Managing naturally occurring radioactive material (NORM) in mining and mineral processing — guideline

NORM–3.4

Monitoring NORM — airborne radioactivity sampling

Government of **Western Australia**
Department of **Mines and Petroleum**
Resources Safety

The Chamber of Minerals & Energy Western Australia

MIAC

Reference

The recommended reference for this publication is:

Department of Mines and Petroleum, 2010. Managing naturally occurring radioactive material (NORM) in mining and mineral processing — guideline. NORM–3.4 Monitoring NORM — airborne radioactivity sampling: Resources Safety, Department of Mines and Petroleum, Western Australia, 24pp. <http://www.dmp.wa.gov.au/>

Published February 2010

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1. General information

1.1. Purpose

To provide practical guidance on airborne radioactivity sampling and assessment of obtained data in relevant exploration, mining and mineral processing operations.

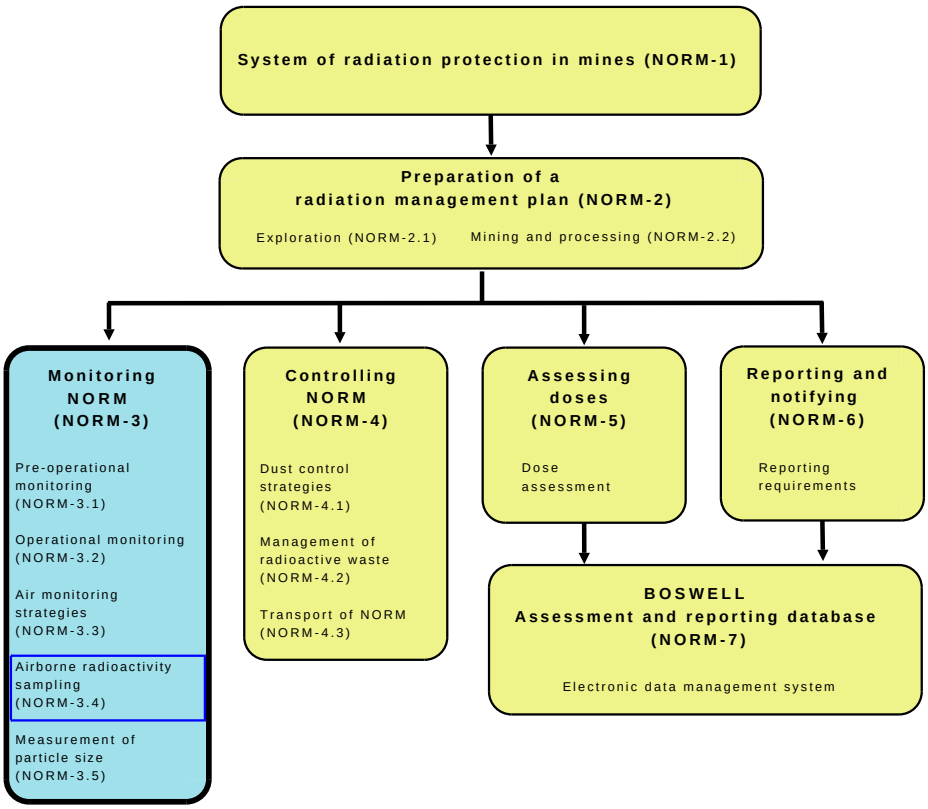
1.2. Scope

This guideline applies to all exploration, mining and mineral processing operations in Western Australia that use or handle naturally occurring radioactive material (NORM) and come within the scope of Part 16 of the Mines Safety and Inspection Regulations 1995 ([1]).

1.3. Relationship to other NORM guidelines

The flowchart in Figure 1.1 shows how the Radiation Safety Guidelines are arranged.

Figure 1.1.: Relationship to other NORM guidelines



2. Guidance

2.1. Introduction

Measurements of airborne radioactivity are undertaken to assess the performance of engineering control systems and to assess exposures of both employees and members of the general public. The most common technique involves portable or stationary air pumps/samplers. Passive air samplers, however, are also used where appropriate.

The major risk associated with airborne radioactivity arises from internal irradiation following inhalation. To evaluate the significance of the measured activity, information is required on Annual Limits of Intake (ALI) through inhalation and derived airborne concentration (DAC) limits of relevant radionuclides. A discussion of these parameters is outside the scope of this guideline and is available in another document (Guideline NORM–5 Dose assessment).

The method for determining gross (or total) alpha activity involves the collection of airborne dust onto a high-efficiency filter paper. The collected dust is usually analysed by counting directly with an alpha counter. The sensitivity of this technique is strongly dependent on sampling volume and can be adjusted to almost any desired value by manipulation of the appropriate sampling parameters (time and flow rate). In addition, the counting time can also be increased to further improve the sensitivity of this monitoring method.

Several different methods are used to determine concentrations of radon/thoron and their progeny. These may vary from short-term air samples that are analysed within several hours or minutes of the sample being taken to passive monitors that are used to collect the data from a particular location for several months before being analysed. Additionally, electronic monitoring equipment is also available for the estimation of radon and thoron concentrations.

In radiation protection, it is common practice to sample total dust by drawing air through a filter and to then compare the measured radioactivity with an operational limit. Total dust is defined as the dust which is collected on the filter of a non-size selective gravimetric sampler.

There are a number of commercially available personal air samplers (PAS), however, the differences in sampling head design and operating flow rate may result in significant variations in particle intake or collection efficiency characteristics. To ensure the consistency of measurements, the sampling and the analysis of data should be undertaken:

- in accordance with the Australian Standard [8]; and
- most importantly, by a person qualified to perform such measurements.

It is expected that, as a minimum, a person undertaking the measurements should be a qualified ventilation officer, as required in accordance with Part 9 of the Regulations [9] and be a ‘registered CONTAM sampler’. As such, the person is expected to have detailed knowledge of:

- human respiratory tract system;
- classification of dusts (including inspirability criteria);
- sampling ‘configurations’ (including different sampling heads and their collection efficiencies); and
- selection of sampling equipment (pumps and filter paper).

Information on the CONTAM system is available on the DMP web site in the Resources Safety area — http://www.dmp.wa.gov.au/6749.aspx.

This guideline, therefore, addresses only issues that are directly relevant to airborne radioactivity sampling.

2.2. Radioactive dust sampling considerations

2.2.1. Selection of counting equipment

Great care should be taken when selecting or purchasing alpha counting equipment to ensure that it is suitable for the purpose intended. Some computer/software controlled alpha counters available are designed for 'American Homeland Security' market where a rapid determination of potential atmospheric contaminants is required and are typically unable to be used for the procedures described on the following pages. Counters using PIPS detectors such as the Canberra Model 7401 (Figure 2.1) and Tennelec TC-257 have been used by the WA mining and mineral processing industry for over a decade with excellent reliability and accurate results.

Figure 2.1.: Alpha counters

Three Canberra Model 7401 NIM modules in a Model 1000 power supply bin.

2.2.2. Sample preparation

1. For the purpose of airborne radioactivity sampling, it is recommended that the filters have as low resistance to airflow as possible (to avoid excessive pump power), a low clogging rate, and collect the aerosol particles close to the surface (to avoid alpha self-absorption issues).

2. Two different types of filter paper are typically used for collection of radioactive dust – PVC (with pore size of 0.8 microns) and glass-fibre (with pore size of 5 microns). The PVC filters are more appropriate in situations where dust concentrations are relatively low (in order of 1–2 mg/m^3) whereas glass-fibre filters are recommended for use when the dust levels are comparatively high so as to minimise the possibility of partial sample loss due to dust particles falling off the filter in the process of sample handling between weighing and counting.
3. Filters must be handled using the tweezers only.
4. To account for the atmospheric humidity, it is recommended that filters are placed in clean containers and left with lids slightly ajar in the laboratory/office overnight to come to equilibrium with the atmosphere.
5. The filter should be pre-weighed to an accuracy ±0.01 mg. The number of the sample and its weight should be recorded and the filter then placed into the sampling cassette.

There are two different cassettes approved for the use in dust sampling by the relevant Australian Standard[8]. The differences between those tow cassettes are described in Appendix C.

2.2.3. Sampling

Dust sampling cassette should be attached to a suitably calibrated constant airflow sampler and worn as close as possible to the employee's breathing zone. Sampling time should be a minimum of four hours but must be as close to the length of the shift as possible. In some cases a 'full shift' sampling may not be possible. In such circumstances, monitoring can be carried out in two different parts of the shift (usually for six hours at the beginning and at the end of the shift) to ensure that the monitoring data is representative.

Different methods of recording sample information may be implemented. As detailed information is required for the data entry into the DMP 'Boswell' database (refer to the guideline NORM–7 Boswell – Assessment and reporting database), it is recommended that the following information is recorded for each sample:

1. The date and start and stop times of sampling.
2. Sample type (personal or positional) and number.
3. The name/occupation of the person wearing the sampler (or a position number).
4. Respiratory protection data.
5. Any other remarks, if required.

After sampling, filters should come to equilibrium with the atmosphere as is done before sampling. The filter should be weighed to an accuracy of ±0.01 mg, the mass of the sample should be recorded and the filter placed in the clean container for the subsequent radiometric analysis.

2.3. Analysis considerations

2.3.1. Filter handling

After air sampling and gravimetric determination the filters should be individually stored in suitably marked containers or protective envelopes (e.g. petri dishes) in readiness for alpha counting. When handling filters, particular care must be taken to avoid damage to them. Filter handling including transportation, and vibration should be kept to a minimum to avoid loss of material before radiological evaluation. Tweezers should be used during all handling to hold the unexposed filter edge. The anti-static guns should be used if necessary.

2.3.2. Calibration and use of alpha counting equipment

A background count, chi-square test and efficiency calculation should be undertaken at least weekly when counting is in progress. These parameters should be monitored regularly to ensure that any deterioration in performance of the system is detected as soon as possible.

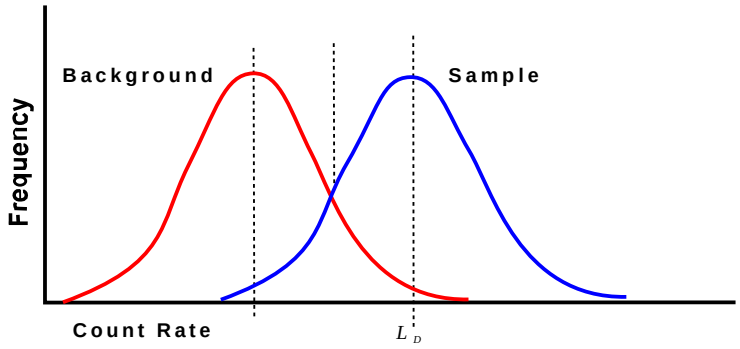
2.3.2.1. Background count

This is typically performed over a relatively long period of time — 12 to 15 hours, with a clean unused filter in the drawer assembly or counting chamber, and the value is used in the assessment of the Minimum Detection Limit (MDL) [11] of a particular counter as follows:

$$MDL = \left(4.65 \times \sqrt{\left(Bc \times \frac{Ct}{Bt}\right)}\right) + \left(Bc \times \frac{Ct}{Bt}\right)$$

where:
MDL – minimum detection limit of the equipment in use for the counting time Ct;
4.65 – the detection limit L_D shown in Figure 2.2;
Bc – number of counts from background for the background counting time Bt;
Bt – background count time (usually 720 or 900 minutes);
Ct – counting time (typically 60 or 100 minutes).

Figure 2.2.: Detection Limit L_D



L_D is the true net signal level that may be expected *a priori* to lead to detection [10].

Calculation example: Data: Background counting results are: in 900 minutes 33 counts were obtained. The actual sample counting will be carried out during 60 minutes.

Solution: Bc = 33 counts; Bt = 900 min; Ct = 60 min;

$$MDL = \left(4.65 \times \sqrt{\left(33 \times \frac{60}{900}\right)}\right) + \left(33 \times \frac{60}{900}\right) = \left(4.65 \times \sqrt{2.2}\right) + 2.2 = 9.097 \approx 9\, counts$$

Therefore, the minimum detection limit of alpha spectrometer is currently 9 counts in 60 minutes. If the sample count does not exceed the MDL then the MDL must be substituted for the sample count in the calculation. In other words, if the sample count will be 5 counts per 60 minutes the value of 9 counts per 60 minutes should be used in the calculation of the dust activity concentration.

2.3.2.2. Chi-square

This test is carried [4] out after obtaining background counts for each counter. If only the standard (25 mm in diameter) samples will be analysed during the following week, 25 mm americium (^{241}Am) calibration source (re-calibrated annually by the Radiation Health Section of WA) must be used.

If personal impactor or environmental samples (37 mm in diameter) are also to be analysed, calibration should also be carried out with the 37 mm calibration source.

Note when purchasing calibration sources, the Eberline Services ^{241}Am model DNS-5SP sources with diameters of 25mm, 36mm and 44.5mm are currently the only sources approved for use in Western Australia as shown in Figure 2.3 — www.eberlineservices.com.

Figure 2.3.: Eberline sources

Several companies have standardised on these three sources.

This is because the geometry of ^{241}Am on the calibration source must be similar to the dust collected on the filter; therefore, 'point' sources where a small amount of the isotope is placed in the middle of the disc are not acceptable. The ^{241}Am should be present on the surface of the disc in the form of a thin film, closely resembling the dust accumulated on the filter.

Ten counts (typically of 30 or 60 seconds) using a calibration source must be carried out and the data and the calculations carried out using the following equation:

$$\chi^2 = \frac{\sum_{i=1}^{n} (\chi_i - \bar{\chi})^2}{\bar{\chi}}$$

where:

χ_i is the i^{th} experimental data value;

$\bar{\chi}$ is the mean of the experimental data values.

The chi-square value should be $3.33 \leq \chi^2 \leq 16.9$. In cases where the value is either lower than 3.33 or above 16.92, the test should be repeated until an acceptable value is obtained. If the results are repeatedly outside the bounds, the counter must be removed from service.

2.3.2.3. Efficiency

The Efficiency for each counter is calculated as follows:

$$Eff\% = 100 \times \frac{C_{STD}}{(T_{STD} \times N \times 2)}$$

where:
C_{STD}– total number of counts from the calibration source (average of ten results);
T_{STD}– counting time for the calibration source in seconds;
N– number of alpha particles emerging from the front surface of the calibration source per second (this number is obtained from the calibration certificate of the source).

2.3.2.4. Excel spreadsheet for data processing

An Excel spreadsheet has been developed in order to the simplify calculations and minimise errors. Data should be entered into the appropriate fields to calculate the values. The program user interface is shown in Figure B.1 on page 19.

The sample Excel Spreadsheet is embedded in the electronic version of this document and may be run from here or saved onto your computer. This spreadsheet is free software; you can redistribute it and/or modify it. The software is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.

Click here if you accept these conditions → 

Calculation example: 'Mean' number of counts is 40807;

Counts were obtained during the 30 seconds interval;

Number of alpha particles from the Certificate is 113,300 per minute;

Calculate number of alpha particles per second;

$$N = \frac{113300}{60} = 1888.3 \, counts \, per \, second$$

Calculate the efficiency;

$$Eff\% = 100 \times \frac{40807}{(30 \times 1888.3 \times 2)} = 36.0\%$$

Six or seven days are allowed to elapse before alpha counting to allow for the decay of short-lived thoron (^{220}Rn) and radon (^{222}Rn) daughter products trapped on the filter. This decay time also provides for the build-up of thoron daughters from ^{224}Ra in the event of thoron emanation from the airborne dust particles. The assumption employed when determining gross alpha activity is that all alpha particles emitted from the ^{232}Th and ^{238}U radioactive decay chains are registered by the counter.

The counting of the filters is typically performed for a minimum of 60 minutes, but this time may be extended to 100 or 200 minutes to increase the accuracy of measurement when it is expected that concentrations of radioactivity would be relatively low (environmental high volume samples, lower stages of personal impactor, or confirmatory samples collected outside supervised and controlled radiation areas).

2.3.3. Gross alpha activity calculation

The activity of the sample (in Becquerels) is calculated as follows:

$$A = \left(\frac{100}{Ct \times Eff}\right) \times \left(\frac{Cc}{Ct} - \frac{Bc}{Bt}\right)$$

where:

A – activity of the sample (in Becquerels);
Cc – number of counts from the sample for the counting time Ct;
Ct – counting time (typically 60 or 100 minutes);
Bc – number of counts from background for the background counting time Bt;
Bt – background count time (usually 900 minutes);
Eff – efficiency of the alpha spectrometer.

Dust activity concentration This is then determined as follows:

$$Ac\left(Bq/m^3\right) = \frac{A\,(Bq)}{V\,(m^3)}$$

The value obtained in accordance with this procedure should be compared with the derived air concentration (DAC) calculated for a particular industry/operation in accordance with the Guideline NORM–5 Dose Assessment.

Calculation example: Data:

Counting results are: sample was counted for 60 minutes; 71 counts were obtained.

Background counting result is: in 900 minutes 33 counts were obtained.

The sample was worn for 370 minutes.

Flow rate of the sampler was 2 litres per minute.

The efficiency of the alpha spectrometer is 31.7%.

Solution:

Bc = 33 counts;

Bt = 900 min;

Cc = 71 counts;

Ct = 60 min;

Eff = 31.7 %;

V = 370 min ×2 litres /min = 740 litres = 0.74 m^3.

The activity of the sample is:

$$A = \left(\frac{100}{60 \times 31.7}\right) \times \left(\frac{71}{60} - \frac{33}{900}\right) = 0.060\,Bq$$

The dust activity concentration is:

$$\frac{0.060\,Bq}{0.74\,m^3} = 0.081\,Bq/m^3$$

The calculations described above are performed when all relevant data is entered into the DMP 'Boswell' database (please refer to guideline NORM–7 Boswell – Assessment and reporting database).

2.4. Other considerations

2.4.1. Alpha self-absorption effects

Self-absorption can seriously affect the final alpha activity concentrations when collected samples have relatively large dust loadings. With knowledge of layer influence, these effects can be minimised.

Alpha particles have a very short range in air (40 mm for alpha particles with the energy of 5.3 MeV) and an even shorter range in more dense substances. The assessment of alpha self-absorption effects may be very complicated as radioactive atoms are distributed throughout the dust matrix, ranging from the surface of the deposit to the deposit/filter paper interface. In some instances penetration of the dust into the filter paper matrix will also intensify this effect.

Although alpha particles will lose considerable energy as they pass through the dust matrix the alpha counter will still register them as long as the distance to the detector is less than their range in the dust matrix. Particle size also becomes important, as alpha particles originating from atoms within a large grain will not pass completely through the grain. Additionally, the filter paper itself may trap dust particles at depth within its matrix and the degree of self-absorption for this situation is estimated as follows:

$$\%SA = \left[\frac{(C2 - C3)}{C1 + C2 + C3}\right] \times 100$$

where:
%SA is the % self absorption;
C1 is the sample count (above background);
C2 is the count obtained by turning the sample filter upside down;
C3 is the count obtained by covering the sample filter (sample side up) with an unused filter paper.

To limit self-absorption the simple solution is to choose a filter paper with a pore size that will ensure the deposit is collected on the surface. In practice, the thickness of the dust deposit on the filter paper determines the degree of self-absorption. Any visible deposit is likely to suffer from self-absorption making an absolute activity determination impossible. It is therefor advisable to carry out periodic checks of filters collected at a particular operation to quantify the degree of self-absorption.

As the flow rate is fixed in accordance with Australian Standard [8] at 2 litres per minute, to limit self-absorption due to layer influence the sampling time must be chosen to ensure that no excessive dust loadings are captured on the filter.

Where appropriate, the statistical analysis of obtained results should be carried out in accordance with Section 3.2 Basic Principles for the reporting of data detailed in the Guideline NORM–6 Reporting requirements.

2.4.2. Partial sample loss

It is possible that in the process of weighing and counting during sample handling, loss of dust may occur (particularly where dust concentrations in excess of 5 mg/m^3 are being registered). In this case, the result of sample count should be deemed invalid. If the circumstances warrant further investigation the following calculation may be carried out:

1. Determine the average dust specific activity (Bq/mg) for the particular work category (excluding the result for the sample in question).
2. Multiply the weight of the sample in question (mg/m^3) by the average dust specific activity (Bq/mg) to obtain expected dust activity concentration for the sample in question (Bq/m^3).
3. The obtained result may be used for ad hoc reporting purposes.

Calculation example: Results of dust monitoring for the sample in question are 14.62 mg/m^3 and 0.077 Bq/m^3. The dust from the sample was partially lost prior to counting. The average dust specific activity for this particular work category in this particular month is 0.081 Bq/mg (data averaged for all other samples in this work category).

The expected dust activity concentration is estimated as follows:

14.62 mg/m^3 × 0.081 Bq/mg = 1.184 Bq/m^3

The value 1.184 Bq/m^3 should be used for reporting purposes instead of questionable 0.077 Bq/m^3.

2.5. Measurement of radon/thoron and their progeny

The radioactive decay chains of ^{238}U and ^{232}Th contain a gaseous member: radon (^{222}Rn) and thoron (^{220}Rn). These gaseous elements can diffuse from different materials and accumulate in the surrounding atmosphere. The radon will continue to decay and the newly formed radon progeny will be attracted to dust particles and will become 'attached' to them.

The measurement of radon progeny concentrations is based on the detection of the alpha particles emitted in the decay process. Most sampling methods require the drawing of a known volume of air through a filter paper. The amount of alpha activity on the filter paper and the decay characteristics exhibited are a function of the radionuclides present and their quantity. Determination of individual progeny activities can be made by performing a sequence of counts at various intervals after sampling, and solving the relevant radioactive in-growth and decay equations.

There are many different methods for the determination of radon progeny concentrations. The radiological significance of ^{220}Rn progeny is considered to be much lower than that of ^{222}Rn progeny because of the comparatively short half-life of ^{220}Rn (55 seconds) and its limited opportunity for release.

Many different monitors are available for both positional and personal assessment of the exposure to radon and its progeny, several monitors capable of detecting thoron are also available. In situations where only a simple assessment is necessary, some of these monitors can be used.

In situations where airborne dust radioactivity measurements are routinely undertaken and an alpha counter is readily available, several methods that utilise gross alpha counts (performed after a suitable interval after the completion of sampling) can be used to determine radon/ thoron progeny concentrations. The measurements are generally simple to perform and detailed description of these methods is provided in Appendix A on page 14.

2.6. Environmental dust monitoring

To ensure the consistency of measurements, sampling and the analysis of data should be undertaken in accordance with the Australian Standard [7]. The sampling is carried out using high volume samplers with the airflow rate of 70 to 80 m^3/hour, for a minimum of 24 hours to ensure that sufficient amount of dust is collected for radioactivity analysis. In some cases it may be necessary to operate the high volume sampler continuously for 5–7 days, while in other cases the 24 hour interval may be sufficient; an additional consultation with DMP is recommended to ensure that the samplers are not overloaded and sufficient amount of dust particulate is collected on the filter.

Five, 37 mm diameter circular representative sub-samples are removed from the active area of the high-volume filter. The sub-samples are stored for a period of six to seven days to allow short lived radioactive products to decay, and are then presented to the alpha spectrometer for the determination of the long-lived alpha radioactivity.

The mean alpha activity from the sub-samples is integrated over the total active area of the sample to determine total collected alpha activity.

The mean activity is multiplied by the correction factor f:

$$f = \frac{total\ active\ surface\ of\ the\ sample}{surface\ of\ the\ 37\ mm\ diameter\ sample}$$

Calculation example: The effective sampling area is usually 382.5 cm^2 (22.5 x 17.0 cm).

The surface of the 37 mm diameter sub-sample is:

$$\pi R^2 = 3.142 \times \left(\frac{3.7}{2}\right)^2 = 10.75\, cm^2$$

Then the factor is:

$$f = \frac{382.5}{10.75} = 35.6$$

If the mean alpha activity for five 37 mm diameter sub-samples is 0.017 mBq/m^3, then the total alpha-activity will be:

$$0.017\, mBq/m^3 \times 35.6 = 0.62\, mBq/m^3$$

2.7. Passive air samplers

The use of passive (non-mechanical) samplers may be advantageous in certain situations. For example, passive samplers for measuring radon progeny exposures are very useful in area measurements as they integrate over a period of several months and give much better measurements than any of the grab sampling techniques.

Passive samplers are also useful in environmental dust monitoring as shown in Figure 2.4 on the next page. Deposition collectors, sticky plates and tacky cloths are typically used. The sticky plate deposition collector is a horizontal or vertical plate covered with a sticky material that traps any fall out that hits it. The tacky cloth sampler consists of a cloth stretched over different forms of wire frames.

These samplers can be placed in reasonable numbers around a particular site. The cloth can then be changed at monthly or quarterly intervals and assessed for trapped radioactive material.

Despite the fact that the results from passive samplers are qualitative rather than quantitative, results from a series of passive samplers around the potential source of radioactive dust can reveal the direction and location of higher concentrations of this dust, and thus indicate the best locations for high volume environmental dust samplers.

Figure 2.4.: Example of a passive dust sampler

A passive dust sampler located next to a ore stockpile at the former WMC Yeelirrie exploration site.

2.8. Stack emissions monitoring

In order to correctly estimate potential exposures for members of the general public, it is necessary to know the content of radioactivity in air discharged from any stacks (ventilation, dust extraction, drying, kilns, etc.). Typically, as air will have been through the exhaust filter, most of the radioactive dust particles are likely to be trapped.

It is, however, important to ensure that all stacks are monitored at regular intervals or as required by licence conditions due to the fact that any radioactive dust emitted from them can travel much further from the point of origin than dust carried by the wind from a stockpile. In cases where chemical and thermal processing of material takes place, it is recommended that the state of secular equilibrium of both uranium and thorium chains is assessed. This will help in determination if any other radionuclides (except thorium and uranium) should be monitored in stack air. Where possible, radionuclides' activity balance calculations should be performed to ensure maintenance personnel are not exposed to significant levels of radiation during the change of exhaust filters, which may have accumulated significant amounts of fine radioactive dust containing radioactive isotopes of polonium and lead from both thorium and uranium decay chains (refer to Appendix B of the guideline NORM–2.1 Preparation of a radiation management plan - exploration). For practical purposes an annual assessment of concentrations of ^{210}Po and ^{210}Pb (from the uranium decay chain) and ^{212}Pb (from the thorium decay chain) is recommended.

Also as part of the operating licence conditions, some processing plants are required to undertake an emissions testing program on their stacks involving isokinetic testing. Isokinetic testing is a technique in which a representative sample from the stack is obtained by removing a sample at the same rate as the stack gas. Once the sampling event is complete, the particulate mass collected on the filter can be determined by weight, or gravimetrically. Several standard sampling 'Methods' developed by the United States Environmental Protection Agency are used to determine stack sample site suitability,

velocity and volumetric flowrate, gas stream density, moisture content, and total particulates using isokinetic sampling trains. Uranium and Thorium emissions collected on the filter are measured at a laboratory using inductively coupled plasma mass spectroscopy (ICP–MS). The isokinetic variation during a sampling run should be between 90% and 110%.

A. Appendix showing methods for the measurement of radon/thoron progeny

There are several methods that utilise a single or multiple gross alpha count (performed after a suitable interval after the completion of sampling) to determine radon (^{222}Rn) and thoron (^{220}Rn) progeny concentrations.

A.1. Rolle method

This method [3] is used for the determination of ^{222}Rn progeny concentration:

Table A.1.: The Rolle method

Sampling time (min)	Delay time (min)	Counting time (min)	Conversion factor	Error (±%)
4	6.46	5	213	12
5	6.06	5	213	11
10	4.35	5	213	11
15	1.36	10	212	10
20	2.12	5	210	10

The ^{222}Rn progeny concentration, in mJ/m^3, is then calculated as follows:

$$X_{Rn} = \frac{[(C_S - C_B) \times 2.1 \times 10^{-2}]}{(E \times F \times V \times T)}$$

where:
X_{Rn} – Rn-222 progeny concentration in mJ/m^3;
C_S– gross count in interval T;
C_B– background count in interval T;
E– efficiency of detection equipment expressed as a fraction;
F– Average factor to convert from counts/minute to WL (working level);
V– volume of air sampled in L;
T– counting time in minutes;
2.1×10^{-2} – factor to convert from WL to mJ/m^3.

For example, for a 10 minute sampling period, followed by a 5 minute counting period, a delay time of 4 minutes and 20 seconds will apply. The conversion factor F for this sampling will be 213, with an error of ±11%.

Due to the short delay times this method is more suitable in situations where the detection equipment is located in close proximity to the sampling point.

A.2. Kusnetz method

This method [5] is similar to the one described in the A.1 on the facing page however:

- the delay period between completion of sampling and beginning of counting is longer;
- the sample is collected for 5–10 minutes and then stored in a petri dish for 40–90 minutes prior to counting;
- the filter is transferred carefully from the filter holder assembly to the detector with the collection side of the filter oriented toward the face of the detector; and
- the total counts for the sample and the time (in minutes after sampling) at the midpoint of the 10-minute time interval are recorded.

The ^{222}Rn progeny concentration is calculated using the equation presented in the A.1 on the preceding page but the conversion factor is taken from the Table Exhibit 3-1 (PHS 1957)A.2:

Table A.2.: Exhibit 3-1

Kusnetz Factors (Public Health Service, 1957)			
Time	Conversion factor	Time	Conversion factor
40	150	66	98
42	146	68	94
44	142	70	90
46	138	72	87
48	134	74	84
50	130	76	82
52	126	78	78
54	122	80	75
56	118	82	73
58	114	84	69
60	110	86	66
62	106	88	63
64	102	90	60

Note: the conversion factor is for the time from end of collection to midpoint of counting

The extended duration of the delay period enables the collection of samples at different site locations and returning them to the laboratory for analysis.

The Kusnetz method is not suitable for atmospheres containing both ^{222}Rn and ^{220}Rn progeny, as the extended delay time allows the in-growth of ^{220}Rn progeny, which will contribute to the gross alpha count.

A.3. Rock method

This method [6] is primarily used for the determination of ^{220}Rn progeny concentration. The method is similar to that of Kusnetz (A.2 on the preceding page), the sampling time is limited to less than 60 minutes, and the delay period between end of sampling and beginning of counting is much longer — between 5 and 17 hours. A preliminary count of the filter conducted between 40 and 90 minutes after sampling (Kusnetz method, 3.2.2) can be used to indicate the presence and concentration of ^{222}Rn progeny.

The ^{220}Rn progeny concentration is then calculated using the equation presented in the A.1 on page 14 but the conversion factor is taken from the Table A.3:

Table A.3.: Rock method

Time after sampling (hours)	Conversion factor
5	13.2
7	11.3
9	9.8
11	8.6
13	7.5
15	6.7
16	6.3

The extended duration of the delay period enables the collection of samples in remote locations and returning them to the laboratory for analysis.

A.4. Cote method

This method [12] uses a 10 minute sampling time followed by several 15 minute gross alpha counts. ^{222}Rn and ^{220}Rn progeny contributions are discriminated by selecting an appropriate delay interval. The first gross alpha count is conducted 1.2 minutes after the completion of sampling, followed by a second count 155 minutes after sampling, with a final count carried out 225 minutes after sampling.

The contribution of ^{220}Rn progeny during the first counting period is negligible; therefore the sample reflects the value of ^{222}Rn progeny concentrations. The conversion factor for this count is 218, which should be used in calculations using the equation presented in A.1 on page 14.

The second count is used to produce a combined ^{222}Rn and ^{220}Rn progeny potential alpha energy concentration (PAEC, in J/m^3) with a conversion factor of 14.1. The final count is used to derive the ^{220}Rn progeny PAEC with a conversion factor of 14.2. These conversion factors are used in calculations using the equation presented in A.1 on page 14.

The counting instrument has to be very close to the sampling location for the completion of the first count. Samples may then be returned to the laboratory for two subsequent counts and it is very important to conduct the counting precisely at the specified delay intervals.

A.5. Borak method

Prompt determinations of potential alpha energy for ^{222}Rn daughters in mJ/m^3 or working level are required for radiation protection purposes in underground mines. A single measurement of gross alpha activity collected on a filter can be optimised by selecting appropriate timing sequences for sampling and counting. The process of optimisation includes inherent uncertainty associated with measuring an unknown mixture of ^{222}Rn daughters as well as the precision of each measurement due to counting statistics. The Borak method allows timing sequences less than 10 min total duration that can yield an estimate of potential alpha energy with uncertainties less than 20% at 0.1 working level.

This method involves taking a 3 minute air sample onto a 25mm 0.8 micron glass fibre filter at 3.5 litres per minute. Waiting 3 minutes for the decay of some of the progeny before counting the sample in a portable detector for a 3 minute count, hence the '333 method'.

The ^{222}Rn progeny concentration (RPC), in microJ/m^3, is then calculated as follows:

RPC (microJ/m^3) = (Counts $\times$ 0.2237)$\div$(Efficiency)
and a conversion of 1 microJ/m^3/h at standard breathing rates gives 1.41 μSv/h.

A.6. Modified Tsivoglou method

The modified Tsivoglou method is more complicated than the Kusnetz, but it yields additional information: the concentration of individual radon progeny [15].

In this method, the sampling procedure is identical to that used for the modified Kusnetz method. After the end of sampling, remove the filter containing radon progeny from the filter holder and transfer it to the counting system for analysis. The standard counting intervals are 2–5, 6–20, and 21–30 min after the end of sampling. These intervals allow adequate time to transfer the filter into the counting system and record the counts from the different counting intervals. The technician or the person who performs the test is required to stand by for 30 minutes unless he uses automated counting equipment operated by a computer.

Calculation The equations needed to calculate the air concentrations from a 5 min sample and for the standard counting intervals are:

$$C_1 = \frac{[6.247N_t\,(2-5) - 3.028N_t\,(6-20) + 2.857N_t\,(21-30)]}{EQ}$$

$$C_1 = \frac{[0.056N_t\,(2-5) - 0.776N_t\,(6-20) + 1.836N_t\,(21-30)]}{EQ}$$

$$C_1 = \frac{[-0.8327N_t\,(2-5) + 1.224N_t\,(6-20) - 1.389N_t\,(21-30)]}{EQ}$$

$$C_p = \frac{[2.011N_t\,(2-5) - 1.372N_t\,(6-20) + 3.954N_t\,(21-30)]}{EQ}$$

where:
C_1, C_2, C_3 = the concentrations of ^{218}Po, ^{214}Pb, and ^{214}Bi, respectively (Bq/m^3);
C_p =the PAEC (nJ/m^3);
$N_t\,(...)$ =the net counts in the intervals 2–5, 6–20, and 21–30;
E =fractional counter efficiency[$(counts/min) \div (disintegrations/min)$];
Q =sampling air flow rate, L/min.

These coefficients were derived using 3.05 min for the half life of ^{218}Po [18]. The half lives used for ^{214}Pb and ^{214}Bi were 26.8 and 19.9 min, respectively[17].

The standard deviation equations which calculate the precision for each radionuclide are:

$$C_1 = \frac{1}{EQ}\left[39.0N_t\,(2-5) + 9.17N_t\,(6-20) + 8.16N\,(21-30)\right]^{1/2}$$

$$C_2 = \frac{1}{EQ}\left[0.003N_t\,(2-5) +).062N\,(6-20) + 3.37N\,(21-30)\right]^{1/2}$$

$$C_3 = \frac{1}{EQ}\left[0.69N_t\,(2-5) + 1.50N_t\,(6-20) + 1.93N\,(21-30)\right]^{1/2}$$

$$C_p = \frac{1}{EQ}\left[4.04N_t\,(2-5) + 1.88N\,(6-20) + 15.6N\,(21-30)\right]^{1/2}$$

where:
S_1, S_2, S_3 = standard deviation of ^{218}Po, ^{214}Pb, and ^{214}Bi, respectively (Bq/m^3);
S_p =standard deviation of the PAEC (nJ/m^3);
$N_t\,(...)$,E and Q where defined earlier.

A.7. Useful conversion factors

To convert:

- picoCuries to Becquerels, divide by 27 (27.027);
- d.p.m. (disintegrations per minute) to Becquerels, divide by 60;
- Becquerels to picoCuries, multiply the number of Becquerels by 27 (27.027);
- picoCuries per cubic meter to Becquerels per cubic metre, multiply pCi/m^3 times 0.037;
- Becquerels per cubic metre to microBecquerels per cubic meter, multiply the Bq/m^3 times 1 x 10^{-6}.

B. Appendix showing the Excel spreadsheet

Figure B.1.: The user interface of the Excel spreadsheet.

	A	B	C	D	E	F	G	H
1		**CHI-SQUARE TEST**				**18/02/08**		
2								
3		**Counts**		**(X-AVG)^2**		**Source:**	Am-241	
4		42795		3648.16		**Serial #:**	1440/93	
5		42773		6789.76		**Diameter (mm):**	25.4	
6		42295		314048.16		**Activity (Bq):**	3905	
7		42918		3918.76				
8		43016		25792.36				
9		42985		16796.16				
10		42935		6336.16				
11		43028		29790.76		**Chi-square value=**	**10.95**	
12		42735		14496.16		Chi-square value must be between 3.33 & 16.9		
13		43074		47785.96				
14	Mean	42855.4	Sum	469402.4				
15								
16		**COUNTING EFFICIENCY**						
17	Counts/minute=			115899				
18	Activity =	3863	Bq					
19	N=	1932	Particles/sec			Sum of counts (Cstd)=	428554	
20						Counting time (Tstd)=	300	
21	Efficiency =		0.37				**%**	**+/-**
22	Error=	ET=	5.67	%		**EFFICIENCY=**	36.98	2.10
23	ER^2=	0.023334	Random errors					
24	ES^2=	25	System errors (5%)					
25								

C. Appendix showing different sampling cassettes

C.1. Configuration differences

There are two different cassettes approved for the use in dust sampling by the relevant Australian Standard[8] — one is SKC 7–hole, another is IOM open face. SKC is a leading manufacturer and supplier of air sampling products —www.skcinc.com.

Figure C.1.: SKC 7-hole and IOM open face cassettes

The SKC 7–hole cassette is predominately used in Western Australian mining and mineral processing industries, but IOM open face ones may also be used, provided that the following considerations are taken into account.

The general disadvantage of adopting the IOM open face cassette for dust sampling in exploration, mining and mineral processing is that for any analyses other than gravimetric, the dust that may adhere to the walls of the cassette must be washed off and added to the material collected on the filter. Where the dust concentrations are relatively low (around 1 – 2 mg/m^3) and the sampling is undertaken for a period of 4 to 6 hours it is unlikely that this will be the case.

However, in circumstances when dust concentrations are comparatively high (above 3 mg/m^3) and the sampling is undertaken for a period of 8 hours or more the dust inside the IOM cassette (but not on the filter) may require special consideration.

Please note that minimum sampling time in accordance with Australian Standard[8] is 4 hours and samples collected over 3.5 hours or less are considered to be invalid.

To allow for such possibility the IOM open face cassettes are typically weighted together with the filter — both prior and after the sampling. When using the SKC 7–hole cassette the filter is weighted separately, prior to loading into the cassette and after the sampling.

Where dust samples require analysis for gross alpha activity concentrations, as described in this guideline, the filters from SKC 7–hole cassettes can be easily analysed.

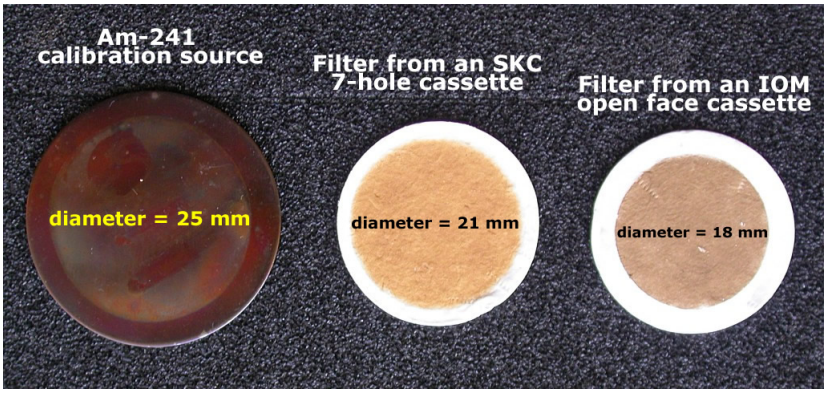
However, in cases where IOM open face cassettes are used and relatively high dust levels are measured the accurate analysis of the dust for gross alpha activity concentrations may, in some cases, become impossible.

It is unlikely that additional analysis steps (such as washing the material from the walls of a cassette, drying it and adding the dust that is already on the filter) will be possible for the implementation on an exploration, mining or mineral processing site, and performing this analysis in an off-site certified laboratory may be cost-prohibitive. In addition, in most cases it is impossible to determine if the dust is present on cassette walls until the cassette is opened.

C.2. Differences in the sample surface area

Further differences between these cassettes are associated with the diameter of the collected sample on the filter and its compatibility with the standard 25 mm ^{241}Am calibration source, as illustrated on Figure C.2.

Figure C.2.: Comparison between diameters of Am-241 calibration source and filters from SKC 7–hole and IOM open face cassettes



It is expected that the number of counts registered would not normally be significantly different between sources of 18, 21 and 25 mm in diameter, when the smaller size detectors are used for counting, such as ones with an active surface of 450 mm^2. However, as the diameter of the source decreases and larger size detectors are used (such as ones with an active surface of 1200 mm^2), the the source (dust on the filter) is behaving more and more like a point source – resulting in better resolution and increased counts.

In this regard it is clear that the filter from an SKC 7–hole cassette (surface of 1390 mm^2) is more closely resembling the calibration source (surface of 1960 mm^2) then the filter from an IOM open face cassette (surface of 1020 mm^2).

The relationships are relatively complex as the number of detected counts is dependent on factors such as active surface of the detector, active surface of the calibration source, active surface of dust on the filter, and the distance between the source and detector.

The same detector will have different geometrical efficiencies for both different size sources and different distances between the source and the detector, and it is not the purpose of this guideline to

provide detailed mathematical analysis, particularly as various sizes of detectors are used in mining and mineral processing industry.

It can, however, be concluded that when sampling of the same dust is undertaken using the SKC 7–hole and IOM open face cassettes — the gross alpha counting of IOM filters is more likely to result in an over-estimation of activity concentrations than counting of SKC filters.

An overall recommendation is that both SKC 7–hole and IOM open face cassettes can be used in exploration, mining and mineral processing in Western Australia — with a preference given to an SKC 7–hole cassette when comparatively high levels of dust and/or airborne radioactivity are expected or measured.

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