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Surveillance of the activity concentrations of airborne radioactive substances in the workplace of nuclear facilities

Surveillance de l'activité volumique des substances radioactives dans l'air des lieux de travail des installations nucléaires

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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The committee responsible for this document is ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

Introduction

Sampling of airborne radionuclides and monitoring of activity concentration in workplaces are critically important for maintaining worker safety at facilities where dispersible radioactive substances are used. Specifically, air sampling and monitoring are critical for evaluation of containment integrity, evaluation of effectiveness of contamination control programs and work practices, providing measurements for qualitative dose assessment, providing a general assessment of the level of the airborne hazard in a room, and for providing workers an immediate warning when the activity concentration exceeds safe levels.

This document sets forth guidelines and performance criteria for sampling airborne radioactive substances and monitoring activity concentration in the workplace of nuclear facilities. Emphasis is on health protection for workers in indoor environments. This document provides best practices and performance-based criteria for the use of sampling devices and systems, including delayed radioactivity measurement samplers and continuous air monitors. Specifically, this document covers air sampling program objectives, design of sampling and monitoring programs to meet program objectives, methods for air sampling and monitoring in the workplace, and quality assurance to ensure system performance toward protecting workers against unnecessary inhalation exposures. Taken together, these activities constitute the sampling or surveillance program.

The primary purpose of the surveillance of airborne activity concentrations in the workplace is to evaluate and mitigate inhalation hazards to workers in facilities where these may become airborne. Results often provide the basis for development and evaluation of control procedures and may indicate if engineering controls or operational changes are necessary.

The surveillance can consist of two general techniques. The first is retrospective sampling, in which constituents of the air are sampled, the collection medium is removed and taken to a radiation detector system and analysed for radioactive substances, and the activity concentration results made available at a later time. In this context, the measured activity concentrations are evaluated retrospectively. The second approach is real-time monitoring, in which activity concentrations are continuously monitored so that workers can be warned that a significant release of airborne activity may have occurred. In implementing an effective sampling program, it is important to achieve a proper balance between the two general approaches of the program. The specific balance depends on the hazard level of the work and the characteristics of each facility.

When designing a surveillance program, the optimization of worker protection minimizes internal and external exposures while balancing social, technical, economic, practical, and public policy considerations that are associated with the use of the radioactive substance.

A comprehensive surveillance program should also consider that the monitoring program is only one element of a comprehensive radiation protection program. Therefore, individuals involved with the monitoring program should interact with personnel working in the other elements of the radiation protection program, such as contamination control and internal dosimetry.

Surveillance of the activity concentrations of airborne radioactive substances in the workplace of nuclear facilities

1 Scope

This document provides guidelines and performance criteria for sampling airborne radioactive substances in the workplace. Emphasis is on health protection of workers in the indoor environment.

This document provides best practices and performance-based criteria for the use of air sampling devices and systems, including retrospective samplers and continuous air monitors. Specifically, this document covers air sampling program objectives, design of air sampling and monitoring programs to meet program objectives, methods for air sampling and monitoring in the workplace, and quality assurance to ensure system performance toward protecting workers against unnecessary inhalation exposures.

The primary purpose of the surveillance of airborne activity concentrations in the workplace is to evaluate and mitigate inhalation hazards to workers in facilities where these can become airborne. A comprehensive surveillance program can be used to

— determine the effectiveness of administrative and engineering controls for confinement,

— measure activity concentrations of radioactive substances,

— alert workers to high activity concentrations in the air,

— aid in estimating worker intakes when bioassay methods are unavailable,

— determine signage or posting requirements for radiation protection, and

— determine appropriate protective equipment and measures.

Air sampling techniques consist of two general approaches. The first approach is retrospective sampling, in which the air is sampled, the collection medium is removed and taken to a radiation detector system and analysed for radioactive substance, and the concentration results made available at a later time. In this context, the measured air concentrations are evaluated retrospectively. The second approach is continuous real-time air monitoring so that workers can be warned that a significant release of airborne radioactivity may have just occurred. In implementing an effective air sampling program, it is important to achieve a balance between the two general approaches. The specific balance depends on hazard level of the work and the characteristics of each facility.

A special component of the second approach which can apply, if properly implemented, is the preparation of continuous air monitoring instrumentation and protocols. This enables radiation protection monitoring of personnel that have been trained and fitted with personal protective equipment (PPE) that permit pre-planned, defined, extended stay time in elevated concentrations of airborne radioactive substances. Such approaches can occur either as part of a planned re-entry of a contaminated area following an accidental loss of containment for accident assessment and recovery, or part of a project which involves systematic or routine access to radioactive substances (e.g. preparing process material containing easily aerosolized components), or handling objects such as poorly characterized waste materials that may contain radioactive contaminants that could be aerosolized when handled during repackaging. In this special case, the role of continuous air monitoring is to provide an alert to health physics personnel that the air concentrations of concern have exceeded a threshold such that the planned level of protection afforded by PPE has been or could be exceeded. This level would typically be many 10's or 100's of times higher than the derived air concentration (DAC) established for unprotected workers. The monitoring alarm or alert would therefore be designed not to be confused with the normal

monitoring alarm, and the action taken in response would be similarly targeted at the specific site and personnel involved.

The air sampling strategy should be designed to minimize internal exposures and balanced with social, technical, economic, practical, and public policy considerations that are associated with the use of the radioactive substance.

A comprehensive air sampling strategy should also consider that the air sampling program is only one element of a broader radiation protection program. Therefore, individuals involved with the air sampling program should interact with personnel working in other elements of the radiation protection program, such as contamination control and internal dosimetry.

This document does not address outdoor air sampling, effluent monitoring, or radon measurements.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 11929, *Determination of the characteristic limits (decision threshold, detection limit and limits of the confidence interval) for measurements of ionizing radiation — Fundamentals and application*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
accuracy
closeness of agreement between a measured value and a true value

3.2
aerodynamic diameter
D_a
diameter of a sphere with density 1 000 kg·m^{-3} that has the same sedimentation velocity in quiescent air as the actual particle of arbitrary shape and density

3.3
aerosol
dispersion of solid or liquid particles in air or other gas

Note 1 to entry: An aerosol is not only the aerosol particles.

3.4
airborne radioactive substance
radioactive substance dispersed in the air in the form of dusts, fumes, particulates, mists, vapours, or gases

3.5
air contamination area
area accessible to individuals where the measured activity concentrations of an airborne radioactive substance exceeds or is likely to exceed the applicable national criteria

3.6
air sampler
device designed to pass a known volume of air containing a radioactive substance through a filter or other media and thereby trapping the airborne radioactive substance on the sampling media

3.7
annual limit on intake
ALI
derived limit for the amount of radioactive substance (in Bq) taken into the body of an adult worker by inhalation or ingestion in a year

3.8
breathing zone
BZ
uniform description of the volume of air directly around the worker‘s upper body and head, which may be drawn into the lungs during the course of breathing

Note 1 to entry: An air sample representative of the breathing zone is usually considered to be representative if drawn from within about 30 cm of the worker’s head.

3.9
breathing zone sampler
BZA
air sampler located in the breathing zone

Note 1 to entry: Other common terms include “personal air sampler” (PAS), “personal air monitor” (PAM), “lapel air samplers” or “fixed air sampler”.

Note 2 to entry: In the case of workers using PPE which includes full face (or even whole body suit) respirator equipment and supplied air, as when preparing for entry into high levels of airborne radioactive substances, special BZA or protective equipment samplers may be needed. Such BZAs are not always mandated then, but the decision should be based on the contaminant levels and types of PPE involved and the potential for contamination entering the suit or air immediately surrounding the suit just as PPE are being doffed.

3.10
continuous air monitor
CAM
instrument that continuously monitors the airborne activity concentration on a near real-time basis

3.11
continuous monitoring
active and continual monitoring of activity concentration in room air in near real time

Note 1 to entry: This approach uses continuous air monitors to assess activity concentration in air and can alarm when predetermined levels are exceeded.

3.12
derived air concentration
DAC
concentration of a radionuclide in air that, if breathed over the period of a work year, would result in the intake of one ALI for that radionuclide

Note 1 to entry: The DAC is calculated by dividing the ALI by the volume of air breathed by reference man under light-activity work during a working year (in $Bq \cdot m^{-3}$).

Note 2 to entry: The parameter values recommended by the International Commission on Radiological Protection for calculating the DAC are a breathing rate of 1,2 $m^3 \cdot h^{-1}$ and a working year of 2 000 h (i.e. 2 400 m^3).

Note 3 to entry: The air concentration can be expressed in terms of a number of DAC. For example, if the DAC for a given radionuclide in a particular form is 0,2 $Bq \cdot m^{-3}$ and the observed concentration is 1,0 $Bq \cdot m^{-3}$, then the observed concentration can also be expressed as 5 DAC (i.e. 1,0 divided by 0,2)

Note 4 to entry: The derived air concentration-hour (DAC-h) is an integrated exposure and is the product of the concentration of a radioactive substance in air (expressed as a fraction or multiple of DAC for each radionuclide) and the time of exposure to that radionuclide, in hours.

[SOURCE: References [5] and [10], modified]

3.13
detection limit
L_D
smallest true value of the measurand which ensures a specified probability of being detectable by the measurement procedure

Note 1 to entry: For a given type-I error (or false alarm probability, i.e. typically 0,05), L_D is the lowest net count (or rate) with the desired probability of detection, i.e. typically 0,95 (otherwise stated as a type-II error of 0,05 or a missed detection probability of 5 %).

Note 2 to entry: The measurand is the quantity subject to measurement.

3.14
grab sample
air sample of a sufficient volume drawn over a relatively short duration

3.15
intake
activity of a radionuclide taken into the body in a given time period or as a result of a given event

[SOURCE: ISO 20553:2006, 3.10]

3.16
personal air monitor
personal air sampler
breathing zone sampler

3.17
personal protective equipment
PPE
equipment designed to limit worker exposure to contaminants in the air or that are easily resuspended from contaminated surfaces

Note 1 to entry: Includes partial or full-face respirators, face masks, gloves, boots, whole body anti-contamination coveralls, and self-contained breathing apparatus (SCBA), depending on conditions.

3.18
potential missed exposure
PME
time-integrated activity concentration or maximum activity concentration, as applicable, that can acceptably be missed

Note 1 to entry: The detection limit of the method of measuring the activity concentration shall be less than or equal to the selected PME, which is defined according to ALARA/ALARP principles, and below legal limits.

3.19
sampling
collection of a radioactive substance on media such as filters, absorbers or adsorbers that is analysed for radioactive content after collection

3.20
standard reference conditions
conditions of temperature and pressure to which measurements are referred for standardization

Note 1 to entry: For this document, the standard reference conditions are 25 °C temperature and 101 325 Pa pressure.

Note 2 to entry: Used to convert air densities to a common basis. Other temperature and pressure conditions may be used and should be applied consistently.

3.21
surveillance
air monitoring and sampling, and the evaluation of the activity concentration measurement

4 Symbols

A activity, in Bq

C activity concentration, defined as activity per volume, in $Bq \cdot m^{-3}$

D_a aerodynamic aerosol particle diameter, in µm

$E(\tau)$ committed effective dose, in Sv

e_{inh} dose coefficient for inhalation, in $Sv \cdot Bq^{-1}$ (committed effective dose per unit intake such as those in Reference [9])

L annual dose limit, in Sv (an annual limit on the total effective dose equivalent to an individual)

q flowrate, in $m^3 \cdot s^{-1}$ or $m^3 \cdot h^{-1}$

Q_B breathing rate, in $m^3 \cdot s^{-1}$ or $m^3 \cdot h^{-1}$

R_N net count rate from the assay system, in s^{-1}

T_E annual exposure time, in s

T_S sampling time span, in s

ε_C collection efficiency

ε_r counting (measurement) efficiency of the assay system for a reference standard, in $Bq^{-1} \cdot s^{-1}$

ε_S efficiency modification factor for counting (measuring) an actual sample as opposed to the reference standard (e.g. the dimensionless alpha self-absorption factor for particulate alpha on glass fiber filters)

5 Developing the surveillance program

5.1 Reasons for conducting a surveillance programme

5.1.1 General

The specific techniques used in a sampling or surveillance program are based on the purpose(s) of the sampling. Even if airborne concentrations are very low, sampling may be conducted routinely due to the potential for high exposures and doses, should releases occur (e.g. in facilities with glove boxes). Sampling in the workplace can be used to determine the following parameters:

— effectiveness of engineering and administrative controls for the confinement of radioactive substances;

— measurement of activity concentrations of airborne radioactive substances in the workplace for assessment of inhalation risk;

— estimation of worker intakes when bioassay methods are deficient or unavailable;

— confirmation of appropriate air contamination area posting requirements;

— appropriateness of PPE;

— provision of early warning or detection of the release of radioactive substances in the workplace.

5.1.2 Sampling when respiratory protective equipment is used

A special component of the second approach which can apply, if properly implemented, is the preparation of continuous air monitoring instrumentation and protocols which enable radiation protection monitoring of personnel that have been trained and are using PPE that permit pre-planned, defined, extended stay time in elevated concentrations of airborne radioactive substances. Such applications can occur either as part of a planned re-entry of a contaminated area following an accidental loss of containment for accident assessment and recovery, or part of a project which involves systematic or routine access to radioactive substances (e.g. preparing process material containing easily aerosolized components), or handling objects such as poorly characterized waste materials that may contain radioactive contaminants that could be aerosolized when handled during repackaging. In this special case, the role of continuous air monitoring is to provide an alert to health physics personnel that the air concentration(s) of concern have exceeded a threshold such that the planned level of protection afforded by PPE has been or could be exceeded. This level would typically be 10's or 100's of DAC. The monitoring alarm or alert would therefore be designed not to be confused with the normal monitoring alarm, and the action taken in response would be similarly targeted at the specific site and personnel involved.

5.1.3 Sampling to establish air contamination areas

Air samplers located to sample general room air or at a specific work location can be used as an aid to evaluate the need for posting the area as an airborne radioactivity area. Areas should not be posted as airborne radioactivity areas on the basis of unlikely accidents; rather, airborne radioactivity areas should be established based on the radioactivity levels normally encountered or on levels that can reasonably be expected to occur when work is being performed.

5.1.4 Air sampling as a basis for determining worker intakes

Air sampling is a tool for internal dosimetry primarily to help identify when an intake may have occurred, and is an indication of the magnitude of an intake. It is not usually the primary tool for individual worker intake and dose assessment, but may be used as such by internal dosimetry programs in the absence of appropriate bioassay data. Specifically, the estimation of internal dose shall be based on bioassay data rather than air concentration values unless bioassay data are 1) unavailable, 2) inadequate, or 3) internal dose estimates based on air concentration values are demonstrated to be as or more accurate. Some regulatory bodies accept air sample results as being appropriate for assigning intakes when circumstances indicate that this would be the most reliable option. There is nothing in this document that is contrary to this practice, provided that use of air sampling, which is generally less accurate for assigning intakes than bioassay, is justified.

5.1.5 Air monitoring for early warning of elevated air concentrations

Air monitors can provide early warning to workers regarding elevated radioactivity concentrations. This real-time monitoring can be an effective method to reduce or eliminate exposures to the airborne radioactive substance or gas.

5.2 Graded approach to sampling

The extent and type of sampling should be based on estimates of worker intakes and on estimated activity concentrations of airborne radioactive substances as illustrated in Table 1. Estimates of intakes and concentrations may be based on historical sampling or bioassay data if these data are available. If the data are not available, a survey program should be established based on likely radiological conditions, probability of change in conditions, and area occupancy factors. Considerations for this evaluation may include the following:

a) quantity of radioactive substance being handled;

b) ALI of the substance;

c) release fraction for the radioactive substance based on its physical form and use;

d) type of confinement for the substance;

e) other factors appropriate for the specific facility (such as national regulations or license requirements).

The estimated prospective intake levels given in Table 1 are an illustration that may be used to guide decisions regarding sampling resources used in different situations. Alternatively, a sampling resource allocation scheme may be based on containment classes (see ISO 17873[1] and ISO 26802[3]) or according to other local or national guidelines. The person in charge of the radiation safety program should use all appropriate information, professional judgment, and historical experience to perform sampling appropriate for the specific situation in keeping with the as low as reasonably achievable/practicable (ALARA/ALARP) principle.

Table 1 — Example of sampling recommendations based on ALI and airborne concentrations expressed as fractions of the ALI

Annual intake as a fraction of ALI	Sampling recommendations
<0,02	Sampling is generally not necessary. However, monthly or quarterly grab samples or some other measurement (e.g. surface contamination) may be appropriate to confirm that airborne levels are indeed low.
≥0,02 and <1,0	Sampling is appropriate. Intermittent or grab samples are appropriate near the lower end of the range depending on the nature of the work being performed. Continuous sampling is appropriate if activity concentrations are likely to cause an exposure exceeding 12 DAC-h during a time period of a week or longer. A demonstration that the samples are representative of the breathing zone air is appropriate if intakes of record are based on sampling. Additional investigation by bioassay methods may be considered.
≥1,0	Perform continuous monitoring with alarm capability, as necessary, provided there is a reasonable potential for concentrations to cause an exposure exceeding 40 DAC-h during a time period of a week or less. Samples should be analysed before work resumes the next day, and results should be available before the next shift ends. Credit may be taken for protection factors if respiratory protection is used.

5.3 Frequency of sampling

5.3.1 General

The frequency of sample collection should be based on occupancy rates, hazard levels, purposes of sampling (e.g. worker protection and/or verifying containment), and requirements for minimum levels of detection. Grab samples may be used in non-routinely occupied work rooms. Often, continuous monitoring is also conducted in routinely occupied areas where workers are likely to be exposed to an activity concentration exceeding 1-DAC over a 40-hour work week or 5-DAC in an 8-hour work day (both typically called 40 DAC-h). The selected sampling approach and frequency should be designed to ensure detection limits, as related to radiation protection goals are met.

5.3.2 Grab vs. continuous sampling

Air sampling may be continuous during work hours or intermittent (e.g. grab samples taken during part of the work). The distinction between grab and continuous air sampling is the duration of collection. The resultant data are an estimate of concentration (DAC, and hence potential exposure rate) averaged over that time. With continuous air *monitoring*, a real-time detection device or system is active during the sampling process, and the resultant data has the form of the product of concentration in air (fraction of DAC) and duration of sampling or potential exposure (number of DAC-h). In the latter case an estimate of a person's dose can be determined. On the other hand, when continuous *sampling* during the work day is performed, a weekly sample exchange period is generally acceptable (except for shorter-lived radionuclides or when airborne dust loading is high enough to cause rapid loss of sample volume). Longer sample exchange periods (i.e. monthly or quarterly) may be appropriate if average airborne radioactive substance concentrations and nuisance dust concentrations are both relatively low. They may also be appropriate when transient elevated concentrations in excess of a significant fraction of a DAC are not expected based on documented knowledge of the source strength and characteristics of the work activity that could lead to loss of containment or airborne release. If large transients are possible, an integrated sample and data averaging may disguise an otherwise unacceptable transient exposure condition. Grab sampling would be appropriate when operations are conducted on an intermittent basis and provided that prompt detection (and alarm) are not needed. When grab sampling is performed for continuous processes, the samples should be collected during times that provide representative measurements or during times of increased risk of airborne releases.

5.3.3 Continuous monitoring of activity concentrations

In situations in which there is a reasonable potential for unintended releases of significance, continuous air monitoring shall be done. These requirements may be set by the relevant national bodies, typically, 40 DAC-h in a week would be an appropriate decision point for monitoring. Facility goals may be set at lower target limit. Continuous monitoring should be evaluated and applied when work conditions causing airborne radioactivity releases require the use of respiratory protection even though the elevated airborne radioactive levels are not unintended releases.

Alarm set points for continuous air monitors shall be set as low as practical for the work being conducted without causing excessive false alarms. The faster the CAM response time is, the higher the activity concentration detection limit is, which also means a higher alarm set point. This relationship can result in a better real-time follow up of contamination events especially in case of short time puff releases and subsequently reduces the exposure time of workers. Thus a proper balance between response time and detection limit should be considered in the radiation protection objectives when a CAM is used in a worker protection role. The alarm set point of CAMs should meet radiation protection objectives, and the set point should be justified and documented, see References [16] and [17].

If continuous air monitors are used, at a minimum, follow the manufacturer's recommendation for checking response and alarm function. Check sources should be used for maintenance/function checks and during calibration to check that the monitor responds appropriately and causes an alarm. Continuous check sources may also be used provided there is no interference with the radionuclide of interest. If the response (e.g. count rate) is not within ±20 % of the normal response, the monitor shall be repaired or recalibrated.

Table 1 shows under which conditions it is recommended to conduct continuous sample collection. When continuous air monitors with automatic alarms are used, the alarm set points shall be set as low as reasonably practical for the work being conducted without causing excessive false alarms.

5.3.4 Prompt analysis of certain samples

For situations with a known or suspected airborne release, retrospective samples can be analysed promptly to help evaluate the impacts (levels and spread) of the released substance. Sample results should be available quickly to help respond to the incident, provide qualitative estimates of dose to workers, or provide assurance that work can be restarted, as appropriate. In evaluating the need for prompt analysis, credit may be taken for respirator protection, if a respiratory protection program is in place.

5.4 Substitutes for air sampling

If experience indicates that worker intakes are generally low, it may be acceptable to substitute other techniques in place of sampling. When implementing air sampling substitutes, the technical basis for the substitution should be documented.

6 Location of samplers and monitors

6.1 General

Activity concentrations of airborne radioactive substances in a room can vary widely in space and time. Properly placed samplers and continuous air monitors are critical for credible measurement interpretation and adequate worker protection[14]. When selecting locations for workplace sampling and monitoring equipment, consideration should be given to the locations of the release points and the workers, the purpose of the sample (i.e. estimating worker intakes, warning of high concentrations, testing for leakage, or defining air contamination areas), and the airflow patterns that affect the temporal and spatial dispersion of the radioactive airborne substance in the workplace after the release.

6.2 Types of air flow studies

6.2.1 General

Systematic airflow studies may be used to determine the airflow patterns in a work area for normal and unusual conditions. Airflow studies may be characterized as either qualitative or quantitative. Qualitative airflow studies rely on visual observation of a tracer released from possible release locations in the work area to observe general airflow patterns. Quantitative airflow studies provide actual measurements of concentrations of released aerosol particles or gas tracer in a workplace. The strategy used for determining the airflow patterns and sampler placement depends on factors, such as the hazard level, number, location of likely release points, room and ventilation complexity, and the purpose of the sample being collected. As a general guide, qualitative tests should be done for work spaces that have a reasonable likelihood for an intake to exceed 2 % of the ALI in a year or the air flow patterns are simple and well-understood. Quantitative tests should be done in work spaces where there is reasonable likelihood for an intake to exceed 2 % of the ALI in a week. Placement of sampling and monitoring equipment should be re-evaluated after changes to the ventilation system or after equipment or structures have been added to the room that could influence airflow. Placement strategies should be re-evaluated no less frequently than every three years.

6.2.2 Qualitative airflow studies

A qualitative airflow study is a common method for determining airflow patterns to help in the placement of samplers. There are several relatively easy and economical methods for qualitative airflow studies:

a) aerosol particle or gas tracers, e.g. smoke candles/tubes or smoke generators;

b) helium-filled balloons that are neutrally-buoyant;

c) isostatic bubbles.

The most common method is a combination of smoke candles/tubes and smoke generators.

Movement and transit times of the smoke, balloons, or bubbles can be roughly estimated by visual observation. The airflow patterns can be recorded on worksheet drawings with narrative descriptions or by using photographs or video.

The uncertainty in evaluating airflow using qualitative techniques should be understood for each application. For example, the use of smoke candles can introduce upward thermal currents near the candle. This initial buoyancy could result in incorrect sampler placement. Also, helium-filled balloons and isostatic bubbles respond to the sum of airflow vectors over the entire surface of the object. Thus, the movement of balloons and bubbles can only provide qualitative information on aerosol particles/gas dispersion. In reality, the dispersion of gases and aerosol particles are mainly governed by small-scale turbulent eddy diffusion, Brownian diffusion, gravitational settling, electrical and thermal forces, and forced advection. Therefore, uncertainty with qualitative techniques is likely to be larger than that associated with quantitative airflow studies.

6.2.3 Quantitative airflow studies

Quantitative airflow tracer studies, which provide measurements of dispersion and transit times, are useful for determining the representativeness of breathing zone samples. These methods are often more expensive and time-consuming than qualitative methods, but they can more accurately determine aerosol particles/gas dynamics in the workspace.

Non-radioactive tracer aerosol or gases are released, at known rates or concentrations, at points that are representative of likely release points for radioactive substances and then the concentrations of the tracer are measured at selected points in the work area. Comparisons can then be made between tracer mass concentrations, either time-averaged or instantaneous, at the release locations and the various sampling locations.

Finally, the conditions for the tracer releases should represent the expected type of release (energetic, passive, transient, continuous, etc.) and location(s) of likely releases. Also, the tracer used should exhibit similar fluid dynamic behaviour compared with the radioactive source substance (i.e. similar aerodynamic equivalent diameters). The uncertainty of the airflow study results and its effect on sampler placement should also be documented. As an aid to determining the uncertainty, releases should be repeated at each test location and under varying ventilation conditions, if they can change substantially.

Validated software for numerical airflow simulations may be used alternatively to, or in combination with, the experimental studies outlined above.

6.3 Location of samplers for estimating committed effective dose

Fixed samplers can be used to collect representative samples of the air that workers inhale if they are strategically placed in or near the breathing zone of the workers. The sampler should be as close as possible to the worker's head, ideally within 30 cm and still allow the worker to move safely around the sampler. The sampler filter may be in a vertical plane to reduce collection of larger particles that might settle onto the filters. Alternatively, if the purpose is to obtain a more conservative dose estimate, the filter may be in the horizontal plane, facing upwards. Particle size selective samplers can be very useful toward estimating the committed effective dose. For most radionuclides, dose determinations made with bioassay techniques are often more accurate and should be used. When estimating the committed effective dose based on samples, the uncertainty of the estimate should be documented. Uncertainties in committed effective dose estimates can result from variations in spatial concentrations in the breathing zone and in size distributions of inhaled particles. Each of these uncertainties can be corrected for, if information about the airborne substance is known.

In the case of air monitoring of workers using respiratory protection equipment in an environment where DAC levels and contaminated dusts and gases are high enough to require full body PPE and face mask (or SCBA gear), sampling the air breathed is typically infeasible. Continuously monitoring the workplace air to enable assessment of the adequacy of the protection factor provided by the type and level of PPE shall be done to assure adequate levels of protection during the job.

6.4 Location of samplers for evaluating effectiveness of containment

Sampler placement should assure sensitive measurement of the activity concentrations in the room and should not interfere with the normal conduct of work. A sampler should be placed near likely release points. As an example, fixed-location samplers can be placed on or near high-risk containment equipment (e.g. hoods and glove boxes) and above the work space (e.g. above the height of the worker). In all cases, it is important that the sampler be located such that the dilution of any released substance is minimal at the sampler position. This provides for maximum detection of releases. Samplers should be placed to avoid the influence of supply ventilation airflow into a room. A sampler placed in the supply airflow is sampling constituents of air that represents the supply air instead of the ambient workplace air. This could result in the underestimation of ambient workplace activity concentrations. If the ventilation system is operated in the recirculation mode without filtration on the recirculated air, sampling of constituents in the supply air may be warranted because the supply air now becomes a likely airborne release point in the work area. Other factors for consideration when placing samplers include the following:

— samplers are placed so that they are easily accessible for changing filters and servicing;

— high-volume samplers are positioned so that their exhaust is directed downstream from the sample collector to avoid sampling their own exhaust air;

— if a sampler is operated on a horizontal surface as a convenient means of support, the air discharged from the sampler is not directed at the surface, where it could cause localized excessive air concentration from re-suspended surface contamination;

— when sampling at an exhaust duct, the collected sample should represent the room air; to this end, placement of the sampling inlet(s) inside the duct, collection efficiency of the entire collection apparatus, and potential dilution of the radioactive substance between the release location and the duct should be considered;

— for activities with a temporary airlock, the sampling and monitoring should be located both inside and outside the airlock close to the airlock exhaust ventilation network and close to the entrance and exit access locations.

6.5 Location of samplers for posting of air contamination areas

Sampling for the purpose of posting air contamination areas requires that the samplers shall be in an area such that they reliably measure activity concentrations representative of the workplace regardless of the release location. In work areas with a single release point, placing the sampler immediately downwind from the release point provides the best indication of concentrations requiring radiological area classification. Placement at an exhaust vent is also appropriate if dilution effects would still allow detection of a release. Such a determination can be made with quantitative methods of analysing airflow and gas/aerosol particles dispersion in the area.

For an area with many possible release points, several alternatives are possible. First, samplers can be placed downwind of each release point. Second, a sampler can be placed at each room exhaust vent when a quantitative evaluation shows that the dispersion dynamics between the sampler and the exhaust vent(s) still allow sensitive detection of the release. Finally, mixing rates in some rooms are sufficient to allow greater detection sensitivity by placing air samplers at locations other than exhaust vent(s).

6.6 Location of portable samplers

Portable samplers are generally used in facilities where the location of airborne radioactive substances changes due to routine or special practices (e.g. maintenance), which often creates actual or likely air contamination areas. Because these samplers can be easily moved, they should be located as close as practical to the worker breathing zone. Knowledge of the airflow in the work area is useful in determining where to locate portable samplers.

6.7 Location of CAM for continuous monitoring of the activity concentration

CAMs should be located to provide workers with sensitive and timely warning when an operation in a space results in an activity release into the air in that space. The purpose of a CAM is to alarm when the airborne activity concentration exceeds a prescribed set point. A method for optimizing the number and placement of CAMs is presented in Reference [15].

7 Collection of samples

7.1 General

Proper techniques for collecting samples are necessary to ensure accurate results and meaningful interpretation. The physical and chemical characteristics of the airborne radioactive substance determine the method of sample collection, and the form of airborne radioactive substance can be categorized as either aerosol particles, vapour or a gas. Sampling methods and strategies are determined based on the purpose of the measurement.

A correction for radon and/or radon progeny interference may be necessary and shall in this case be taken into account when analysing the count results and statistics, types of particle and gas samples.

7.2 Sampling of aerosol particles

Sampling of aerosol particles is typically done by drawing an aerosol through a filter with the particles collecting on the filter. The collected particles are then analysed using nuclear counting techniques.

The sample should be representative with respect to the air and the aerosol particles of concern. Sedimentation of aerosol particles between the volume of interest and the sampler should be taken into account.

Selection of the filter type should consider the following:

— efficiency of collection on the filter;

— burial of particles and its effects on counting efficiency and spectral resolution;

— pressure drop across the filter.

If the efficiency of collection on the filter is less than 95 %, or the burial of particles results in a reduction of the count rate by more than 5 %, corrections to the results of the concentration measurements are required. An extensive list of filters is given in ISO 2889[4].

Using a sample transport tube (a tube to transport the sampled air from a location some distance from the collection media) is permitted where justified (e.g. sampling aerosol particles from very high radiation areas). Using a sampling nozzle can decrease penetration due to particle deposition in the tube, where penetration is the percent of particles reaching the collection media to the total number of particles entering the sampling tube. The design of the sampling tube should maximize penetration. The penetration should exceed 50 % for polydisperse particles with a D_a of 5 µm and a geometric standard deviation of about 2,5 (Reference [8]). ISO 2889[4] provides information on estimating penetration efficiency. In cases where additional data about the relevant size distribution (e.g. activity size distribution) are available, the test aerosol particle size may be selected accordingly.

Validated computer codes or validated hand calculations may be used to assist in the design of the sampling line. The computations can be used to extrapolate measured penetration efficiency values to other particle sizes, and can be used further in the cases of modification of flow rate or changes of sampling line geometry.

If particle loss is greater than 10 % from the sample intake to the sample collector, then corrections to the activity concentration measurements shall be made.

7.3 Gas Sampling

Sampling for radioactive gases can be performed using active or passive techniques. Active sample collection involves drawing air through media into or through a suitable gas sample container which may be equipped with a radiation detector. Passive sampling relies on the Brownian diffusion of the gas to the collection sites. After sampling, the collection media can be directly analysed for the amount of collected radioactive gas, or the gas can be desorbed (i.e. by heating) and collected for analysis. Corrections to the measured concentration are required for collection efficiencies less than 95 %.

Activated charcoal is often used for sampling radioactive gases and has relatively high collection efficiency for iodine, organic vapours and halogens. Collection efficiency on the charcoal is dependent on contact time, temperature, humidity, charcoal particle size, gas concentrations, packing density and the age of the charcoal. The optimal size of the charcoal for iodine ranges from 0,6 mm to 1,7 mm (12 mesh to 30 mesh) and a size in this range should be used. Silver Zeolite can also be used for sampling iodine and has the advantage of collecting iodine and excluding other halogens.

Some gases, iodine in particular, also collect on aerosol particles. The sampling of the particle fraction can require techniques outlined in 7.2 on aerosol particle sampling. Combination samplers that collect the particulate fraction on a filter first then collect the gas fraction using, for example, activated charcoal should be used.

The decay products of radon gas, particularly those which are relatively long-lived, are particulates and readily attach to ambient aerosols and are thus collected by air sampling (both retrospective and continuous). In most or all designs of gas sampling with detection devices, correction for radon and/or radon progeny interference is necessary. In the case of gas sampling for radon by sampling into a collection chamber coated by a scintillator or by diffusion into an ion chamber, it is the decay of the radon progeny which generates radiations that are detected, and shall therefore be taken into account when analysing the count results and statistics.

Methods for sampling for tritium depend on the chemical form. The activity concentration of elemental tritium (HT) can be measured using a flow-through ionization chamber or proportional counter, or it can be sampled using a catalyst for oxidation to HTO and then captured in a bubbler or molecular sieves. Oxidized tritium activity concentrations can be measured using an absorbent, adsorbent or a flow-through ionization chamber. For accurate measurement of the activity concentration of tritium when using a flow-through ionization chamber, the responses should be corrected for nearby gamma sources and/or other interfering radionuclides.

ISO 2889[4] provides detailed information about the sampling of gaseous compounds of radionuclides.

8 Evaluation of sampling results

8.1 Determining the average activity concentration

The average activity concentration C is determined by the following Formulae (1) and (2):

$$C = \frac{A}{q_s \cdot T_s \cdot \varepsilon_c} \quad (1)$$

where

C is the average activity concentration, in $Bq \cdot m^{-3}$;

q_s is the average sample flow rate, in $m^3 \cdot s^{-1}$;

ε_c is the collection efficiency;

T_s is the sampling time span, in s;

A is the activity on (or within) the filter media at the time the sample was taken, given by:

$$A = \frac{R_N}{\varepsilon_r \cdot \varepsilon_S} \quad (2)$$

where

R_N is the net count rate from the assay system, in s^{-1};

ε_r is the counting efficiency of the assay system for a reference standard, in $Bq^{-1} \cdot s^{-1}$;

ε_S is the efficiency modification factor (a dimensionless factor) for counting an actual sample as opposed to the reference standard (e.g. the alpha self-absorption factor for alpha-emitting particulate on glass fiber filters).

NOTE 1 Any temporal variations in the concentration are not known; only the average concentration is determined.

NOTE 2 Continuous air monitoring requires a more complex calculation of detection limit, minimum detectable activity, and minimum detectable concentration due to the nature of real-time data collection and analysis in which concentrations of both target radionuclides (net activity) and background interference activity can change over the course of continuous monitoring operation. This typically involves maintaining a record of the previous time-step counts of net activity and background and utilizing these along with current data to determine the rate at which activity is being added, and from that, the present concentration. Reference to manufacturer manuals and firmware documentation is mandatory to understand the nature of and limitations of the reported results.

The connection of the average activity concentration and the term “DAC-h”, sometimes used in radiation protection, is given in Annex C.

8.2 Uncertainty

The uncertainty of measurements for an air sampling program shall be calculated according to ISO 11929.

NOTE Example of calculations are given in Annex A.

8.3 Techniques for correcting for radon progeny interference

Short-lived progeny of ^{222}Rn and ^{220}Rn interfere with the detection of alpha and beta emitters of interest in occupational air samples. This interference shall be corrected.

NOTE Examples of methods to correct for this interference are presented in Annex B.

8.4 Evaluating changes in activity concentration over time

As was mentioned previously, temporal variations in the activity concentration during the sampling are not determined and are beyond the scope of Clause 8. It is only the average concentration that is determined here. This does, however, highlight one of the advantages of the time integrated concentration, whose value is relatively independent of the temporal variations in the concentration. However, there may be a need to evaluate for changes in activity concentration to ensure engineering and administrative controls continue to function at a high level with no appreciable degradation.

8.5 Review of sampling results

The type of review to be conducted depends on the purpose of the air sampling.

A short-term review is used for the purposes of determining the need for respiratory protection, assessing hazards for temporary work or conditions, or for determining the radiological posting (signalization) at the entrance to a workplace. In these cases, the measured activity concentration is compared to the various trigger or investigation levels established for those purposes.

A long-term review is used for the purposes of monitoring the effectiveness of containment, assessing the hazards of new facilities or operations, or influencing the bioassay program as an integral component of the internal dosimetry program. This may involve a review of sampling data collected over a time period of a calendar quarter or longer. The reasons for this review are varied and numerous, but include effective communication to the management and occupants of the workplace so that informed decisions for better containment, procedures, or training may be made. Additionally, the long-term results may be compared to bioassay program trigger levels to aid in the interpretation of positive bioassay data.

The results may be expressed as activity concentration (e.g. $Bq \cdot m^{-3}$), fraction of a derived concentration (e.g. DAC) or a dose-based-related quantity (e.g. number of DAC-h). Additionally, a graphical presentation is recommended. Factors to consider in the interpretation of the sampling data may include:

— presentation of the activity of each sample within a room or the summed activity of all of the samples within that room;

— presence of long-lived ^{222}Rn decay products, especially the activity concentration of the alpha emitting ^{210}Po, which is typically 30 $\mu Bq \cdot m^{-3}$ to 300 $\mu Bq \cdot m^{-3}$ [12];

— the possible non-conservative nature of workplace air sampling (e.g. accounting for concentration differences in sampled volume relative to breathing-zone concentrations);

— occupancy factors;

— appropriate isotope identification, particle size correction, pulmonary retention (i.e. solubility).

The correctly interpreted sample activities may then be summed over an appropriate time period and be directly compared to the ALI and/or bioassay data. The results may also trigger bioassay program participation or a request for special bioassay samples, or aid in the interpretation of positive bioassay data. Trends can also be identified. Increases in the sample activities should lead to decisions for better containment, procedures, etc. and reductions of activity concentrations in air demonstrate the effectiveness of previous changes.

9 Evaluating the effectiveness of the sampling program

9.1 General

The sampling program should be reviewed on a periodic basis to confirm whether the measurements and techniques are accurate, reliable, and have adequate sensitivity to meet the goals of the sampling program. The following should be considered:

— the accuracy of sample collection techniques, sampler placement, airflow, counting systems, etc. should be periodically reviewed for adequacy;

— the sampling techniques for the radionuclides and environmental conditions should be appropriate;

— the number of sampling locations and associated airflow should be adequate for representative sampling;

— the counting systems should be relevant and properly calibrated;

— the procedures and training programs should be adequate;

— interferences such as dust burial, radon progeny, humidity, etc. should be accounted for in sample analysis;

— the number, location, type, and operation of the sampling equipment should be appropriate.

All areas should be continually re-evaluated as operations change with time.

The reliability of pumps, sampling lines, sampling heads, counting systems, and any other related equipment should also be reviewed for adequacy. The equipment should be periodically inspected for leaks, alterations in sampling efficiency, changes in uniformity of sample collection on the collection substrate, or any other condition that might cause errors. Instruments used in nuclear counting should be part of an instrument maintenance and calibration program.

The sensitivity of the measurements should also be periodically reviewed for adequacy. This is addressed in detail in 9.2.

The monitoring program review should also include selected trending and comparison of the results of data from fixed samplers, continuous air monitors, personal samplers, grab samplers, surface contamination data, and bioassay results, if available, to evaluate the effectiveness of the monitoring program. The radiation protection staff should carefully select the sampler types and locations for these comparisons to support a meaningful evaluation of the monitoring program. Investigation action levels should be developed where appropriate for use in responding to anomalies in the sampling data. Whenever possible, the review should be combined with reviews of other aspects of the radiation protection program to provide an integrated assessment of the role and adequacy of monitoring in the program. A technical basis document for the sampling program shall be developed to provide a description and framework for the evaluation, and maintenance of the program.

9.2 Dose-based assessment of the adequacy of the sampling program

The sensitivity of the monitoring approaches should be evaluated to ensure that the program is sufficient to meet the sampling goals (e.g. maintaining worker exposures below an ALARA/ALARP goal). The minimum detection capability for the sampling program is intimately coupled with both the purposes of sampling and the potential missed exposure to airborne contaminants. The potential missed exposure (PME) is introduced here as a time-integrated concentration or maximum concentration, as applicable, that may be acceptable to miss (i.e. not be detected at the 95 % confidence level). The PME is related to regulated dose limits (e.g. 20 mSv per year), but usually lower PME values may be selected based on ALARA/ALARP considerations, local regulations and license conditions. Example recommended minimum detection capabilities that account for the frequency of sample collection for some various purposes of sampling are given as a fraction of the PME in Table 2. Note that the PME value may be

defined differently for each sampling purpose. It does not apply to an individual, but to the sampling program, equipment and measurement system. Examples of the application of PME are given in Annex D.

Table 2 — Example of minimum detection capability for various purposes of sampling

Purpose	Task	Typical duration of sampling program	Typical number of samples	Recommended typical minimum detection capability (per sample)
Evaluating the effectiveness of containment	Confirm the integrity of containment	Annual (i.e. continuous)	50	0,02 PME
Assess hazards for temporary work or conditions	Estimate potential for doses and/or actual exposure incurred	<hour to days	1	1 PME
Confirm the adequacy of respiratory protection	Estimate the concentration	<hour to days	1	1 PME
Continuous monitoring	Alarm as soon as possible following actual releases	<hour to annual (i.e. continuous)	1	1 PME

10 Quality assurance and quality control

10.1 General

The quality of workplace sampling and monitoring measurements should be assessed in all phases of the program including:

a) sample identification, handling and storage;

b) the function of sampling and monitoring equipment;

c) the accuracy and reliability of counting room equipment;

d) record keeping.

10.2 Sample identification, handling, and storage

All samples collected should be uniquely identified to ensure that a sample from one location cannot be confused with samples taken at another location. Sample designators should be placed on all collection envelopes or containers to reduce the possibility of mislabelling a sample. Information included with the sample as a minimum is the sample date, time period when the sample was collected, the sample volume, sample location, and the equipment utilized to obtain the sample.

Samples should be handled carefully to prevent cross-contamination and should be placed in appropriately labelled containers to reduce the likelihood of loss. Arrangements should be made for sample storage prior to counting and between counts, if multiple counts are required.

10.3 Sampling and monitoring equipment

10.3.1 General

The accuracy of the sampling measurements and the calibration of the measuring instrumentation shall be suitable to ensure accurate and reliable measurement of the radioactive substance. This subclause

describes the minimum requirements necessary to ensure accurate measurements of the radioactive substance in air.

10.3.2 Performance of measuring instruments

10.3.2.1 Calibration

Measuring instruments should be calibrated periodically, and traceable to national or international standards. Target values for function checks should be defined at the time of calibration and used with a frequency adequate for the equipment. For the example of a CAM detector function check, the target value would be the count rate resulting from the test source. In the case where radon progeny are a principal cause of interference and source of false alarms, it may be difficult to rely simply on a plated check source, in which case a more extensive calibration and performance check procedure may be required.

Airflow meters, differential pressure indicators, and other devices used to determine volumetric flow rates of samplers and monitors should be calibrated, e.g. to within 10 % of the true reading.

10.3.2.2 Function checks

Measurement instruments should have appropriate function checks at a predetermined frequency.

10.3.2.3 Operability check

The operability of continuous monitoring equipment should be verified periodically. On a daily basis, operability checks should include the appropriate airflow indication, presence of a typical non-zero response to background radiation, and the appropriate response to check sources. Electronic or manual means can be used for the operability checks.

10.3.2.4 Performance of sampling flow rate measurements

All samplers to be used for quantitative measurements should have means to determine the sample volume. This recommendation applies to fixed location air samplers, portable samplers, and lapel samplers.

10.3.3 Air in-leakage testing

A leak in the sampling system or around the sample collector can cause the indicated sample flow rate to be in error, leading to improper functioning of the sample collector. A sampling system should be inspected for leaks at the time of installation and at any time when either significant maintenance is performed or during an inspection. The inspection or test methodology should be practical for the installation and documented.

Leakage under flowing conditions should not exceed 5 % of the nominal sampling flow rate. Bypass around a sample collector should be less than 5 %.

10.4 Documentation and record keeping

Records of the results of the surveillance for activity concentration of an airborne radioactive substance shall be maintained. Records should include the following common elements:

a) purpose of the activity concentration measurement;

b) results for activity concentration measurements with associated uncertainty as appropriate for the measurement purpose;

c) documentation of all parameters used in the calculation of activity concentrations and the associated uncertainty, including flow rate, sampler collection efficiency, filter collection efficiency, self-absorption, sampling period, and detector counting efficiency;

d) location of the sample being taken, including the identification of individuals monitored using lapel air samples;

e) the model and serial number of the laboratory counting equipment and sampling equipment used;

f) records of all calibration, maintenance, repair, and modification data for each instrument. Each record shall be dated and shall identify the individual performing the work. Each record shall be filed with previous records on the same instrument and shall be readily retrievable;

g) a full history and calibration data, including certificates, for all standards and applicable calibration equipment;

h) a documented analysis of calibration uncertainty;

i) all procedures used for providing calibration services;

j) instruments used to measure activity for quantification of activity concentrations can be labelled with the following information:

— date of most recent calibration;

— initials or other specific identifying mark of the calibrator;

— date when calibration is due;

— special-use or limited calibration label (if applicable);

— serial number of instrument or other unique identification number used by the facility to identify a specific instrument;

k) routine quality control records;

l) the results of all performance testing;

m) records detailing the training of all staff and supervisory personnel associated with operations within the sampling program;

n) documentation of the minimum detectable activities and concentrations in the context of the goals of the radiation protection program;

o) performance of CAMs in fluctuating backgrounds and the false alarm rates should be recorded and evaluated.

Annex A
(informative)

Examples for the determination of uncertainty, decision threshold and detection limit according to ISO 11929

A.1 General

This annex demonstrates the application of ISO 11929 to a direct measurement of an airborne radionuclide and sampling of radioactive aerosol particles on a filter with online or delayed counting.

The first step in determining uncertainty, decision threshold and detection limit according to ISO 11929 is the construction of an analytical model of the measurand Y as a function G of its input quantities X_i, as given in Formula (A.1):

$$Y = G(X_1, \ldots, X_m) \tag{A.1}$$

The uncertainty $u(y)$ of a primary measurement result y in dependence on the estimates x_i of the input quantities X_i and their respective uncertainties $u(x_i)$ can be calculated according to Formula (A.2):

$$u^2(y) = \sum_{i=1}^{m} \left(\frac{\partial G}{\partial X_i} \right)^2 u^2(x_i) \tag{A.2}$$

X_1 is assigned a special part in the calculation of the decision threshold and detection limit. To fulfil this part, X_1 has to meet additional requirements

— X_1 is taken as that quantity whose value, x_1, is not given when a true value, $\tilde{y}$, of the measurand, Y, is specified, and

— $u(x_1)$ is given as a function $h_1(x_1)$ of x_1.

In most cases, the uncertainty $\tilde{u}(\tilde{y})$ of the true value $\tilde{y}$ can be explicitly specified, provided that $u(x_1)$ is given as a function $h_1(x_1)$ of x_1. In such cases, y shall be formally replaced by $\tilde{y}$ and Formula (A.1), formulated for the estimates x_i of the input quantities X_i shall be solved for x_1. With a specified $\tilde{y}$, the value x_1 can be calculated, which results in x_1 as a function of $\tilde{y}$ and x_2,..., x_m. This function shall replace x_1 in Formula (A.2) and in $u(x_1) = h_1(x_1)$, which finally yields $\tilde{u}(\tilde{y})$ instead of $u(y)$.

The decision threshold, y^*, is calculated using the $1-\alpha$ quantile of the standardized normal distribution $k_{1-\alpha}$ as, given in Formula (A.3):

$$y^* = k_{1-\alpha}\, \tilde{u}(0) \tag{A.3}$$

The detection limit, $y^\#$, can be derived from the decision threshold utilizing the $1-\beta$ quantile of the standardized normal distribution $k_{1-\beta}$, as given in Formula (A.4):

$$y^\# = y^* + k_{1-\beta}\, \tilde{u}(y^\#) \tag{A.4}$$

Formula (A.4) is then solved for the unknown detection limit, $y^\#$.

A.2 Direct measurement of airborne activity

A.2.1 Model

The air under consideration is measured directly with a detector placed in a defined volume.

The air is sampled with a flow rate q through a sampling line and reaches the measuring volume V after a time t_1. The activity concentration C of the radionuclide with decay constant λ in V is measured by counting n_g pulses in the counting time t_2 with a detector of efficiency η and background count rate r_0.

The differential equation for the number of atoms N of the radionuclide in the measuring volume can thus be formulated in dependence of the radionuclide activity concentration C_0 at the sampling point, as given in Formula (A.5):

$$\frac{\partial N(t)}{\partial t} = \frac{C_0\, e^{-\lambda t_1}\, q}{\lambda} - \lambda\, N(t) - \frac{N(t)\, q}{V} \tag{A.5}$$

where the first term on the right side describes the incoming air, the second term the radioactive decay in the measuring volume and the right term the removal of air from the measuring volume. The solution of the differential equation is, as given in Formula (A.6):

$$N(t) = \frac{V\, C_0\, q}{\lambda\left(\lambda\, V + q\right)} e^{-\lambda t_1}\left(1 - e^{\frac{-\left(\lambda V + q\right)t}{V}}\right) \tag{A.6}$$

The measuring signal is obtained by counting the decaying atoms in the time interval t_2 yielding, as given in Formula (A.7):

$$n_g = \int_0^{t_2}\left(\eta\,\lambda\, N(t) + r_0\right)dt = \frac{C_0\, q\,\eta\, V\left(\left(\lambda V + q\right)t_2 - V\left(1 - e^{\frac{t_2\left(\lambda V + q\right)}{V}}\right)\right)}{e^{\lambda t_1}\left(\lambda V + q\right)^2} + r_0\, t_2 \tag{A.7}$$

Thus, C_0 can be determined as, as given in Formula (A.8):

$$C_0 = \frac{e^{\lambda t_1}\left(\lambda V + q\right)^2\left(n_g - r_0\, t_2\right)}{q\,\eta\, V\left(\left(\lambda V + q\right)t_2 - V\left(1 - e^{\frac{t_2\left(\lambda V + q\right)}{V}}\right)\right)} \tag{A.8}$$

A.2.2 Determination of uncertainty

The uncertainty is calculated in the following Formula (A.9), giving the uncertainty $u(C_0)$ of C_0 as function of its input quantities:

$$u^2(C_0) = \left(\frac{\partial C_0}{\partial n_g}\right)^2 u^2(n_g) + \left(\frac{\partial C_0}{\partial t_1}\right)^2 u^2(t_1) + \left(\frac{\partial C_0}{\partial t_2}\right)^2 u^2(t_2) + \left(\frac{\partial C_0}{\partial \lambda}\right)^2 u^2(\lambda) + \left(\frac{\partial C_0}{\partial \eta}\right)^2 u^2(\eta)$$
$$+ \left(\frac{\partial C_0}{\partial V}\right)^2 u^2(V) + \left(\frac{\partial C_0}{\partial q}\right)^2 u^2(q) + \left(\frac{\partial C_0}{\partial r_0}\right)^2 u^2(r_0) \tag{A.9}$$

A.2.3 Determination of decision threshold and detection limit

The number of gross counts n_g is the only input quantity in the model which is unknown for a given value of C_0 and is accordingly designated as x_1. Assuming a Poisson distribution of the counts, the uncertainty function $h(n_g)$ is given by the square root of n_g. The functional relation of n_g with C_0 is already defined in Formula (A.7), enabling the calculation of decision threshold and detection limit according to Formulae (A.3) and (A.4).

A.2.4 Numerical example

Table A.1 gives numerical values for the calculations according to Formulae (A.3) to (A.9).

Table A.1 — Numerical values for input parameters and resulting uncertainty, decision threshold and detection limit

Quantity	Value	Estimated uncertainty[a]	Unit
t_1	190	60	s
t_2	600	0,1	s
q	2,2E-3	2E-4	$m^3 \cdot s^{-1}$
V	6,3E-2	1E-3	m^3
η	2,6E-4	2E-5	$s^{-1} \cdot Bq^{-1}$
r_0	7,8E-3	4E-4	s^{-1}
λ	1,1E-4	1E-6	s^{-1}
n_g	80	9	
C_0	8 234	1 174	$Bq \cdot m^{-3}$
decision threshold[b], C_0^*	392		$Bq \cdot m^{-3}$
detection limit[b], $C_0^\#$	1 099		$Bq \cdot m^{-3}$

[a] Standard deviation of a normal distribution.

[b] If the probability α of the error of the first kind and the probability β of the error of the second kind are both considered equal to 5 % then $k_{1-\alpha}$, $k_{1-\beta} = 1{,}645$.

If the probability $1-\gamma$ for the confidence interval is considered equal to 0,95 then $\gamma = 0{,}05$ and $k_{1-\gamma/2} = 1{,}96$.

A.3 Measuring activity on a filter during sampling

A.3.1 Model

This example considers the measurement of activity on a filter while it is being collected on that filter.

The air is sampled with a flow rate q through a sampling line and reaches the filter after a time t_1. The activity concentration C of the radionuclide with decay constant λ is measured by counting n_g pulses of the activity deposited on the filter in the counting time t_2 with a detector of efficiency η and background count rate r_0.

The differential equation for the number of atoms N of the radionuclide on the filter can thus be formulated in dependence of the radionuclide activity concentration C_0 at the sampling point, as given in Formula (A.10):

$$\frac{\partial N(t)}{\partial t} = \frac{C_0\, e^{-\lambda t_1}\, q}{\lambda} - \lambda\, N(t) \tag{A.10}$$

where the first term on the right side describes the deposition on the filter and the second term the radioactive decay of the activity on the filter. Assuming N_0 atoms of the radionuclide already on the filter at the start of sampling, the solution of the differential equation is, as given in Formula (A.11):

$$N(t) = \frac{C_0\, q\, e^{-\lambda t_1}}{\lambda^2}\left(1 - e^{-\lambda t}\right) + N_0\, e^{-\lambda t} \tag{A.11}$$

The measuring signal is obtained by counting the decaying atoms in the time interval t_2 yielding, as given in Formula (A.12):

$$n_g = \int_0^{t_2} \left(\eta\, \lambda\, N(t) + r_0\right) dt = \eta\, N_0 \left(1 - e^{-\lambda t_2}\right) + \frac{\eta\, C_0\, e^{-\lambda t_1}\, q}{\lambda^2}\left(\lambda t_2 + e^{-\lambda t_2} - 1\right) + r_0\, t_2 \tag{A.12}$$

Thus, C_0 can be determined as given in Formula (A.13)

$$C_0 = \frac{\lambda^2\, e^{\lambda t_1}\left(n_g - \eta\, N_0\left(1 - e^{-\lambda t_2}\right) - r_0\, t_2\right)}{q\,\eta\left(\lambda t_2 + e^{-\lambda t_2} - 1\right)} \tag{A.13}$$

A.3.2 Determination of uncertainty

The uncertainty is calculated in the following Formula (A.14), giving the uncertainty $u(C_0)$ of C_0 as function of its input quantities:

$$u^2(C_0) = \left(\frac{\partial C_0}{\partial n_g}\right)^2 u^2(n_g) + \left(\frac{\partial C_0}{\partial t_1}\right)^2 u^2(t_1) + \left(\frac{\partial C_0}{\partial t_2}\right)^2 u^2(t_2) + \left(\frac{\partial C_0}{\partial \lambda}\right)^2 u^2(\lambda) + \left(\frac{\partial C_0}{\partial \eta}\right)^2 u^2(\eta)$$
$$+ \left(\frac{\partial C_0}{\partial N_0}\right)^2 u^2(N_0) + \left(\frac{\partial C_0}{\partial q}\right)^2 u^2(q) + \left(\frac{\partial C_0}{\partial r_0}\right)^2 u^2(r_0) \tag{A.14}$$

A.3.3 Determination of decision threshold and detection limit

The number of gross counts n_g is the only input quantity in the model which is unknown for a given value of C_0 and is accordingly designated as x_1. Assuming a Poisson distribution of the counts, the uncertainty function $h(n_g)$ is given by the square root of n_g. The functional relation of n_g with C_0 is already defined in Formula (A.12), enabling the calculation of decision threshold and detection limit according to Formulae (A.3) and (A.4).

A.3.4 Numerical example

Table A.2 gives numerical values for the calculations according to Formulae (A.3), (A.4), (A.13) and (A.14).

Table A.2 — Numerical values for input parameters and resulting uncertainty, decision threshold and detection limit

Quantity	Value	Estimated uncertainty[a]	Unit
t_1	100	10	s
t_2	600	0,1	s
q	3,3E-4	3E-5	$m^3 \cdot s^{-1}$
N_0	0	5E4	
η	1,3E-2	1E-3	$s^{-1} \cdot Bq^{-1}$
r_0	0,05	1E-3	s^{-1}
λ	1,0E-6	1E-9	s^{-1}
n_g	30	5	
C_0	0	7	$Bq \cdot m^{-3}$
decision threshold[b], C_0^*	12		$Bq \cdot m^{-3}$
detection limit[b], $C_0^\#$	28		$Bq \cdot m^{-3}$

[a] Standard deviation of a normal distribution.

[b] If the probability α of the error of the first kind and the probability β of the error of the second kind are both considered equal to 5 % then $k_{1-\alpha}$, $k_{1-\beta}$ = 1,645.

If the probability $1-\gamma$ for the confidence interval is considered equal to 0,95 then γ = 0,05 and $k_{1-\gamma/2}$ = 1,96.

A.4 Measuring activity on a filter after sampling

A.4.1 Model

This example considers the measurement of activity on a filter after it has been removed from the sampling system.

The air is sampled with a flow rate q through a sampling line and reaches the filter after a time t_1. The activity concentration C of the radionuclide with decay constant λ is sampled at the filter location in the time interval t_2, then the filter is removed. The activity on the filter is measured after a delay t_3 by counting n_g pulses in the time interval $t_4 - t_3$ with a detector of efficiency η and background count rate r_0.

The differential equation for the number of atoms N of the radionuclide on the filter during sampling is identical to Formula (A.10) and can be formulated in dependence of the radionuclide activity concentration C_0 at the sampling point, as given in Formula (A.15):

$$\frac{\partial N(t)}{\partial t} = \frac{C_0\, e^{-\lambda t_1} q}{\lambda} - \lambda\, N(t) \tag{A.15}$$

where the first term on the right side describes the deposition on the filter and the second term the radioactive decay of the activity on the filter. Assuming an activity free filter at the start of sampling, the solution of the differential equation is, as given in Formula (A.16):

$$N(t) = \frac{C_0\, q\, e^{-\lambda t_1}}{\lambda^2}\left(1 - e^{-\lambda t}\right) \tag{A.16}$$

At the end of sampling, $N(t_2)$ atoms of the radionuclide are present on the filter. The activity decreases hereafter by radioactive decay. As a new differential equation governs the process, a different clock is started at t_2. The measuring signal is obtained by counting the decaying atoms in the time interval [t_3, t_4] yielding, as given in Formula (A.17):

$$\begin{aligned} n_g &= \int_{t_3}^{t_4} \left(\eta\, \lambda\, N(t) + r_0\right) dt = \int_{t_3}^{t_4} \left(\eta\, \lambda \frac{C_0\, q\, e^{-\lambda t_1}}{\lambda^2}\left(1 - e^{-\lambda t_2}\right) e^{-\lambda t} + r_0\right) dt \\ &= \frac{\eta\, C_0\, q\, e^{-\lambda t_1}}{\lambda^2}\left(1 - e^{-\lambda t_2}\right)\left(e^{-\lambda t_3} - e^{-\lambda t_4}\right) + r_0\left(t_4 - t_3\right) \end{aligned} \tag{A.17}$$

Thus, C_0 can be determined as, as given in Formula (A.18):

$$C_0 = \frac{\lambda^2\, e^{\lambda t_1}\left(n_g - r_0\left(t_4 - t_3\right)\right)}{q\,\eta\left(1 - e^{-\lambda t_2}\right)\left(e^{-\lambda t_3} - e^{-\lambda t_4}\right)} \tag{A.18}$$

A.4.2 Determination of uncertainty

The uncertainty is calculated in the following Formula (A.19), giving the uncertainty $u(C_0)$ of C_0 as function of its input quantities:

$$\begin{aligned} u^2(C_0) = &\left(\frac{\partial C_0}{\partial n_g}\right)^2 u^2(n_g) + \left(\frac{\partial C_0}{\partial t_1}\right)^2 u^2(t_1) + \left(\frac{\partial C_0}{\partial t_2}\right)^2 u^2(t_2) + \left(\frac{\partial C_0}{\partial t_3}\right)^2 u^2(t_3) + \left(\frac{\partial C_0}{\partial t_4}\right)^2 u^2(t_4) \\ &+ \left(\frac{\partial C_0}{\partial \lambda}\right)^2 u^2(\lambda) + \left(\frac{\partial C_0}{\partial \eta}\right)^2 u^2(\eta) + \left(\frac{\partial C_0}{\partial q}\right)^2 u^2(q) + \left(\frac{\partial C_0}{\partial r_0}\right)^2 u^2(r_0) \end{aligned} \tag{A.19}$$

A.4.3 Determination of decision threshold and detection limit

The number of gross counts n_g is the only input quantity in the model which is unknown for a given value of C_0 and is accordingly designated as x_1. Assuming a Poisson distribution of the counts, the uncertainty function $h(n_g)$ is given by the square root of n_g. The functional relation of n_g with C_0 is already defined in Formula (A.17), enabling the calculation of decision threshold and detection limit according to Formulae (A.3) and (A.4).

A.4.4 Numerical example

Table A.3 gives numerical values for the calculations according to Formulae (A.3), (A.4), (A.18) and (A.19).

Table A.3 — Numerical values for input parameters and resulting uncertainty, decision threshold and detection limit

Quantity	Value	Estimated uncertainty[a]	Unit
t_1	10	1	s
t_2	604 800	0,5	s
t_3	17 526	20	s
t_4	24 726	20	s
q	3,3E-4	3E-5	$m^3 \cdot s^{-1}$
η	1,8E-2	1E-3	$s^{-1} \cdot Bq^{-1}$
r_0	7,8E-3	5E-4	s^{-1}
λ	1,4E-7	1E-10	s^{-1}
n_g	2 223	47	
C_0	87	9	$mBq \cdot m^{-3}$
decision threshold[b], C_0^*	0,6		$mBq \cdot m^{-3}$
detection limit[b], $C_0^\#$	1,2		$mBq \cdot m^{-3}$

[a] Standard deviation of a normal distribution.

[b] If the probability α of the error of the first kind and the probability β of the error of the second kind are both considered equal to 5 % then $k_{1-\alpha}$, $k_{1-\beta}$ = 1,645.

If the probability $1-\gamma$ for the confidence interval is considered equal to 0,95 then γ = 0,05 and $k_{1-\gamma/2}$ = 1,96.