the time selected for sealing the device and returning it to the laboratory.

2.4.6 Measurement Criteria

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

2.4.7 Deployment

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

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

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

2.4.8 Retrieval of Detectors

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

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

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

2.4.9 Documentation

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

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

2.4.10 Analysis Requirements

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

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

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

2.4.11 Quality Assurance

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

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

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

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

2.4.11.4 Control Detectors

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

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

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

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2.5 Protocol for Using Charcoal Liquid Scintillation (LS) Devices to Measure Indoor Radon Concentration

2.5.1 Purpose

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

2.5.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency.

2.5.3 Method

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

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

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

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

2.5.4 Equipment

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

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

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

2.5.5 Predeployment Considerations

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

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

2.5.6 Measurement Criteria

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

2.5.7 Deployment

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

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

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

2.5.8 Retrieval of Devices

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

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

2.5.9 Documentation

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

2.5.10 Analysis Requirements

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

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

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

2.5.11 Quality Assurance

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

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

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

2.5.11.3 Duplicate (Collocated) Devices. Anyone providing measurement services with LS devices

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

2.5.11.4 Control Devices

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

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

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

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2.6 Protocol for Using Grab Radon Sampling (GB, GC, GS) Pump/Collapsible Bag Devices (PB), and Three-day Integrating Evacuated Scintillation Cells (SC) to Measure Indoor Radon Concentrations

2.6.1 Purpose

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

Results of grab sampling are influenced greatly by conditions that exist in the building during and for up

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

2.6.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency.

2.6.3 Methods

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

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

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

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

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

period of the sample will affect the accuracy of the measurement. A number of suitable battery- and/or charger-operated pumps with controlled flow rates are available commercially.

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

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

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

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

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

2.6.4 Equipment

2.6.4.1 Grab Radon Sampling Techniques

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

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

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

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

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

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

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

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

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

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

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

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

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

2.6.5 Predeployment Considerations

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

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

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

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

2.6.6 Measurement Criteria

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

2.6.7 Deployment

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

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

long as they remain undamaged and functional.

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

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

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

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

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

2.6.8 Retrieval of Devices

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

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

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

2.6.9 Documentation

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

For GBs, GCs, and GSs, the serial numbers of cells, cartridges, bags, pumps, and counting equipment should also be recorded.

For PBs, the serial numbers of bags, pumps, and equipment used for analysis of the radon concentration should also be recorded.

For SCs, the start-time and stop-time vacuum gauge readings should also be recorded, along with the serial numbers of the cells and counting equipment.

2.6.10 Counting and Calculations

2.6.10.1 Grab Radon Sampling Techniques

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

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

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

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

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

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

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

2.6.11 Analysis Requirements

2.6.11.1 Sensitivity.

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

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

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

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

2.6.12 Quality Assurance

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

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

2.6.12.1 Calibration

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

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

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

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

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

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

2.6.12.2 Known Exposure Measurements. Anyone providing measurement services using these methods should submit devices with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per

month. Known exposure (spiked) devices should be labeled in the same manner as the field devices to assure identical processing. The results of the known exposure analyses should be monitored and recorded, and any significant deviation from the known concentration to which they were exposed should be investigated.

2.6.12.3 Duplicate (Collocated) Devices. Anyone providing measurement services with these methods should place duplicate devices in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. To the greatest extent possible, care should be taken to ensure that the samples are duplicates, are taken in close proximity, and are away from drafts. The samples selected for duplication should be distributed systematically throughout the entire population of samples. The duplicate devices should be shipped, stored, exposed, and analyzed under the same conditions, and not identified as duplicates to the processing laboratory. Groups selling measurement services to homeowners can accomplish this by making two side-by-side measurements in a random selection of homes. Data from duplicate devices should be evaluated using the procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.6.12.4 Background Measurements/Control Devices

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

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

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

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

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

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

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

1. The cells to be used are flushed with aged air or nitrogen to remove traces of the previous sample. It may be necessary to store cells for 24 hours prior to reuse if the cell had contained a high activity sample. Each cell is placed in the counter, and allowed two minutes for the system to

become dark-adapted. The background of the cell is then counted for ten minutes. Background data are recorded for each cell.

2. At the survey site, the sample is collected by flowing air into the longer tube in the top of the double-valve cell for a period sufficient to allow 10 air exchanges. For the single-valve cells, it is only necessary to open the valve on the evacuated cells and allow 10 to 15 seconds for complete filling. Cells must be filled with air forced through a filter to prevent entry of airborne particulates.
3. The filled cells must be allowed to equilibrate for four hours prior to counting. The cells should not be exposed to bright light prior to counting.
4. The cells are placed in the counters, and the systems are allowed to dark-adapt for two minutes. The cells are then counted. Counting time will vary based on the activity in the cell; however, at least 1,000 counts is desirable to provide good statistics.
5. The activity in the sample is calculated and corrected for ingrowth and decay as described below.

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

pCi/L = cpm(s) - cpm (bkg)/E x C/A x 1/V

Where:

cpm(s) = Counts per minute for the sample

cpm(bkg) = Counts per minute for background

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

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

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

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

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

Background count for system = 10 counts in 10 minutes, or 1 cpm

Sample count for 120 minutes = 1200 counts, or 10 cpm

System efficiency (E) from cell calibration = 4.62 cpm/pCi

Count time correction (C) for 120 minutes = 1.00757

Delay time correction (A) for 4 hours = 0.97026

Volume correction (V) for cell = 0.170 L

pCi/L = 10 cpm - 1 cpm/4.62 cpm/pCi x 1.00757/0.97026 x 1/0.170 L = 11.9

Exhibit 2-1

Radon Correction Factors

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

C = Correction for radon decay during counting

Radon Correction Factors									
	A			C		A			C
Time	Minutes	Hours	Days	Hours	Time	Minutes	Hours	Days	Hours

0	1.00000	1.00000	1.00000	1.0000	31	0.99611	0.79137	0.00364	1.12155
1	0.99987	0.99248	0.83431	1.00378	32	0.99598	0.78542	0.00304	1.12562
2	0.99975	0.98502	0.69607	1.00757	33	0.99586	0.77951	0.00253	1.12971
3	0.99962	0.97761	0.58074	1.01136	34	0.99573	0.77365	0.00211	1.13380
4	0.99950	0.97026	0.48451	1.01517	35	0.99561	0.76784	0.00176	1.13790
5	0.99937	0.96296	0.40423	1.01899	36	0.99548	0.76206	0.00147	1.14201
6	0.99925	0.95572	0.33726	1.02281	37	0.99536	0.75633	0.00123	1.14613
7	0.99912	0.94854	0.26138	1.02665	38	0.99523	0.75064	0.00102	1.15026
8	0.99899	0.94140	0.23475	1.03050	39	0.99511	0.74500	0.00085	1.15440
9	0.99887	0.93432	0.19586	1.03435	40	0.99498	0.73940	0.00071	1.15854
10	0.99874	0.92730	0.16341	1.03821	41	0.99486	0.73384	0.00059	1.16270
11	0.99862	0.92033	0.13633	1.04209	42	0.99473	0.72832	0.00050	1.16687
12	0.99849	0.91340	.011374	1.04597	43	0.99461	0.72284	0.00041	1.17105
13	0.99837	0.90654	0.09490	1.04986	44	0.99448	0.71741	0.00035	1.17523
14	0.99824	0.89972	0.07917	1.05377	45	0.99435	0.71201	0.00029	1.17943
15	0.99811	0.89295	0.06605	1.05768	46	0.99423	0.70666	0.00024	1.18363
16	0.99799	0.88624	0.05511	1.06160	47	0.99410	0.70134	0.00020	1.18784
17	0.99786	0.87958	0.04598	1.06553	48	0.99398	0.69607	0.00017	1.19207
18	0.99774	0.87296	0.03836	1.06947	49	0.99385	0.69084	0.00014	1.19630
19	0.99761	0.86640	0.03200	1.07342	50	0.99373	0.68564	0.00012	1.20054
20	0.99749	0.85988	0.02670	1.07738	51	0.99360	0.68049	0.00010	1.20479
21	0.99736	0.85342	0.02228	1.08135	52	0.99348	0.67537	0.00008	1.20905
22	0.99724	0.84700	0.01859	1.08532	53	0.99335	0.67029	0.00007	1.21332
23	0.99711	0.84063	0.01551	1.08931	54	0.99323	0.66525	0.00006	1.21760
24	0.99699	0.83431	0.01294	1.09331	55	0.99310	0.66025	0.00005	1.21189
25	0.99686	0.82803	0.01079	1.09732	56	0.99298	0.65528	0.00004	1.22619
26	0.99673	0.82181	0.00901	1.10133	57	0.99286	0.65036	0.00003	1.23050
27	0.99661	0.81563	0.00751	1.10536	58	0.99273	0.64547	0.00003	1.23481
28	0.99648	0.80950	0.00627	1.10939	59	0.99261	0.64061	0.00002	1.23914
29	0.99636	0.80341	0.00523	1.11344	60	0.99248	0.63579	0.00002	1.24347
30	0.99623	0.79737	0.00436	1.11749					

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2.7 Interim Protocol for Using Unfiltered Track Detection (UT) to Measure Indoor Radon Concentrations

2.7.1 Purpose

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

Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.7.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency.

2.7.3 Method

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

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

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

2.7.4 Equipment

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

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

- The UT detector packaged in an individual, shielded container to prevent extraneous exposure before deployment;
- An instruction sheet for the occupant, a sample log sheet, and a shipping container (along with a mailing label, if appropriate;
- At the time of retrieval, some means for sealing the detector prior to returning it to the supplier for analysis; and
- A data collection log, if appropriate.

2.7.5 Predeployment Considerations

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

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

2.7.6 Measurement Criteria

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

2.7.7 Deployment

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

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

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

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

2.7.8 Retrieval of Detectors

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

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

2.7.9 Documentation

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

2.7.10 Analysis Requirements

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

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

2.7.11 Quality Assurance

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

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

- UT detectors should be exposed in a radon chamber at several different radon and decay product concentrations similar to those expected in the tested buildings (a minimum of three different concentrations). Concentrations of radon decay products must be known in order to be included in the calculation of the calibration factor.
- A minimum of 10 detectors should be exposed at each level.
- A calibration factor should be determined for each batch of detector material received from the material supplier. Alternatively, calibration factors may be established from several sheets, and these factors extended to detectors from sheets exhibiting similar sensitivities (within pre-established tolerance limits).
- Altitude of the radon chamber must be known if located at more than 600 feet (200 meters) above sea level so that a correction can be included in the calculation of the calibration factor.

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

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

2.7.11.4 Control Detectors

2.7.11.4.1 Laboratory Control Detectors. The laboratory background level for each batch of UT detectors should be established by each supplier. Suppliers should measure the background of a statistically significant number of unexposed detectors that have been

processed according to their standard operating procedures. Normally, the analysis laboratory or supplier calculates the net readings (which are used to calculate the reported sample radon concentrations) by subtracting the laboratory blank values from the results obtained from the field detectors.

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

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

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"Indoor Radon and Radon Decay Product Measurement Device Protocols"

Section 3: Indoor Radon Measurement Device Protocols

3.1 Protocol for Using Continuous Working Level Monitors (CW) to Measure Indoor Radon Decay Product Concentrations

3.2 Protocol for Using Radon Progeny Integrating Sampling Units (RPISU or RP) to Measure Indoor Radon Decay Product Concentrations

3.3 Protocol for Using Grab Sampling-Working Level (GW) to Measure Indoor Radon Decay Product Concentrations

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3.1 Protocol for Using Continuous Working Level Monitors (CW) to Measure Indoor Radon Decay Product Concentrations

3.1.1 Purpose

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

3.1.2 Scope

This protocol covers, in general terms, the sample collection and analysis method, the equipment needed, and the quality control objectives of measurements made with CW. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency.

3.1.3 Method

The CW method samples the ambient air by filtering airborne particles as the air is drawn through a filter cartridge at a low flow rate of about 0.1 to one liter per minute. An alpha detector such as a diffused-junction or surface-barrier detector counts the alpha particles produced by the radon decay products as they decay on the filter. The detector is set normally to detect alpha particles with energies between two and eight MeV. The alpha particles emitted from the radon decay products radium A (Po-218) and radium C' (Po-214) are the significant contributors to the events that are measured by the detector. All CW detectors are capable of measuring individual radon and thoron decay products, while some can be adapted to measure the percentage of thoron decay products. The event count is

directly proportional to the number of alpha particles emitted by the radon decay products on the filter. The unit contains typically a microprocessor that stores the number of counts and elapsed time. The CW detector can be set to record the total counts registered over specified time periods. The unit must be calibrated in a calibration facility to convert count rate to Working Level (WL) values. This may be done initially by the manufacturer, and should be done periodically thereafter by the operator.

3.1.4 Equipment

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

3.1.5 Predeployment Considerations

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

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

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

Verify that a new filter has been installed and the input parameters and clock are set properly;

Measure the detector's efficiency with a check source such as Am-241 or Th-230 and ascertain that it compares well with the technical specifications for the unit; and

Verify the operation of the pump.

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

In addition, participation in a laboratory intercomparison program should be conducted initially and at least once every

12 months thereafter, and after equipment repair, to verify that the conversion factor used by the microprocessor is accurate. This is done by comparing the unit's response to a known radon decay product concentration. At this time, the correct operation of the pump also should be verified by measuring the flow rate.

3.1.6 Measurement Criteria

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

3.1.7 Deployment and Operation

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

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

3.1.8 Retrieval of Detectors

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

3.1.9 Documentation

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

In addition, the serial number of the CW detector and calibration

factor used should be recorded.

3.1.10 Analysis Requirements

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

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

3.1.11 Quality Assurance

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

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

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

count rate may be monitored more frequently by operating the CW in a low radon environment.

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

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

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

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3.2 Protocol for Using Radon Progeny Integrating Sampling Units (RPISU or RP) to Measure Indoor Radon Decay Product Concentrations

3.2.1 Purpose

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

3.2.2 Scope

This protocol covers, in general terms, the equipment, procedures, analysis, and quality control objectives for measurements made with RPs. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency.

3.2.3 Method

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

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

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

Etching and counting of the alpha track assembly is carried out

by mailing the detector film to the analysis laboratory. Interpretation of the results of this measurement requires a calibration for the detector and the analysis system based on exposure to known concentrations of radon decay products.

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

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

3.2.4 Equipment

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

3.2.5 Predeployment Considerations

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

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

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

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

3.2.6 Measurement Criteria

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

3.2.7 Deployment and Operation

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

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

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

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