppliers instructions. If the occupant is terminating the sampling, the instructions given to the occupant should tell the occupant when to terminate the sampling period and should indicate that a deviation from the schedule by up to six hours is acceptable if the time of termination is documented on the canister. In addition, the occupant should also be instructed to send the canister to the laboratory as soon as possible, preferably the day of or the day following termination.

At the end of the monitoring period, the canister 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 canister should be resealed using the original protective cover.

After the canister is retrieved, it must be returned to the laboratory as soon as possible for analysis. The canister should not be analyzed before three hours after the end of sampling to allow for ingrowth of decay products.

2.4.9 Documentation

It is important that enough information about the measurement be recorded in a permanent log so that data interpretations and comparisons can be made. The information includes the following:

- The date and start and stop time of the measurement;
- Whether standardized conditions, as previously specified, are satisfied;
- Exact location of the canister, on a diagram of the room and house, if possible;
- Serial number of the canister and a code number or description which uniquely identifies customer, building, room, and sampling position;

- Other easily gathered information that may be useful, such as the type of house, type of heating system, and the existence of a basement or crawl space.

2.4.10 Analysis Requirements

Canisters 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 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. The canister 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 by George (George 1984).

2.4.10.1 Sensitivity. For a two- to seven-day exposure period, the lower level of detection (LLD) (Altshuler and Pasternack 1963) should be 0.5 pCi/L or less. This can normally be achieved with a counting time of up to 30 minutes. This LLD should be calculated using the results of the charcoal background determination that is described in Section 2.4.11.3 of this protocol.

2.4.10.2 Precision. The coefficient of variation should not exceed 10 percent (1 sigma) at radon concentrations of 4 pCi/L or greater. This precision should be monitored using the results of the duplicate canister analyses described in this protocol. Charcoal canisters can achieve an average coefficient of variation of less than 5 percent at concentrations of 4 pCi/L or greater.

2.4.11 Quality Assurance

The quality assurance program for charcoal canisters includes four parts: (1) calibration canisters, (2) known exposure (spiked) canisters, (3) duplicate canisters, and (4) controls. 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, as described by Goldin (Goldin 1984).

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For

further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

2.4.11.1 Calibration Factors. Determination of calibration factors for charcoal canisters requires exposure of canisters to known concentrations of radon-222 in a radon exposure chamber. The calibration factors depend on the exposure time and also may depend on the amount of water adsorbed by the canister during exposure. These calibration factors should be determined using the procedures described by George (George 1984). Calibration factors should be determined for each charcoal canister system (container type, amount of charcoal, etc.).

2.4.11.2 Known Exposure Canisters. Both suppliers of charcoal canister services and large users of these services should submit charcoal canisters with known radon exposures (spiked samples) for analysis on a regular schedule. Known exposure (spiked) canisters should be labeled in the same manner as the field canisters to assure identical processing. The number of canisters submitted for analysis should be a few percent of the total number of canisters analyzed. The results of the spiked canister 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 (Colocated) Canisters. Duplicate canisters should be placed in enough houses to monitor the precision of the measurements. This will usually be approximately 10 percent of the houses to be tested each month or 50, whichever is smaller. The duplicate canisters 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 systematically distributed throughout the entire population of samples. 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 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 canisters should be evaluated using the procedures described by Goldin in section 5.3 of his report (Goldin 1984). The method should achieve a coefficient of variation of 10 percent (1 sigma) or less at radon concentrations of 4 pCi/L or greater. Consistent failure in duplicate agreement may indicate a problem in the measurement process that should be investigated.

2.4.11.4 Control Devices.

2.4.11.4.1 Laboratory Control Canisters. The laboratory background level for each batch of charcoal canisters should be

established by each supplier. Suppliers should measure the background of a statistically significant number of unexposed canisters that have been processed according to their standard operating procedures (laboratory blanks). This value normally is subtracted by the analysis laboratory or supplier from the results obtained from the field devices to arrive at the net readings used to calculate the sample radon concentrations.

2.4.11.4.2 Field Control Canisters. Field control canisters (field blanks) should consist of a minimum of 5 percent of the devices that are deployed every month or 25, whichever is smaller. Commercial 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 canisters 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 only a few of the field control canisters have concentrations significantly greater than the LLD established by the supplier it may indicate defective canisters 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 canister concentrations and the supplier notified of a possible problem.

2.5 INTERIM PROTOCOL FOR USING CHARCOAL LIQUID SCINTILLATION DEVICES TO MEASURE INDOOR RADON CONCENTRATIONS

2.5.1 Purpose

This protocol provides guidance for using charcoal liquid scintillation (CLS) devices to obtain accurate and reproducible measurements of indoor radon concentrations. Following the protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce screening measurements of radon concentration representative of closed-house conditions. Such screening measurements have a smaller variability and are more reproducible than measurements made when the house conditions are not controlled.

If measurements with CLS devices are for a purpose other than a screening measurement, the investigator should follow guidance provided by EPA in "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 520/1-86-014-1, 1987).

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 adopted into standard operating procedures. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency (EPA), Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C., 20460.

2.5.3 Method

CLS 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 uniformly integrate 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 charcoal liquid scintillation detector technique is described by Prichard (Prichard and Marien 1985). A type of CLS device now provided by several companies is a capped, 20 ml liquid scintillation vial that is approximately 25 mm. in diameter by 60

mm. and contains 1 to 3 grams of charcoal. In some cases the vial contains a diffusion barrier over the charcoal which improves the uniformity of response of the device to variations of radon concentration with time, particularly for longer exposures. Some CLS devices include a few grams of desiccant which reduces interference from moisture adsorption by the charcoal (Perlman 1989). All CLS devices are sealed with a radon-proof closure after preparation.

A measurement with the CLS device is initiated by removing the radon-proof closure to allow radon-ladened air to diffuse into the charcoal where the radon is adsorbed. At the end of the measurement the device is securely resealed and returned to the laboratory for analysis.

At the laboratory the devices are prepared for analysis by radon desorption techniques which reproducibly transfer 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 (for example, ten minutes) or until the standard deviation of the count is acceptable (for example, less than 10 percent).

2.5.4 Equipment

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

The following equipment will be required to measure radon with a CLS device:

- CLS devices properly sealed by the supplier;
- Instruction sheet for occupant, a shipping container, if sent by mail, a prepaid mailing label for returning devices to the analytical laboratory;
- Data collection log.

2.5.5 Predeployment Considerations

The measurement should not be made if the occupant is planning remodeling, changes in the heating, ventilating and air conditioning (HVAC) system, or other modifications that may influence the radon concentration during the measurement period.

The CLS 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 following conditions should exist prior to and during a measurement period to ensure that the conditions are as standardized as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows 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 of 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 and other reasons discussed in section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operating during the measurement and for at least 12 hours before the measurement is initiated. Air conditioning systems that recycle interior air may be operated.

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

- Measurements should not be conducted if severe storms with high winds or rapidly changing barometric pressure are predicted during the measurement period. Weather predictions available on local news stations may provide sufficient information to determine if this condition is satisfied.

2.5.7 Deployment

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

2.5.7.2 Location Selection. The following criteria should be applied to select the location of a CLS device within a room.

- A position should be selected where the device will not be disturbed during the measurement period.

- The device should not be placed near drafts caused by HVAC vents, windows, and doors. Avoid locations near excessive heat, such as fireplaces or in direct strong sunlight, and areas of high humidity.

- The device should be placed on a shelf or table at least 75 centimeters (30 inches) above floor level and at least 10 centimeters (4 inches) from other objects.

- The device should not be placed close to the outside walls of the house.

- The device should not be placed in kitchens or bathrooms.

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. Inspect the device to see that it has not been damaged during handling and shipping. It should be intact, with no charcoal leaking. Place the device with the open vial mouth up. Nothing should impede air flow around the device.

Accurately fill in the information called for on the data form on the device. Record the device serial number in a log book along with a description of the location in the house where the device was placed. If the device is relocated during the measurement period the new location and data should be noted in the log book.

2.5.8 Retrieval of Devices

The device should be deployed for the measurement period (usually less than one week) specified in the instructions supplied by the analytical laboratory. If the occupant is terminating the sampling, the instructions given to the occupant should tell the occupant 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.

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

It is important that enough information about the measurement be recorded in a permanent log so that data interpretations and comparisons can be made. The information includes the following:

- The date and start and stop time of the measurement;
- Whether standardized conditions, as previously specified, are satisfied;
- Exact location of the instrument, on a diagram of the room and house, if possible;
- Serial number of the device and a code number or description which uniquely identifies customer, building, room and sampling position;
- Other easily gathered information that may be useful, such as the type of house, type of heating system, and existence of basement or crawl space.

2.5.10 Analysis Requirements

CLS 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 sensitivity is an important consideration. 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. The 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) (Altshuler and Pasternak 1963) should be specified by individual suppliers for CLS devices exposed and shipped according to their directions. It is estimated that LLDs of a few tenths of a picocurie per liter are achievable for some CLS devices. (Prichard 1988, Cohen 1988, Grodzins 1988, Perlman 1988). The LLD should be calculated using the results of the laboratory control devices discussed in this protocol.

2.6.10.2 Precision. The coefficient of variation should not exceed 10 percent (1 sigma) at radon concentrations of 4 pCi/L or greater. This precision should be monitored and periodically recorded using the results of the duplicate device analyses described in Section 2.5.11.3 of this protocol.

2.5.11 Quality Assurance

The quality assurance (QA) program for CLS devices includes four parts: (1) calibration devices, (2) known exposure (spiked) devices, (3) duplicate devices, and (4) control devices. The purpose of a QA 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, as described by Goldin (Goldin 1984).

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

2.5.11.1 Calibration Factors. Determination of calibration factors for charcoal liquid scintillation 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. Both suppliers of CLS device services and large users of these services should submit devices with known radon exposures (spiked samples) for analysis on a regular schedule. Known exposure (spiked) devices should be labeled in the same manner as the field devices to ensure identical processing. The number of blind calibration devices submitted for analysis should be a few percent of the total number of devices analyzed. 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 (Colocated) Devices. Duplicate devices should be placed in enough houses to monitor the precision of the measurements. This usually will be approximately ten percent of

the houses to be tested each month or 50, whichever is smaller. The duplicate devices should be shipped, stored, exposed, and analyzed under the same conditions. The samples for duplication should be systematically distributed throughout the entire population of samples. 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 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 the procedures described by Goldin in section 5.3 of his report (Goldin 1984). The method should achieve a coefficient of variation of 10% (1 sigma) or less at radon concentrations of 4 pCi/L or greater. Consistent failure in duplicate agreement may indicate a problem in the measurement process that 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 CLS devices should be established by each supplier. Suppliers should measure the background of a statistically significant number of unexposed CLS devices that have been processed according to their standard operating procedures (laboratory blanks). This value normally is subtracted by the analysis laboratory or supplier from the results obtained from the field devices to arrive at the net readings used to calculate the sample radon concentrations.

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. Commercial 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 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 only a few of the field control canisters 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.

2.6 INTERIM PROTOCOL FOR USING EVACUATED SCINTILLATION CELLS TO MAKE THREE-DAY INTEGRATED MEASUREMENTS OF INDOOR RADON CONCENTRATIONS.

2.6.1 Purpose

This protocol provides guidance for using an evacuated scintillation cell to obtain accurate and reproducible measurements of indoor radon air concentrations integrated over a 3-day period. Following the protocol will help ensure uniformity among measurement programs and allow valid comparisons of results. Measurements made in accordance with this protocol will produce screening measurements of radon concentrations representative of closed-house conditions. Such screening measurements have a smaller variability and are more reproducible than measurements made when the house conditions are not controlled.

If measurements with this device are for other than a screening measurement, the investigator should follow guidance provided by EPA in "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 520/1-86-014-1, 1987).

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 adopted into standard operating procedures. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency (EPA), Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C. 20460.

2.6.3 Method

The three-day evacuated cell radon collectors are 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 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. The sample is counted no sooner than six hours after the end of the measurement period to allow radon and its daughter products to grow into equilibrium and to allow any radon daughter products that may have been collected to decay.

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, however, 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 is 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

The following equipment will be required to measure radon with an evacuated cell:

- An evacuated cell with restricter valve and vacuum gauge prepared by the supplier;
- Instruction sheet, a shipping container and, if it is to be mailed, a prepaid mailing label for returning the detector to the laboratory;
- Data collection log.

2.6.5 Predeployment Considerations

The measurement should not be made if the occupant is planning remodeling, changes in the heating, ventilating, and air conditioning system, or other modifications that may influence the radon concentration during the measurement period.

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

2.6.6 Measurement Criteria

The following house conditions should exist prior to and during a measurement to standardize the measurement conditions as much as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows 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 of 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 and others discussed in Section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operated during the measurement and for at least 12 hours before the measurement is initiated. Air conditioning systems that recycle interior air may be operated.

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

- Measurements should not be conducted if severe storms with high winds or rapidly changing barometric pressure are predicted during the measurement period. Weather predictions available on local news stations may provide sufficient information to determine if this condition is satisfied.

2.6.7 Deployment

2.6.7.1 Timely Deployment. Evacuated cell 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.

2.6.7.2 Location Selection. The following criteria should be applied to select the location of an evacuated cell device within a room.

- A position should be selected where the device will not be disturbed during the measurement period.

- The device should not be placed near drafts caused by HVAC vents, windows, and doors.

- The device should be placed on a shelf or table at least 75 centimeters (30 inches) above floor level and at least 10 centimeters (4 inches) from other objects.

- The device should not be placed close to the outside walls of the house.

To deploy the evacuated cell 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

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 given to the occupant should tell the occupant 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 also should be instructed to send the device to the laboratory as soon as possible, preferably 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

It is important that enough information about the measurement be recorded in a permanent log so that data interpretations and comparisons can be made. The information includes the following:

- The date and start and stop time of the measurement;

- Whether standardized conditions, as previously specified, are satisfied;

- Exact location of the device, on a diagram of the room and house, if possible;

- Other easily gathered information that may be useful, such as the type of house, type of heating system, and existence of basement or crawl space;

- Serial number and supplier of the evacuated cell device along with a code number or description which uniquely identifies customer, building, room, and sampling position.

2.6.10 Analysis Requirements

Evacuated cell 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 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.

2.6.10.1 Sensitivity. The lower limit of detection (LLD) (Altshuler and Pasternack 1963) should be specified by individual suppliers for evacuated cell devices exposed and shipped according to their directions. It is estimated that LLDs of a few tenths of a picocurie per liter are achievable with these devices. The LLD should be calculated using the results of the laboratory control devices. A commercial supplier of evacuated cell devices has reported that for samples analyzed within four days of collection, concentrations as low as 0.2 pCi/L can be measured to within 25% and concentrations of 1 pCi/L can be measured to within 10%.

2.6.10.2 Precision. The coefficient of variation should not exceed ten percent (1 sigma) or less at radon concentrations of 4 pCi/L or greater. This precision should be monitored and periodically recorded using the results of the duplicate device analyses described in Section 2.6.11.3 of this protocol.

2.6.11 Quality Assurance

The quality assurance program for evacuated cell devices includes four parts: (1) calibration devices, (2) known exposure (spiked) devices, (3) duplicate devices, and (4) control devices. The purpose of this 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 as described by Goldin (Goldin 1984).

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and

Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

2.6.11.1 Calibration Factors. Determination of calibration factors for evacuated cell devices 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 periodically recalibrated at radon levels similar to those found in tested houses. Scintillation counting systems used to count exposed cells should either be the system used to calibrate the cell or one calibrated against that system.

2.6.11.2 Known Exposure Measurements. Both suppliers of evacuated cell device services and large users of these services should submit devices with known radon exposures (spiked samples) for analysis on a regular schedule. Known exposure (spiked) devices should be labeled in the same manner as the field devices to assure identical processing and avoid bias. The number of blind calibration devices submitted for analysis should be a few percent of the total number of devices analyzed. The results of the calibration device analysis should be monitored and recorded, and any significant deviation from the known concentration to which they were exposed should be investigated.

2.6.11.3 Duplicate (Colocated) Devices. Duplicate devices should be placed in enough houses to monitor the precision of the measurements. This usually will be approximately ten percent of the houses to be tested 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 systematically distributed throughout the entire population of samples. Groups selling measurements to homeowners can do this by making two measurements side-by-side in a random selection of homes. Data from duplicate devices should be evaluated using the procedures described by Goldin in section 5.3 of his report (Goldin 1984). The method should achieve a coefficient of variation of 10 percent (1 sigma) or less for radon concentrations of 4 pCi/L or greater. Consistent failure in duplicate agreement may indicate a problem in the measurement process that should be investigated.

2.6.11.4 Control Devices.

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

2.6.11.4.2 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. Commercial 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 will be clear to the analysis laboratory that these cells are blanks because they will still indicate full vacuum but it is not feasible to fill these cells with radon-free air in the field. Careful initial and final readings of the vacuum gauges on these control cells and the cell background counts on analysis will be of some use in detecting an occasional leaking cell, but any background detected is not relevant to the measured field sample concentrations.

2.7 INTERIM PROTOCOL FOR USING PUMP/COLLAPSIBLE BAG DEVICES TO MEASURE RADON CONCENTRATIONS

2.7.1 Purpose

This protocol provides guidance for using a pump with a collapsible bag as a device to obtain accurate and reproducible measurements of indoor radon concentrations. Following the protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce screening measurements of radon concentration representative of closed-house conditions. Such screening measurements have a smaller variability and are more reproducible than measurements made when the house conditions are not controlled.

If measurements with these devices are for a purpose other than a screening measurement, the investigator should follow guidance provided by EPA in "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 520/1-86-014-1, 1987).

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 adopted into standard operating procedures. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency (EPA), Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C., 20460.

2.7.3 Method

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.

A practical method is to use a small pump with a very low and uniform flow rate to pump ambient air into a collapsible radon proof bag (Sill 1977). After the desired sampling period the concentration of radon in the bag can be analyzed by any of the standard methods such as the scintillation cell grab sample

protocol (Section 2.8) using the appropriate radon decay correction factors (Appendix A). 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. Suitable bags with a measured very low loss of radon by diffusion through the bag have been made of laminated Mylar, aluminized laminated Mylar, and Tedlar®. 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 commercially available.

Since this method accumulates radon over a period of time for subsequent analysis it is not an 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.

2.7.4 Equipment

The following equipment will be required to conduct measurements using the pump/collapsible bag method.

- Pump with a suitable uniform flow rate. The materials of the pump should not absorb or off-gas any substantial amount of radon.
- Collapsible bag of tested low radon loss material.
- Data collection log.

2.7.5 Predeployment Considerations

The measurement should not be made if the occupant is planning remodeling, changes in the heating, ventilating and air conditioning (HVAC) system, or other modifications that may influence the radon concentration during the measurement period.

2.7.6 Measurement Criteria

The following conditions should exist during a measurement period to ensure that the conditions are as standardized as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows 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 of 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 and others discussed in Section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operated during the measurement and for at least 12 hours before the measurement is initiated. Air conditioning systems that recycle interior air may be operated.

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

- Measurements should not be conducted if severe storms with high winds or rapidly changing barometric pressures are predicted during the measurement period. Weather predictions available on local news stations may provide sufficient information to determine if this condition is satisfied.

2.7.7 Location Selection

The following criteria should be applied to select the location of a pump/collapsible bag device within a room.

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

- The device should not be placed near drafts caused by HVAC vents, windows, and doors. Avoid locations near excessive heat, such as fireplaces or in direct, strong sunlight.

- The air sampled should be from at least 75 centimeters (30 inches) above floor level and at least 10 centimeters (4 inches) from other objects.

- The air sample should not be from close to the outside wall of the house.

2.7.8 Documentation

It is important that enough information about the measurement be recorded in a permanent log so that data interpretations and comparisons can be made. The information includes the following:

- The date and start and stop time of the measurement;
- Serial numbers of bags, pumps, and equipment used for analysis of the radon concentration;
- Whether standardized conditions, as previously specified, are satisfied;
- Exact location of the instrument, on a diagram of the room and house, if possible;
- Other easily gathered information that may be useful, such as the type of house, type of heating system, and existence of basement or crawl space.

2.7.9 Analysis Requirements

If the radon concentration in the collapsible bag is to be analyzed on site, the appropriate radon grab sample protocol (Section 2.8) 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.

2.7.9.1 Sensitivity. The lower limit of detection (LLD) for a pump/collapsible bag device will depend on the method used to analyze the contents of the bag. If a scintillation cell method is used, an LLD of a few tenths of a picocurie per liter should be possible.

2.7.9.2 Precision. The coefficient of variation for split measurements (from the same bag) using the scintillation cell analysis method should not exceed 10 percent (1 sigma) at radon concentrations of 4 pCi/L or greater.

2.7.10 Quality Assurance

The quality assurance program for radon measurements using the pump/collapsible bag method includes calibration and duplicate measurements. The quality assurance program should include the maintenance of control charts, as described by Goldin (Goldin 1984).

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

2.7.10.1 Calibration. If a scintillation flask method of measuring the radon concentrations is used, the appropriate procedure on calibration given in Section 2.8 should be followed.

2.7.10.2 Duplicate Samples. Duplicate samples should be collected with sufficient frequency to test the precision of the procedure. This number should be at least ten percent of the total samples collected. Care should be taken to ensure that the samples are duplicates to the greatest extent possible. Duplicate samples should be taken in close proximity and away from drafts. The samples selected for duplication should be systematically distributed throughout the entire population of samples. Data from duplicate samples should be evaluated using the procedures described by Goldin in section 5.3 of his report (Goldin 1984). Consistent failure in duplicate agreement may indicate a problem in the measurement process that should be investigated.

2.8 PROTOCOL FOR THE DETERMINATION OF INDOOR RADON CONCENTRATION BY GRAB SAMPLING

2.8.1 Purpose

This protocol provides guidance for using grab sampling techniques to provide accurate and reproducible measurements of indoor radon concentrations. Following the protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce measurements of radon concentration representative of closed-house conditions. (See Section 1.3.2.) Such screening measurements have a smaller variability and are more reproducible than measurements made when the house conditions are not controlled.

The results of grab sampling are greatly influenced by conditions that exist in the house 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-house conditions for 12 hours before the measurement. Grab techniques are not recommended for follow-up measurements made to estimate health risks or to determine the need for remedial action.

2.8.2 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 adopted into standard operating procedures. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency (EPA), Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch, 401 M Street, S.W., Washington, D.C. 20460.

2.8.3 Method

There are two grab sampling methods covered by this protocol. In the first method, 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 flask 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 flask. The flask is counted about four hours after filling to allow the short-lived radon decay products to reach equilibrium with the radon. Correction factors (see Appendix A) are applied to the counting results to compensate for decay during the time between collection and counting, and to account for decay during counting.

A second method covered by this protocol uses air pumped through activated carbon to collect the sample. A charcoal filled cartridge is placed into a sampler and air is pumped through the carbon cartridge. The pump-carbon 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 so a correction can be applied for the reduced sensitivity of the charcoal due to absorbed water. The cartridges are analyzed by placing them on a sodium iodide gamma scintillation system or a germanium gamma detector. The pump-carbon cartridge system must be calibrated by analyzing cartridges pumped with known concentrations of radon in a qualified facility.

2.8.4 Equipment

2.8.4.1 Flask Grab Sampling. The equipment needed for flask sampling includes the following:

- A scintillation flask or flasks 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 in use);
- A clock to measure time from collection to counting;
- A filter and filter holder to attach to the air inlet valve of the cell;
- 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 Bureau of Standards (NBS)-traceable alpha check source and scintillation disc;
- A calibration flask or cell;
- A vacuum pump and flask flushing apparatus;

- Aged air or nitrogen for flushing counting flasks.

2.8.4.2 Pump-Carbon Sampling. The equipment needed for pump-carbon samplers includes the following:

- 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;
- Sodium iodide gamma scintillation detector and analyzer;
- Analytic scale capable of weighing the small difference in weight (up to several grams) due to water adsorbed by the charcoal.

Laboratory analysis of the saturated pump-carbon 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 multichannel gamma spectrometer or with a single-channel analyzer calibrated to include the appropriate gamma energies.

2.8.5 Premeasurement Considerations

Prior to collection of the 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 flask should be determined prior to sampling. This may be done using the procedures described in Appendix A for flask counting.

For highly accurate flask measurements, it is necessary to standardize flask pressure prior to counting, because the path lengths of alpha particles are a function of air density. For example, a flask calibrated at sea level and used to count a sample collected at Grand Junction, Colorado (1370 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).

2.8.6 Measurement Criteria

The following conditions should exist prior to and during the sampling to ensure that the conditions are as standardized as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows 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 of 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 and others discussed in Section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operated during the measurement and for at least 12 hours before the measurement is initiated. Air conditioning systems that recycle interior air may be operated.

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

- Short-term measurement should not be conducted if severe storms with high winds or rapidly changing barometric pressure are predicted during the measurement period. Weather predictions available on local news stations may provide sufficient information to determine if this condition is satisfied.

2.8.7 Documentation

It is important that enough information about the measurement is recorded in a permanent log so that data interpretations and comparisons can be made. This will include the following:

- The time and date of the start and end of the measurement;

- Whether standardized conditions, as previously specified, are satisfied;

- Exact location of the measurement, on a diagram, of the room and house, if possible;

- Other easily gathered information that may be useful, such as the type of house, type of heating system, existence of crawl space or basement, and operation of humidifiers, air filters, or electrostatic precipitators;

- Serial numbers of flasks, cartridges, and counting equipment.

2.8.8 Sampling Operations

2.8.8.1 Location Selection. The following criteria should be applied to select the location of the measurement within a room.

- The sample should not be collected near drafts caused by HVAC vents, windows, doors, etc. Avoid locations near excessive heat, such as fireplaces or in direct, strong sunlight.

- Measurements should be made at least 75 centimeters (30 inches) from the floor and at least 10 centimeters (4 inches) from other objects.

- The measurement should not be made close to the outside walls of the house.

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

2.8.8.2 Sampling. All air samples drawn into scintillation flasks must be filtered to remove radon decay products and other airborne radioactive particulates. Filters may be reused many times as long as they remain undamaged.

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

To sample using the double-valve, flow-through type flask, attach the filter to the inlet valve and a suitable vacuum pump to the other valve. The pump may be motor driven or hand operated. Open both valves and operate the pump to flow at least ten

complete air exchanges through the flask. Stop the pump and close both valves.

Sampling using the pump-carbon cartridge method is accomplished by opening a prepared sealed cartridge and attaching it to the sampling pump. The pump should draw air through the cartridge at approximately the rate 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 pump-carbon cartridge systems.

All pertinent sampling information should be recorded after completing the sample, including the date and time, location, flask/cartridge number, name of person collecting the sample, and any other significant conditions within the house or notes on the weather conditions. The detectors should be carefully packaged 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.

2.8.9 Counting and Calculations

2.8.9.1 Flask Sampling. Flasks should not be counted for at least four hours following the time of collection. Background and check sources should be counted as described in Appendix A. The flask to be counted is placed on the photomultiplier tube, the cover placed over the flask, and the system allowed to dark adapt. The flask then may be counted for a sufficient period to collect an adequate number of counts for good counting statistics in relation to the system background counts.

2.8.9.2 Pump-Carbon Sampling. 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 then should 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 absorption. 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.

2.8.10 Flask Flushing and Storage

After the flasks have been counted and data are satisfactorily recorded, the flasks must be flushed with aged air or nitrogen to remove the sample. Flow-through flasks are flushed with at least ten volume exchanges at a flow of about two liters a minute. Flasks with single valves are evacuated and refilled with aged

air or nitrogen at least five times. The flasks 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 flask is ready for reuse.

2.8.11 Results

2.8.11.1 Sensitivity. The sensitivity of the flask method is dependent on the volume of the cell being used. However, sensitivities of 0.1 pCi/L are achievable (George 1980, George 1983). For the pump-carbon method, the lower limit of detection should be 1.0 pCi/L or less. This can normally be achieved with a counting time of up to 30 minutes.

2.8.11.2 Precision. The coefficient of variation for duplicate flask samples should not exceed 10 percent (1 sigma) at radon concentrations of 4.0 pCi/L or more. This precision should be monitored using the results of duplicate measurements described in this protocol. Sources of error in the procedure may result from improper cell calibration, leaking flasks, and improperly calibrated counting equipment. The coefficient of variation for the pump-carbon method should not exceed 10 percent (1 sigma) at radon concentrations of 4.0 pCi/L or more.

2.8.12 Quality Assurance

The quality assurance program for radon measurements using grab sampling includes calibration, duplicate, and background measurements.

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

2.8.12.1 Calibration.

2.8.12.1.1 Flask Calibration. The flask counting system consisting of the scaler, detector, and high-voltage supply must be calibrated. The correct high voltage is determined via a plateau (incrementing the high voltage and plotting the resultant counts). This procedure is described elsewhere (George 1983). Each counting system should be calibrated before being put into service, after any repair, or at least once per year. Also, a check source or calibration flask should be counted in each counter system each day to demonstrate proper operation prior to counting any samples.

A separate calibration factor must be obtained for each flask in the counting system. This is done by filling each flask with radon of a known concentration and counting the flask to determine the conversion factor or counts per minute per picocurie. 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 elsewhere in more detail (George 1976; Lucas 1957; Beckman 1975). Recalibration of each cell should be done every six months.

2.8.12.1.2 Pump-Carbon Cartridge Calibration. The pump-carbon cartridge 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.

2.8.12.2 Duplicates. Duplicate samples should be collected with sufficient frequency to test the precision of the procedure. This number should be at least ten percent of the total radon grab samples collected or 50 per month, whichever is smaller. Care should be taken to ensure that the samples are duplicates to the greatest extent possible. Duplicate samples should be taken in close proximity and away from drafts. The samples selected for duplication should be systematically distributed throughout the entire population of samples. Data from duplicate samples should be evaluated using the procedures described by Goldin in section 5.3 of his report (Goldin 1984). The method should achieve a coefficient of variation of 10 percent or less for the flask and 10 percent or less for the cartridge. Consistent failure in duplicate agreement may indicate a problem in the measurement process that should be investigated.

2.8.12.3 Backgrounds. A background count for each cell is determined prior to measurement, as described in Appendix A. When the pump-carbon cartridge method is used, the background of the carbon should also be routinely assessed.

Section 3: RADON DECAY PRODUCT MEASUREMENT PROTOCOLS

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

3.1.1 Purpose

This protocol provides guidance for using continuous working level monitors (CWLM) to obtain accurate and reproducible measurements of indoor radon decay product concentrations. Following the protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce screening measurements of radon decay product (RDP) concentrations representative of closed-house conditions. Such screening measurements have a smaller variability and are more reproducible than measurements made when the house conditions are not controlled.

If measurements with CWLMs are for a purpose other than a screening measurement, the investigator should follow guidance provided by EPA in "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 520/1-86-014-1, 1987).

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 a CWLM. It is not meant to replace an instrument manual, but rather provides guidelines that should be incorporated into standard operating procedures. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency (EPA), Office of Radiation Programs, Radon Division (ANR-464), Problem Assessment Branch 401 M Street, S.W., Washington, D.C., 20460.

3.1.3 Method

A CWLM 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 1 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 normally set to detect alpha particles with energies between 2 and 8 MeV. The alpha particles emitted from the radon decay products Po-218 and Po-214 are the significant contributors to the events that are measured by the detector. Some CWLMs are capable of measuring individual radon and thoron decay products, and others can 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 typically contains a microprocessor that stores the number of counts and elapsed time. The CWLM 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 CWLM, equipment needed includes replacement filters, a readout or programming device (if not part of the CWLM), an alpha-emitting check source, and an air-flow rate meter.

3.1.5 Predeployment Testing

The CWLM should be carefully tested before and after each measurement 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 168 hours of operation to measure the background count rate using the procedures that may be identified in the operating manual for the instrument.

In addition, participation in a laboratory intercomparison program at least semiannually will verify that the conversion factor used in 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 following house conditions should exist prior to and during a measurement to standardize the measurement conditions as much as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows 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 of 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 and others discussed in Section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operated during the measurement and for at least 12 hours before the measurement is initiated. Air conditioning systems that recycle interior air may be operated.

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

- Grab measurements should not be conducted if severe storms with high winds or rapidly changing barometric pressure are predicted. Weather predictions available on local news stations may provide sufficient information to determine if this condition is satisfied.

3.1.7 Deployment and Operation

3.1.7.1 Location Selection. The following criteria should be applied to select the location of the CWLM within a room.

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

- The measurement location should not be close to the outside walls of the house.

- The unit should be placed on a table or stool so that the air intake is at least 75 centimeters (30 inches) from the floor.

3.1.7.2 Operation. The CWLM should be programmed to run continuously, recording the hourly integrated WL measured and, when possible, the total integrated average WL. The sampling period should not be less than 24 hours for most purposes. The longer the operating time, the smaller the uncertainty associated with the measurement result. The integrated average WL over the measurement period should be used as the measurement result.

3.1.7.3 Documentation. It is important that the operator of the CWLM record enough information about the measurement in a permanent log so that data interpretations and comparisons can be made. This will include the following:

- The time and date of the start and end of the measurement;
- Serial number of the CWLM and calibration factor used;
- Whether standardized conditions, as specified, are satisfied;
- Exact location of the instrument, on a diagram if possible;
- Other easily gathered information that may be useful, such as the type of house, type of heating system, existence of crawl space, occupants smoking habits, and operation of humidifiers, air filters, or electrostatic precipitators.

3.1.8 Results

3.1.8.1. Lower Limit of Detection. Most CWLMs are capable of an LLD of 0.005 WL or less.

3.1.8.2. Precision. Most CWLMs can acheive a coefficient of variation of less than 10% (1 sigma) at radon concentrations of 4 pCi/L or greater.

3.1.9 Quality Assurance

The elements of a quality assurance program for the CWLM are as follows.

- Calibration in a radon decay product exposure calibration chamber before being put in service and at least every 6 months, and after instrument repair or modification.
- Checks using an Am-241 or Th-230 similar-energy alpha check source (before and after each measurement).
- Background count-rate checks (after at least every 168 hours of operation).
- When two or more CWLMs are available, the coefficient of variation of the measurements can be estimated by operating the CWLMs side by side. The analysis of duplicate results should follow the methodology described by Goldin in section 5.3 of his report (Goldin 1984).

The quality assurance program should include the maintenance of control charts, as described by Goldin (Goldin 1984).

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

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

3.2.1 Purpose

This protocol provides guidance for using a RPISU to produce accurate and reproducible measurements of indoor radon decay product concentrations. Following the procedure will help ensure uniformity in measurement programs and allow valid inter-comparison of results. Measurements made in accordance with this protocol will produce screening measurements of radon decay product (RDP) concentrations representative of closed-house conditions. Such screening measurements have a smaller variability and are more reproducible than measurements made when the house conditions are not controlled.

If measurements with RPISUs are for a purpose other than a screening measurement, the investigator should follow guidance provided by EPA in "Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements" (EPA 520/1-86-014-1, 1987).

3.2.2 Scope

This protocol covers, in general terms, the equipment, procedures, analysis, and quality control objectives for measurements made with RPISUs. It is not meant to replace an instrument manual, but rather provides guidelines to be adopted into standard operating procedures. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency (EPA), 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 TLD RPISU. There are two types of RPISUs. 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 thermoluminescent dosimeters (TLDs). One TLD measures the radiation emitted from radon decay products collected on the filter, and the other TLD is used for background gamma correction. This RPISU is intended for a sampling period of three days to a few weeks.

Analysis of the detector TLDs is performed in a laboratory using a thermoluminescent dosimeter 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.

3.2.3.1 ATD RPISU. The second type of RPISU consists of an air sampling pump and a detector 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. Opposed to the side of the filter where the RDPs 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). 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 RPISU is intended for a sampling period of three days 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.

Both types of RPISUs are true integrating instruments if the pump flow rate is uniform throughout the sampling period.

3.2.4 Equipment

Both types of RPISU sampling systems include the sampling pump and the detector assembly. Sampling with the TLD-type RPISU requires either a fresh detector assembly or fresh TLD chips to be inserted in the detector assembly. Sampling with the alpha track detecting RPISU requires a fresh film disc. An air flow rate meter should be available for checking flow rates with either RPISU, and spare filters should be available as replacements as needed.

3.2.5 Predeployment Considerations

Prior to installation in the house, 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 house to ensure that entry to the house can be made 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 following house conditions should exist prior to and during a

measurement to standardize the measurement conditions as much as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows 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 of 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 and other reasons discussed in Section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operated during the measurement and for at least 12 hours before the measurement is initiated. Air conditioning systems that recycle interior air may be operated.

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

- Short-term measurement should not be conducted if severe storms with high winds or rapidly changing barometric pressure are predicted during the measurement period. Weather predictions available on local news stations may provide sufficient information to determine if this condition is satisfied.

3.2.7 Deployment and Operation

Install the RPISU and, if possible, check the air flow rate with a calibrated flow meter. Record the location, date, starting time, running time meter reading, and flow rate on the detector assembly envelope and in a log. Observe the RPISU for a few minutes after starting to ensure continued operation; also inform the occupants about the RPISU and request that they report any problems or pump shut down. The occupants should be aware of the length of time the RPISU will be operated, and an appointment should be arranged to retrieve the unit. The criteria for the standardized measurement conditions should be repeated to the occupants.

The sampling period should be at least 72 hours. A longer

operating time decreases the uncertainty associated with the measurement result.

3.2.7.1 Location Selection. The following criteria should be used to select the location of the RPISU within a room:

- A position should be selected where the device will not be disturbed during the sampling period;
- The RPISU should not be placed near drafts caused by HVAC vents, windows, or doors;
- The air intake (sampling head) should be placed at least 75 centimeters (30 inches) above the floor and at least 20 centimeters (8 inches) from surfaces that may obstruct flow;
- The RPISU should not be placed close to the outside wall of the house;
- The RPISU should not be placed in kitchens or bathrooms.

3.2.8 Retrieval

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. Return the detector assembly or detector film to its envelope and record the date, time, running time meter reading, and flow rate both on the envelope and in a log book. Check the filter for holes or dust loading and record 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

It is important that enough information about the measurement is recorded in a permanent log so that data interpretations and comparisons can be made. This will include the following:

- The time and date of the start and end of the measurement;
- Serial numbers of RPISUs, film discs or TLDs;
- Whether standardized conditions, as previously specified, are satisfied;
- Exact location of the instrument, on a diagram of the room and house, if possible;

- Other easily gathered information that may be useful, such as the type of house, type of heating system, existence of crawl space, occupants smoking habits, and operation of humidifiers, air filters, or electrostatic precipitators.

3.2.10 Analysis

Analysis of the film from the alpha track detector RPISUs requires an analysis laboratory equipped to etch and count alpha track film.

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

3.2.10.1 Sensitivity. The lower limit of detection (LLD) (Altshuler and Pasternack 1963) should be specified by individual suppliers for RPISU 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. The coefficient of variation should not exceed ten percent (1 sigma) at radon decay product concentrations of 0.02 WL or greater. This precision should be monitored and recorded using the results of the duplicate detector analyses described in section 3.2.11.3.

3.2.11 Quality Assurance

The quality assurance program for measurements of radon decay product concentrations in terms of working levels comprises four elements: (1) calibration, (2) known exposure (spiked) detectors (3) duplicate measurements and (4) control dosimeters to measure exposure during shipment and storage. The quality assurance program should include the maintenance of control charts, as described by Goldin (Goldin 1984).

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For

further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M St., SW; Washington, D.C., 20460.

3.2.11.1 Calibration. Calibration of RPISUs 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 RPISU sampling pumps. The environmental conditions in the chamber during all exposures should be similar to those that are found in the tested houses. Calibration should include exposure of a minimum of four detectors exposed at different RDP concentrations representative of the range found in routine measurements. The relationship of thermoluminescent dosimeter reader units or etched track reader units to working level for a given sample volume and the standard error associated with this measurement should be determined. Calibration of the RPISUs also includes testing to ensure accuracy of the flow rate measurement.

After the initial calibration, periodic processing of exposed detectors should be done to assure that the detection system has not changed.

3.2.11.2 Known Exposure Devices. Both suppliers and large users of RPISU services of both types should submit detectors with known radon exposures (spiked samples) for analysis on a regular schedule. Known exposure detectors should be labeled in the same manner as the field detectors to assure blind processing. The number of known exposure detectors submitted for analysis should be a few percent of the total number of devices analyzed. 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 (Colocated) Detectors. Large users should make duplicate measurements in enough houses to monitor the precision of the measurements. This usually will be approximately ten percent of the houses to be tested 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 systematically distributed throughout the entire population of samples. Groups selling measurements to homeowners can do this by making two side-by-side measurements instead of one in a random selection of homes. Data from duplicate detectors should be evaluated using the procedures described by Goldin in Section 5.3 of his report (Goldin 1984). The method should achieve a coefficient of variation of 10 percent (1 sigma) or less at radon decay product concentrations of 0.02 WL or greater. Consistent failure in

duplicate agreement may indicate a problem in the measurement process that should be investigated.

3.2.11.4 Controls. Thermoluminescent dosimeter RPISUs 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 individual detector assemblies. The two TLDs are processed identically and the environmental gamma exposure is subtracted from the sample reading.

3.2.11.4.1 Laboratory Control Detectors. The laboratory background level for each batch of assembled thermoluminescent detectors 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. This laboratory blank value is subtracted by the analysis laboratory from the results obtained from the field detectors to arrive at the net readings used to calculate the reported sample radon concentrations.

Similarly, the laboratory background level for each batch of alpha track RPISUs 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. This laboratory blank value is subtracted by the analysis laboratory from the results obtained from the field detectors to arrive at the net readings used to calculate the reported sample concentrations.

3.2.11.4.2 Field Control Detectors (Blanks). For thermoluminescent detector RPISUs and alpha track RPISUs, field control detectors (field blanks) should consist of a minimum of five percent of the detectors deployed each month or 25, whichever is smaller. Commercial users should set these aside from each shipment, keep them sealed, label them in the same manner as the field detectors, and send them back to the supplier as blind controls with one shipment each month. These field blank detectors 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 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.

3.3 PROTOCOL FOR THE DETERMINATION OF INDOOR RADON DECAY PRODUCT CONCENTRATION BY GRAB SAMPLING

3.3.1 Purpose

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

The results of grab sampling are greatly influenced by conditions that exist in the house 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-house conditions for 12 hours before the measurement. Grab techniques are not recommended for follow-up measurements made to estimate health risks or to determine the need for remedial action.

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 adopted into standard operating procedures. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency (EPA), 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 RDP 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 following collection. Several methods for performing such measurements have been developed and have been described by George (George 1980). Comparable results may be obtained using all these methods. This procedure, however, will describe two methods that have been most widely used with good results. These are the Kusnetz procedure and the modified Tsivoglou procedure.

The Kusnetz procedure (Kusnetz 1956, ANSI 1973) 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 5-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 working levels using the appropriate "Kusnetz factor" (see Appendix B, Table B-1) for the counting time used.

The Tsivoglou procedure, as modified by Thomas (Tsivoglou et al. 1953; Thomas 1972), may be used to determine WL and the concentration of the individual RDPs. 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 2 and 5 minutes, 6 and 20 minutes, and 21 and 30 minutes following completion of sampling. Count results are used in a series of equations to calculate concentrations of the three RDPs and working level. These equations and an example calculation appear in Appendix B.

3.3.4 Equipment

Equipment required for RDP concentration determination by grab sampling consists of the following items:

- An air pump capable of collecting samples at the desired flow rate;
- A filter holder to accept a 25- or 47-mm diameter, 0.8-micron membrane or glass fiber filter;
- A calibrated flow meter to determine air flow through the filter during sampling;
- A clock for accurate timing of sampling and counting;
- A scintillation counter (such as the Randam Electronics Model SC-5, or the EDA Instruments Model RD-200) and a zinc sulfide scintillation disc;
- A National Bureau of Standards (NBS)-traceable alpha calibration source to determine counter efficiency;
- A data collection log.

3.3.5 Premeasurement Considerations

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 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 NBS-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 following house conditions should exist prior to and during a measurement to standardize the measurement conditions as much as possible.

- The measurement should be made under closed-house conditions. To the extent reasonable, windows 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 of 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 and others discussed in Section 1.3.1, measurements should be made during winter periods whenever possible.

- Internal-external air exchange systems (other than a furnace) such as high-volume attic and window fans should not be operating during the measurement and for at least 12 hours before the measurement is initiated. Air conditioning systems that recycle interior air may be operated.

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

- Short-term measurement should not be conducted if severe storms with high winds or rapidly changing barometric pressure are predicted during the measurement period. Weather predictions available on local news stations may provide sufficient information to determine if this condition is satisfied.

3.3.7 Documentation

It is important that enough information about the measurement is recorded in a permanent log so that data interpretations and comparisons can be made. This information includes the following:

- The time and date of the start and end of the measurement;
- Serial numbers of equipment and a description which uniquely identifies customer, building, room, and sampling position;
- Whether standardized conditions, as previously specified, are satisfied;
- Exact location of the measurement, on a diagram of the room and house, if possible;
- Other easily gathered information that may be useful, such as the type of house, type of heating system, the existence of crawl space or basement, occupants smoking habits, and operation of humidifiers, air filters, or electrostatic precipitators.

3.3.8 Sampling Operations

3.3.8.1 Location in Room. The following criteria should be applied to select the location of the measurement within a room.

- The measurement should not be made near drafts caused by heating, ventilating and air conditioning vents, doors, and windows.
- The measurement location should not be close to the outside walls of the house.
- The unit should be placed on a table or stool so that the air intake is at least 75 centimeters (30 inches) from the floor and at least 10 centimeters (4 inches) from other objects.
- In general, measurements should not be made in kitchens or bathrooms.

3.3.8.2 Sampling. A new filter should be placed in the filter holder prior to entering the house. Care should be taken to avoid puncturing the filter and to avoid leaks. The sampling is begun by starting the pump and the clock simultaneously. Note the air flow rate and record it in a log book. Also record the time the sampling was begun. The sampling period should be five

minutes, and the time from the beginning of sampling to the time of counting must be precisely recorded.

3.3.9 Analysis

Analysis may be done using the Kusnetz, modified Tsivoglou, or other procedure 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 ten minutes during this period is usually used.

Remove the filter from the holder using forceps and carefully place it 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 may be found in the references (Kusnetz 1956, Tsivoglou 1953, Thomas 1972).

3.3.10 Grab Sampling Results

3.3.10.1 Sensitivity. For a five-minute sampling period (10 to 20 liters of air) on a 25-mm filter, the sensitivity using the Kusnetz or modified Tsivoglou counting procedure should be approximately 0.0005 working level (George 1980).

3.3.10.2 Precision. The coefficient of variation should not exceed 10 percent (1 sigma) at radon decay product concentrations of 0.005 WL or greater. This precision should be monitored using the results of duplicate measurements. 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 amount of radioactivity on the filter.

3.3.11 Quality Assurance

The quality assurance program for RDP concentration measurements by grab sampling includes calibration and duplicate measurements. The quality assurance program should include the maintenance of control charts, as described by Goldin (Goldin 1984).

The EPA has established the National Radon Measurement Proficiency (RMP) Program. This quality assurance program enables participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. For

further information please write to the U.S. Environmental Protection Agency; Radon Division; Mitigation, Prevention, and Quality Assurance Branch; National RMP Program; 401 M Street, SW; Washington, D.C., 20460.

3.3.11.1 Calibration. Pumps and flow meters used to sample air must be routinely calibrated to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy. This should be done every six months or after any instrument repair or modification.

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 NBS-traceable alpha calibration source such as thorium-230.

At least once a year, grab measurements should be made in a calibration chamber with known RDP 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 during the year requires that the new material be checked for collection efficiency in a calibration chamber.

3.3.11.2 Duplicates. Duplicate grab samples should be collected with sufficient frequency to test the precision of the measurement. The number of duplicates should be at least ten percent of the total samples collected or 50 per month, whichever is smaller. Care should be taken to ensure that the samples are duplicates to the greatest extent possible. The filter heads should be relatively close to each other and away from drafts. Care also should 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 systematically distributed throughout the entire population of measurements.

Data from duplicate samples should be evaluated using the procedures described by Goldin in Section 5.3 of his report (Goldin 1984). The method should achieve a coefficient of variation of 10 percent (1 sigma) or less for radon decay product concentrations of 0.02 WL or greater. Consistent failure in duplicate agreement may indicate a problem in the measurement process that should be investigated.

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APPENDIX A

SUPPLEMENTARY INFORMATION FOR GRAB RADON SAMPLING

(SCINTILLATION CELL METHOD)

A.1 EQUIPMENT

Equipment to measure radon concentration using grab sampling into scintillation cells is available from several commercial suppliers. Equipment required is listed below.

- Scintillation cells
- Pump to evacuate single valve cells or to flow air through double valve cells
- Filter holder and filter to remove particulates
- Detector-scaler-high voltage assembly for counting
- Timer
- Calibration cell or check source
- Aged air or nitrogen

A.2 GENERAL METHOD DESCRIPTION

- Air to be sampled for radon is either flushed through a cell using a low volume air pump or is drawn into an evacuated cell through a filter.
- The sample in the cell is allowed to equilibrate to optimize counting efficiency.
- The cell is placed on a photomultiplier tube and scintillations counted.
- Radon concentration is calculated based on the sample counts and corrected using appropriate ingrowth and decay factors.

A.3 PROCEDURE

The procedure described below is that used by the U.S. Environmental Protection Agency, Office of Radiation Programs, in its field measurement programs. It is designed for measurements made using the Randam Electronics Model SC-5 cell counters and associated cells or the EDA Instruments Model RD-200 System.

However, 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 the calculations. The following is a general procedure using the Randam or EDA equipment.

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. Place each cell in the counter, wait two minutes for the system to become dark adapted, and count background of the cell for ten minutes. Record background data for each cell.

2. At the site to be surveyed, collect the sample by flowing air into the longer tube in the top of the EDA cell (double valve) for a period sufficient to allow ten air exchanges. For the Randam (single valve) cells it is only necessary to open the valve on the evacuated cells and allow ten to fifteen 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, the systems are allowed to dark adapt for two minutes, and the cells are 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.

A.4 CALCULATION OF RESULTS

The radon concentration in picocuries per liter 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 system determine for each cell. For the EDA and Randam cells, the factor is typically 4-5 cpm/pCi.

C = Correction for decay during counting from table A-1.

A = Correction for decay of radon from time of collection to start of counting from table A-1.

V = Volume of counting cell in liters,

V = 0.170 L for EDA cells
V = 0.125 L for Randam cells

A.5 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 EDA cell = 0.170 L

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

Table A-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	0.99887	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	0.28138	1.02665
8	0.99899	0.94140	0.23475	1.03050
9	0.99887	0.93432	0.19586	1.03435
10	0.99874	0.92730	0.16341	1.03821
11	0.99862	0.92033	0.13633	1.04209
12	0.99849	0.91340	0.11374	1.04597
13	0.99837	0.90654	0.09490	1.04986
14	0.99824	0.89972	0.07917	1.05377
15	0.99811	0.89295	0.06605	1.05768
16	0.99799	0.88624	0.05511	1.06160
17	0.99786	0.87958	0.04598	1.06553
18	0.99774	0.87296	0.03836	1.06947
19	0.99761	0.86640	0.03200	1.07342
20	0.99749	0.85988	0.02670	1.07738
21	0.99736	0.85342	0.02228	1.08135
22	0.99724	0.84700	0.01859	1.08532
23	0.99711	0.84063	0.01551	1.08931
24	0.99699	0.83431	0.01294	1.09331
25	0.99686	0.82803	0.01079	1.09732
26	0.99673	0.82181	0.00901	1.10133
27	0.99661	0.81563	0.00751	1.10536
28	0.99648	0.80950	0.00627	1.10939
29	0.99636	0.80341	0.00523	1.11344
30	0.99623	0.79737	0.00436	1.11749

Table A-1: Radon Correction Factors (Continued)

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
31	0.99811	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
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

APPENDIX B

SUPPLEMENTARY INFORMATION FOR GRAB RADON DECAY PRODUCT SAMPLING

B.1 EQUIPMENT

a. Air sampling pump A pump capable of maintaining a flowrate of 2 to 25 liters per minute through the selected filter is required. The flowrate should not vary significantly during the sampling period. A calibrated air flow measurement device is also required.

b. Filters and filter holder assembly Membrane type filters are recommended with a pore size not exceeding 0.8 microns and a filter holder assembly suitable for the type of filters being used. Adapters for attachment of the filter holder to the pump are also required.

c. Alpha counting system A detector and scaler-timer system is required that can accurately measure the alpha particles emitted by radon decay products on a filter. The counting system must be calibrated and the efficiency should not vary significantly with alpha energy over the range of 4 to 7 MeV. Downward-looking detectors with a mylar seal are very energy dependent, and if such detectors are used the efficiency is best determined using Po-214.

d. Timer A stopwatch or timer to measure the sampling time and counting times is required.

B.2 GENERAL DESCRIPTION OF METHODS

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.

B.3 PROCEDURE

a. Sample Collection

(1) Install the filter in the filter holder assembly and attach to the pump.

(2) Operate the pump for exactly 5 minutes, pulling air through the filter. Record starting time and air flow rate.

Note Sample counting and analysis for two different techniques are described.

(3) Stop the pump at the end of the 5-minute sampling time and start or reset the stopwatch.

b. Sample Counting

(1) Modified Tsivoglou Technique

(a) Carefully transfer the filter from the filter holder assembly to the detector. Orient the collection side of the filter toward the face of the detector.

(b) Operate the counter for the following time intervals, after sampling has stopped: 2 to 5 minutes, 6 to 20 minutes, and 21 to 30 minutes. Record the total counts for each time period.

(2) Kusnetz Technique

(a) Carefully transfer the filter from the filter holder assembly to the detector. Orient the collection side of the filter toward the face of the detector.

(b) Operate the counter over any 10-minute time interval between 40 minutes and 90 minutes after sampling starts. Record the total counts for the sample and the time (in minutes after sampling) at the midpoint of the 10-minute time interval.

c. Data Analysis

(1) Modified Tsivoglou Technique

The concentration in pCi/L of each of the radon decay products, Po-218, Pb-214 and Po-214 can be determined by using the following calculations:

$$C_2 = \frac{1}{FE} (0.16746\ G_1 - 0.0813\ G_2 + 0.0769\ G_3 - 0.0566R)$$

$$C_3 = \frac{1}{FE} (0.00184\ G_1 - 0.0209\ G_2 + 0.0494\ G_3 - 0.1575R)$$

Note: The constants in these equations are based on a 3.11-minute half-life of Po-218, and are therefore slightly different than those used by Thomas (Thomas 1972). The working level associated with these concentrations can then be calculated using the following relationship:

$$C_4 = \frac{1}{FE} (-0.0235\ G_1 + 0.0337\ G_2 - 0.0382\ G_3 - 0.0576R)$$

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

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 lpm

E = counter efficiency in cpm/dpm

G_1 = gross alpha counts for the time interval 2 to 5 minutes

G_2 = gross alpha counts for the time interval 6 to 20 minutes

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

R = background counting rate in cpm

Reference: (Thomas 1972).

(2) Kusnetz Technique

Calculate WL as follows:

$$WL = \frac{C}{K(_t)\ V\ E}$$

where:

C = Sample cpm - Background cpm

K_t = Factor determined from Table B-1 for time from end of collection to midpoint of counting

V = Total sample air volume in liters from:

flow rate (1/m) x sample time (m)

E = Counter efficiency in cpm/dpm.

TABLE B-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

MODIFIED TSIVOGLOU TECHNIQUE

SAMPLE PROBLEM

F = Sampling Flow Rate = 3.5 lpm

E = Counting Efficiency = 0.47 cpm/dpm

$G_1 = 880$

$G_2 = 2660$

$G_3 = 1460$

$R = 0.5$

$$C_2 = \frac{1\ (0.16746 \times 880 - 0.0813 \times 2660 + 0.0769 \times 1460 - 0.0566 \times 0.5)}{3.5 \times 0.47}$$

$C_2 = 26.3$ pCi/L

$$C_3 = \frac{1\ (0.00184 \times 880 - 0.0209 \times 2660 + 0.0494 \times 1460 - 0.1575 \times 0.5)}{3.5 \times 0.47}$$

$C_3 = 11.0$ pCi/L

$$C_4 = \frac{1\ (-0.0235 \times 880 + 0.0337 \times 2660 - 0.0382 \times 1460 - 0.0576 \times 0.5)}{3.5 \times 0.47}$$

$C_4 = 8.0$ pCi/L

$$WL = (1.028 \times 10^{-3} \times 26.3 + 5.07 \times 10^{-3} \times 11.0 + 3.728 \times 10^{-3} \times 8.0)$$

$WL = 0.113$

KUSNETZ TECHNIQUE

SAMPLE PROBLEM

- Background Count = 3 counts in 5 minutes, or 0.6 cpm
- Standard Count = 5,985 counts in 5 minutes, or 1,197 cpm
- Efficiency = $\frac{1{,}197 \text{ cpm} - 0.6 \text{ cpm}}{2430 \text{ dpm}}$ = 0.49 (known source of 2430 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 Table B-1 = 130

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

$$WL = 0.04$$