Canadian Nuclear Safety Commission
Commission canadienne de sûreté nucléaire

REGULATORY GUIDE

Measuring Airborne Radon Progeny at Uranium Mines and Mills

G-4

June 2003

Canada

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MEASURING AIRBORNE RADON PROGENY AT URANIUM MINES AND MILLS

1.0 PURPOSE

This regulatory guide is intended to help users measure and compute instantaneous concentrations of airborne radon progeny at uranium mines and mills.

2.0 SCOPE

This document describes a method that Canadian Nuclear Safety Commission (CNSC) inspectors use to assess concentrations of airborne radon progeny at Canadian uranium mines and mills. This method, or methods of comparable accuracy, may be used by uranium mine or mill licensees.

3.0 BACKGROUND

Radon–222 is a chemically inert element, a radioactive gaseous by-product of other naturally occurring radioactive elements. Radon gas is released into the atmosphere as a result of both natural processes and human activities. It continuously undergoes spontaneous radioactive decay. Four solid, short-lived radionuclides — polonium–218, lead–214, bismuth–214 and polonium–214 — form in sequence as radon–222 decays to create lead–210. These four short-lived products are the "radon progeny" referred to in this guide.

To protect workers and to comply with federal requirements, uranium mine and mill licensees monitor and record the exposure of their workers to radiation hazards, including radon progeny. Uranium mines and mills also monitor concentrations of radon and its progeny in support of engineering design and workplace planning.

Alpha, beta and gamma radiation are emitted during the decay of radon gas to create lead–210. Of these forms of radiation, alpha particles typically pose the most significant radiation hazard to workers because, over time, the inhalation of air containing elevated concentrations of alpha-emitting radon progeny may increase the incidence of lung cancers in humans.

Under natural conditions, radon gas and its progeny are typically encountered in relatively low concentrations. However, higher concentrations can occur under special conditions, including those associated with uranium mining and processing activities.

Although all uranium mines and mills encounter radon and its progeny during their operations, the significance of these elements as potential radiation hazards in a specific situation will depend upon case-specific factors. Examples of such factors include source characteristics, geologic and climatic factors, production technology and methods, plant and mechanical designs, air-exchange rates, work processes, and personnel protection provisions.

With or without special control measures, radon and radon-progeny concentrations in uranium mine or mill workplaces can vary significantly over time and space. Typically, uranium mines and mills maintain radon and radon-progeny concentrations at safe levels by ensuring that their workplaces are adequately ventilated. This may involve exhausting air that contains significantly elevated concentrations of radon and its progeny, or introducing outside air that contains lower or background concentrations of radiation.

4.0 OVERVIEW OF METHOD

Uranium mines and mills in Canada use various methods to determine instantaneous concentrations of airborne radon progeny (References 2, 5, 9, 10, 11, 12). The sample collection, counting and computational procedures that are used by CNSC inspectors rely on the modified Kusnetz method.

To accurately measure the airborne radon progeny in a specific atmosphere, one must first sample, on either an instantaneous basis or a continuous basis, a representative volume of air. Instantaneous samples are, typically, those collected over short, discrete intervals of a few minutes. Continuous samples are those collected over much longer time intervals, typically hours or days.

The measurement approach described in this guide involves:

- filtering a representative volume of air to collect a sample of airborne radon progeny;
- measuring the alpha emissions that occur during radioactive decay of the collected progeny; and
- using observed, measured and known data, and established formulae, to estimate the atmospheric concentration of radon progeny at the time of sampling.

Initially, a sample of airborne radon progeny is collected by using a portable air pump to draw air through a low-porosity filter. The radon progeny that are present in the air attach to the inlet face of the filter used. These progeny subsequently decay, emitting alpha particles and other forms of radiation in the process. During this decay, the emissions of-alpha particles are detected and counted, using an instrument (an alpha counter) designed and manufactured for that purpose.

The counting results obtained are then used along with other pertinent data and observations to estimate the concentration, in units called working levels (WLs) of airborne radon progeny originally present in the air sampled. A working level "means the concentration of radon progeny in 1 m^3 of air that has a potential alpha energy of 2.08×10^{-5} J" [*Radiation Protection Regulations*, subsection 1(1)]. The formula for estimating the concentration of radon progeny in a sample of air, in working levels, is provided in subsection 9(e) of this guide.

The concentration of radon progeny, expressed in working levels, is calculated from a formula that mathematically relates alpha disintegrations per working level over the interval between the end of sampling and the middle of alpha counting, the volume of air sampled, the alpha activity of collected and resultant radon progeny, the efficiency and radioactive background of the alpha counter, and the absorption characteristics of the filter used during sampling.

5.0 SELECTING EQUIPMENT

The equipment and supplies typically required to determine radon-progeny concentrations in accordance with the method described in section 4 include:

- a portable, battery-powered, constant-flow air pump rated at 0.001-5 L/min;
- hoses and fittings of 0.25 in (6.35 mm) inside diameter for use with the air pump;
- cellulose-ester or glass-fibre filters of 0.8 micron porosity and 25 mm diameter;
- open-faced filter holders suitable for use with the pump, lines and filters selected;
- a bubble tube, or a flow meter that is accurate to within ±5%;

- an alpha counter comprised of a radiation detector[1] and related electronics;
- an americium–241 calibration source[2] that is certified accurate to within ±5% and mounted on a stainless steel disc of area equal to that of the filter paper to be used for sampling;
- an accurate timing device, such as a stop watch or digital wrist watch;
- tweezers;
- a battery-powered calculator;
- recording supplies, such as a log or record book, pencils and pens.

6.0 PREPARING FOR SAMPLING

To prepare for sample collection and analysis, follow the steps below:

(a) Assemble the equipment and supplies listed in section 5 of this guide.

(b) Perform the following checks on the sample pump:
- Check the pump battery to verify that it is charged.
- Using the flow meter or bubble tube, measure the rate of air flow through the assembly — air pump, hose and filter holder containing an unexposed filter — that is to be used to collect samples of radon progeny. A constant flow rate of approximately 2 L/min is recommended. Follow the manufacturers' instructions provided with the flow meter, bubble tube and air pump. Note the reading registered on the flow-rate indicator of the air pump. If the flow rate measured by the calibrated flow meter or bubble tube is different than the air pump reading, adjust the calibration of the pump following the manufacturer's instructions. Record the equipment number or other identifying characteristics of the air pump, the date and details of its calibration, and its measured flow rate in litres per minutes, as F.

(c) Perform the following checks on the alpha counter, immediately before and after daily use:
- Perform any relevant checks of the alpha counter recommended by the manufacturer. Include a battery check.
- Determine the alpha counter background by measuring the alpha activity of an unexposed filter. If the measured activity exceeds 5 counts per minute (CPM), suspend use of the equipment until it has been cleaned or repaired. Record the background count rate.
- Determine if the alpha counter is performing consistently by conducting a Chi-Square test on a set of 10 successive measurements, following the method described in Appendix A of this guide. Compare the variability of the 10 successive measurements against the variability to be expected as a feature of radioactive decay. If the counter repeatedly fails the Chi-Square test, discontinue its use until it has been satisfactorily repaired.
- Determine the efficiency, E, of the alpha counter by dividing the mean (in CPM of alpha activity) of the results of the 10 one-minute measurements that were conducted for the Chi-Square test, by the nominal activity (in DPM of alpha activity) of the Am–241 source used for the 10 measurements. If the alpha counter has a zinc-sulphide radiation detector, the calculated efficiency, E, of the counter should lie between 0.35 and 0.50. Within this range, the calculated efficiency of the counter, using the same Am–241

[1] A scintillation detector that uses zinc sulphide as the phosphor is recommended.
[2] Am-241 is recommended as a suitable calibration source because the energy emitted by its alpha particle (5.5 MeV) is similar to the energies emitted by radon progeny (5.5 - 7.7 MeV).

source, should not vary significantly from one day to the next, if the counter is operating satisfactorily. For example, a difference of 0.02 (approximately 1 standard deviation) or so in the calculated efficiencies of the counter over successive days is considered acceptable. However, if the calculated efficiency of the counter is outside of the recommended range (0.35 to 0.50), or if it drops suddenly, discontinue using the counter until it has been satisfactorily repaired.

– When counting radon-progeny samples of high concentration, or when counting radon-progeny samples that have been collected under dusty conditions, check the background of the alpha counter more frequently to determine whether it is becoming contaminated.

7.0 SELECTING SAMPLING LOCATIONS

Select air-sampling locations that accurately reflect the conditions to be assessed. Avoid non-representative or adverse sampling conditions such as areas of turbulent air flow — duct exhausts, junctures or intersections of ventilation passageways, door or window openings.

When collecting radon-progeny samples for purposes of estimating or confirming radiation doses to workers, sample the actual atmospheres breathed by the respective workers. Where possible, sample at the individuals' workstations over a representative period. Alternatively, if concentrations of airborne radon progeny are similar over a large area, it may suffice to collect representative samples while moving through the area, or at appropriate points within the area. The latter approach may be particularly appropriate within uranium processing plants and in travel-ways and/or similar areas of mines.

Samples that are intended to aid in the planning, development and evaluation of engineering works and production processes must be representative of the conditions that they are intended to assess. Accordingly, these samples should be collected at appropriate locations and times. For example, to determine the impact of modifications to mine or building ventilation systems, or to guide the installation of such systems, it may be necessary to collect several air samples at multiple locations, before, after or during the changes.

8.0 COLLECTING SAMPLES

(a) Record the previously determined flow rate, *F*, of the air pump in litres per minutes; as well as the previously determined efficiency factor, *E*, and the previously determined background, in CPM, of the counter that is to be used to detect and record alpha emissions.

(b) Assemble the sampling equipment in the correct configuration for use. Mount an unexposed filter in the filter holder, handling the filter by its edge without touching either face. Connect this filter holder securely to the inlet hose of the air pump.

(c) Record the sampling location, the date and the identification number of the holder that contains the filter paper to be used to collect the sample.

(d) If a significant quantity of airborne particulate or moisture is likely to be present during sampling, ensure that the inlet of the sample filter holder faces slightly downwards in preparation for sampling. Maintain this position during sampling to help prevent dust or moisture from depositing on the inlet face of the sample filter, and possibly clogging or damaging it.

(e) Start the air pump and timing device. Record the time of day at the beginning of air sampling. Try to collect the air sample over a timed interval of exactly 5 minutes. If you operate the air pump for more than a 5-minute-and-3-second sampling interval, extend the sample collection and pump operating time to 6 minutes. Observe the flow rate, F, during sampling and suspend air sampling if the pump flow rate decreases by 20% or more. Periodically check the sampling equipment to ensure that the filter is not blocked or clogged, and that the pump hoses remain connected and free of constrictions or obstructions. Record the time of day when air sampling is completed. Record the actual duration of the sampling interval in minutes as t_s.

(f) Once collection of a sample of airborne radon progeny has been completed, turn off the pump and detach the filter holder that contains the exposed filter. Securely store the exposed filter assembly in a protective container. Do not touch or disturb the face of the exposed filter during handling. If filter holders containing unexposed filters and filter holders containing exposed filters are to be stored in the same container, place the assemblies containing unexposed filters in the case with their inlet faces up. After sampling, return the filter holder assemblies to the carrying case with their exposed (inlet) faces down.

(g) Repeat steps (a) to (f) to collect additional samples.

9.0 COUNTING SAMPLES AND COMPUTING RESULTS

To determine the concentrations of radon progeny present in sampled air, count the alpha emissions from the exposed filters and compute the results, in accordance with the following steps:

(a) Transfer the exposed filter from its holder to the fixed or removable sample holder of the alpha counter. Handle the filter by its edge, using tweezers. Ensure that the exposed surface of the filter faces the scintillant of the counter. This step should be performed as quickly as possible to ensure that the counter's photo-multiplier tube is not exposed to any more light than necessary.

(b) Initiate and complete the counting of alpha emissions from the exposed filter within strict time limits. Begin this counting not less than 40 minutes after the end of sampling, and ensure that the midpoint of the selected counting interval is reached not later than 90 minutes after collection of the sample.

Select an appropriate duration for the counting interval. The counting interval is the length of time over which the alpha emissions from an exposed filter are to be measured.

Although 5-minute counting intervals are typical, the selection of an appropriate interval may require that special case-specific considerations be taken into account. These considerations could include the concentration of radon progeny likely to be present in the air sampled, the volume of air sampled, and the counting precision desired. To select appropriate counting intervals, consult Appendix C, "Dependencies among radon-progeny sampling parameters, working level concentrations and the precision of alpha-counting results", which illustrates key relationships.

Operate the counter in accordance with the manufacturer's instructions. Observe and record the time of day at the start and end of the alpha-counting interval.

(c) Note and record the alpha-counting interval in minutes as t_c and the net number of counts — total number of counts minus the number of counts due to instrument background —

obtained during this interval as C. Calculate the elapsed time from the completion of air sampling to the midpoint of the selected alpha-counting interval for the active filter, and record it as t_k.

(d) Use Appendix D or other references to determine the Kusnetz factor, K, that corresponds to t_k or calculate K from the appropriate equation of the following set:

$$K = 230 - 2t_k \text{ when } 40 \leq t_k \leq 70$$

or

$$K = 195 - 1.5t_k \text{ when } 70 \leq t_k \leq 90$$

(h) Calculate the concentration of airborne radon progeny at the time of sample collection using the following equation:

$$WL = \frac{C(1+S)}{F t_s t_c K E}$$

where:

WL is the concentration in working levels;
C is the total number of alpha counts recorded over the interval of t_c minutes, minus the background alpha counts over interval t_c;
S is any correction factor, as per Appendix B, that is necessary in order to compensate for the absorption of radon progeny on the sample filter;
F is the air sampling flow rate in litres per minute;
t_s is the air sampling interval in minutes;
t_c is the interval, in minutes, over which alpha emissions from the sample are counted;
K is the Kusnetz factor in disintegrations per minute per litre of air per working level; and
E is the efficiency factor of the alpha counter.

GLOSSARY

alpha counter
An instrument designed and manufactured for the purpose of detecting and counting alpha particle emissions.

binomial distribution
A frequency distribution of the possible number of successful outcomes in a given number of trials in each of which there is the same probability of success.

Chi-Square test (χ^2)
Described in Appendix A; an operational check of the counting equipment.

modified Kusnetz method
A method of determining and expressing atmospheric concentrations of radon progeny in terms of latent alpha energy; requires the use of an alpha counter equipped with an electronic scaler to measure the emission of alpha particles.

Poisson distribution
A discrete frequency distribution which gives the probability of events occurring in a fixed time; named after French mathematician, S.D. Poisson.

radon progeny
For purposes of this guide, four solid, short-lived radionuclides — polonium-218, lead-214, bismuth-214 and polonium-214, which form in sequence as radon-222 decays to create lead-210.

working level (WL)
The concentration of radon progeny in 1 m^3 of air that has a potential alpha energy of 2.08×10^{-5} J.

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APPENDIX A
Using Chi-Square tests to evaluate the performance of alpha counters

Background

For the long-lived standards that are typically used to test whether alpha counters are operating correctly, the number of transformations that occur is quite small relative to the number of radioactive atoms that are present in the standard.

Statistically, when the probability of an event, such as radioactive decay by alpha emission of a long-lived standard that is used to test alpha counter operation, is quite small (very much less than 1), the binomial distribution approaches the Poisson distribution.

By taking a series of counts of the number of alpha emissions from a radioactive standard, one can compare the variation in counting results to that predicted for situations where the probability over time behaves similarly to what would be predicted by a Poisson distribution.

In the application described below, the Chi-Square test is a method that compares the variability of "successive counts" obtained with an alpha counter to the variability in alpha counts that is predicted by a Poisson distribution. The object of the comparison is to identify any inconsistencies in the respective variability that would not be consistent with the random nature of radioactive decay. If the results obtained with a counter for a series of counts from a given radioactive sample (under controlled conditions) are too consistent (demonstrate little variability), then it is likely that the counter is not performing properly. Similarly, if the observed variability in results is excessive, then the counter system is also likely to be performing incorrectly.

Method

To check the performance of an electronic counter with the Chi-Square test, do the following:

(a) Using the counter to be tested, count the alpha activity of an americium–241 source of known decay rate. Make 10 separate counts, each of one-minute duration. Note and record the total number of counts for each of the 10 measurements.

(b) To calculate the Chi-Square for the above:
- Sum the squares of the differences between the observed count rates for the individual one-minute measurement intervals and the mean count rate over the total (10-minute) measurement period.
- Divide the sum obtained above by the mean count rate over the 10-minute period. The result is the Chi-Square value for the situation tested.

  Thus, the Chi-Square value for a given situation can be calculated according to the formula:

$$\chi^2 = \frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{\overline{X}}$$

(c) If $3.33 \le \chi^2 \le 16.92$, the results of the Chi-Square test are consistent with a counter that is performing well.

(d) If $\chi^2 < 3.33$ or $\chi^2 > 16.92$, repeat the Chi-Square test. If the Chi-Square results obtained are repeatedly outside these bounds remove the counter from service until it has been repaired.

APPENDIX B
A method to determine correction factors to compensate for the absorption of radon progeny on sample filters

To compensate for errors due to the absorption of alpha particles by glass-fibre or cellulose-ester filters, an appropriate correction factor must be applied during the associated calculations of radon-progeny concentrations. To determine this correction factor:

(a) Collect a sample of radon progeny; allow the sample to decay for at least 40 minutes, but not more than 90 minutes.

(b) Measure the alpha activity in CPM from the face of the sample filter; record this reading as *A*. Note the time of day.

(c) Measure the alpha activity in CPM from the back of the sample filter and record this reading as *B*. Note the time of day.

(d) With a duplicate, unused filter placed over the face of the sample filter as an absorber, measure the alpha activity in CPM and record this reading as *C*. Note the time of day.

(e) Repeat step (b) to get a repeat reading *D* and note the time of day.

(f) If $D < 0.9A$, repeat step (c) to obtain another reading *E*, and note the time of day.

(g) Use readings *A* and *D* to estimate a reading *F* at the time at which *C* was observed. Use readings *B* and E to estimate *G* at the time at which *C* was observed.

(h) Calculate the correction factor for absorption on the filter, *S*, using one of the following formulas:

$$S = \frac{B - C}{2A + B - C}$$

or

$$S = \frac{G - C}{2F + G + C}$$

For a cellulose-ester filter, *S* will probably be less than 0.02. For a glass-fibre filter, *S* may exceed 0.10.

APPENDIX C
Dependencies among radon-progeny sampling parameters, working level concentrations and the precision of alpha-counting results

The computed entries in the table below are calculated for t_k = 65 minutes, where t_k is the time interval, in minutes, between the end of sampling and the mid-point of the sample-counting interval. For other values of t_k, the data will be commensurately different.

Expected concentration of radon progeny in working levels	Flow rate in litres per minute	Sample volume in litres	Measurement interval in minutes for an alpha-counting precision of: ±2%	±5%	±10%
0.05	2	10	150	30	6
	5	25	60	10	4
	10	50	30	6	2
0.10	2	10	80	20	4
	5	25	30	6	2
	10	50	20	4	1
0.20	2	10	40	6	2
	5	25	20	4	1
	10	50	10	2	1
0.40	2	10	20	4	1
	5	25	10	2	1
	10	50	4	1	1
0.80	2	10	10	2	1
	5	25	4	1	1
	10	50	2	1	1

Note:
This chart illustrates the typical relationships among radon-progeny sampling parameters such as the concentrations of radon progeny in the air that has been sampled, the sample flow rates and volumes, the filter count times and precision of results. For example, the length of the counting intervals that are necessary to attain results of similar precision are inversely proportional to the volumes of air sampled and the concentrations of radon progeny in the air sampled. For samples of greater volume but similar concentration, shorter alpha-counting times will suffice to attain results of comparable precision. To shorten the necessary counting times for filters exposed to low concentrations of radon progeny, use pumps of greater capacity to sample larger volumes of air over the specified sampling interval. Or, when smaller samples of air with lower concentrations of radon progeny are collected, increase the precision of the results by adopting longer counting intervals. When concentrations of radon progeny are 0.05 WL or less, counting intervals that result in a precision of ±10% are adequate. Consult references 1 and 2 to determine appropriate flow rates for air sampling and effective sample-counting intervals.

APPENDIX D
Determining Kusnetz correction factors for use in calculations of radon-progeny concentrations

Delay time in minutes	40	41	42	43	44	45	46	47	48	49
Kusnetz correction factor	150	148	146	144	142	140	138	136	134	132

Delay time in minutes	50	51	52	53	54	55	56	57	58	59
Kusnetz correction factor	130	128	126	124	122	120	118	116	114	112

Delay time in minutes	60	61	62	63	64	65	66	67	68	69
Kusnetz correction factor	110	108	106	104	102	100	98	96	94	92

Delay time in minutes	70	71	72	73	74	75	76	77	78	79
Kusnetz correction factor	90	88.5	87	85.5	84	82.5	81	79.5	78	76.5

Delay time in minutes	80	81	82	83	84	85	86	87	88	89	90
Kusnetz correction factor	75	73.5	72	70.5	69	67.5	66	64.5	63	61.5	60

Note :
Kusnetz correction factors may be determined from the above tables or by calculations.

Using the tables above

For the given delay period (i.e., the time, in minutes, from the end of sampling to the middle of counting), select the Kusnetz correction factor that appears in the same column, directly under the delay time in minutes.

For example:

- For a delay time of 60 minutes, the corresponding Kusnetz correction factor is 110.
- For a delay time of 68 minutes, the Kusnetz correction factor is 94.

To calculate Kusnetz correction factors

Calculate the appropriate Kusnetz correction factor by solving the applicable equation of the following set:

$$K = 230 - 2t_k \text{ when } 40 \leq t_k \leq 70$$

or

$$K = 195 - 1.5t_k \text{ when } 70 \leq t_k \leq 90$$

where t_k is the time interval, in minutes, between the end of sampling and the mid-point of the sample-counting interval.