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Monitoring radioactive gases in effluents from facilities producing positron emitting radionuclides and radiopharmaceuticals

Surveillance des gaz radioactifs dans les effluents des installations produisant des radionucléides et des produits radiopharmaceutiques émetteurs de positrons

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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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This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document focuses on monitoring the activity concentrations of radioactive gases. They allow the calculation of activity releases in the gaseous effluent discharge from facilities producing positron emitting radionuclides and radiopharmaceuticals. Such facilities produce short-lived radionuclides used for medical purposes or research. They include accelerators, radiopharmacies, hospitals and universities. This document provides performance-based criteria for the use of air monitoring equipment including probes, transport lines, sample monitoring instruments, and gas flow measuring methods. It also provides information covering monitoring program objectives, quality assurance, developing air monitoring control action levels, system optimisation, and system performance verification.

The goal of achieving an accurate measurement of radioactive gases, which are well mixed in the airstream, is accomplished either by direct (in-line) measurement within the exhaust stream or by extraction (bypass) from the exhaust stream for measurement remote from the duct. This document sets forth performance criteria and recommendations to assist in obtaining valid measurements.

Monitoring radioactive gases in effluents from facilities producing positron emitting radionuclides and radiopharmaceuticals

1 Scope

This document focuses on monitoring the activity concentrations of radioactive gases. They allow the calculation of the activity releases, in the gaseous effluent discharge from facilities producing positron emitting radionuclides and radiopharmaceuticals. Such facilities produce short-lived radionuclides used for medical purposes or research and can release gases typically including, but not limited to ^{18}F, ^{11}C, ^{15}O and ^{13}N. These facilities include accelerators, radiopharmacies, hospitals and universities. This document provides performance-based criteria for the design and use of air monitoring equipment including probes, transport lines, sample monitoring instruments, and gas flow measuring methods. This document also provides information on monitoring program objectives, quality assurance, development of air monitoring control action levels, system optimisation and system performance verification.

The goal of achieving an unbiased measurement is accomplished either by direct (in-line) measurement on the exhaust stream or with samples extracted from the exhaust stream (bypass), provided that the radioactive gases are well mixed in the airstream. This document sets forth performance criteria and recommendations to assist in obtaining valid measurements.

NOTE 1 The criteria and recommendations of this document are aimed at monitoring which is conducted for regulatory compliance and system control. If existing air monitoring systems were not designed according to the performance criteria and recommendations of this document, an evaluation of the performance of the system is advised. If deficiencies are discovered based on a performance evaluation, a determination of the need for a system retrofit is to be made and corrective actions adopted where practicable.

NOTE 2 The criteria and recommendations of this document apply under both normal and off-normal operating conditions, provided that these conditions do not include production of aerosols or vapours. If the normal and/or off-normal conditions produce aerosols and vapours, then the aerosol collection principles of ISO 2889 also apply.

2 Normative references

There are no normative references in this document.

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:

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

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

3.1
abatement equipment
apparatus used to reduce contaminant concentration in the airflow exhausted through a stack or duct

[SOURCE: ISO 2889:2010, 3.1]

3.2
accident (conditions)
any unintended event, including operating errors, equipment failures and other mishaps, the consequences or potential consequences of which are not negligible from the point of view of protection and safety

3.3
accuracy
closeness of agreement between a measured quantity and the true quantity of the measurand

[SOURCE: ISO 2889:2010, 3.4]

3.4
action level
threshold concentration of an effluent contaminant at which it is necessary to perform an appropriate action

[SOURCE: ISO 2889:2010, 3.5]

3.5
aerosol
dispersion of solid or liquid particles in air or other gas

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

[SOURCE: ISO 2889:2010, 3.8]

3.6
analyser
device that provides for near real-time data on radiological characteristics of the gas (air) flow in a sampling system or duct

Note 1 to entry: Usually, an analyser evaluates the concentration of radionuclides in a sampled air stream; however, some analysers are mounted directly within or just outside a stack or duct.

[SOURCE: ISO 2889:2010, 3.12]

3.7
bend
gradual change in direction of a *sample* (3.38) transport line

[SOURCE: ISO 2889:2010, 3.14]

3.8
bulk stream
air flow in a stack or duct, as opposed to the *sample* (3.38) flow rate

[SOURCE: ISO 2889:2010, 3.15]

3.9
bypass system
system whereby a *sample* (3.38) is withdrawn from the effluent stream and analysed at a location that is remote from the region where the extraction takes place

3.10
calibration
operation that, under specified conditions, in a first step establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

3.11
coefficient of variation
C_V
quantity that is the ratio of the standard deviation of a variable to the mean value of that variable

Note 1 to entry: It is usually expressed as a percentage.

[SOURCE: ISO 2889:2010, 3.18]

3.12
continuous air monitor
CAM
near real-time sampler and associated detector that provide data on radionuclides (e.g. concentration of alpha-emitting aerosol particles) in a sample stream

Note 1 to entry: A CAM is used for monitoring and detecting radioactive gases.

[SOURCE: ISO 2889:2010, 3.21]

3.13
continuous monitoring
continuous near real-time measurements of one or more sampling characteristics

[SOURCE: ISO 2889:2010, 3.22]

3.14
coverage interval
interval containing the set of true quantity values of a measurand with a stated probability, based on the information available

[SOURCE: ISO 11929-1:2019, 3.4]

3.15
cyclotron
particle accelerator that is commonly used in nuclear medicine to produce positron emitting radionuclides

Note 1 to entry: Charged particles (e.g. protons or deuterons) are accelerated along a spiral path from the centre outward to an appropriate target.

3.16
decision threshold
value of the estimator of the measurand, which, when exceeded by the result of an actual measurement using a given measurement procedure of a measurand quantifying a physical effect, is used to decide that the physical effect is present

Note 1 to entry: The decision threshold is defined such that in cases where the measurement result exceeds the decision threshold, the probability of a wrong decision, namely that the true value of the measurand is not zero if in fact it is zero, is less or equal to a chosen probability α.

Note 2 to entry: If the result is below the decision threshold, it is decided to conclude that the result cannot be attributed to the physical effect; nevertheless, it cannot be concluded that it is absent.

[SOURCE: ISO 11929-1:2019, 3.12]

3.17
detection limit
smallest true value of the measurand which ensures a specified probability of being detectable by the measurement procedure

Note 1 to entry: With the decision threshold, the detection limit is the smallest true value of the measurand for which the probability of wrongly deciding that the true value of the measurand is zero is equal to a specified value, β, when, in fact, the true value of the measurand is not zero. The probability of being detectable is consequently $(1 - \beta)$.

[SOURCE: ISO 11929-1:2019, 3.13]

3.18
effluent
waste stream flowing away from a process, plant, or facility to the environment

Note 1 to entry: In this document, the focus is on effluent air that is discharged to the atmosphere through stacks, vents and ducts.

[SOURCE: ISO 2889:2010, 3.29]

3.19
emission
contaminants that are discharged into the environment

[SOURCE: ISO 2889:2010, 3.30]

3.20
emit
discharge contaminants into the environment

[SOURCE: ISO 2889:2010, 3.31]

3.21
flow rate
rate at which a mass or volume of gas (air) crosses an imaginary cross-sectional area in either a sampling system tube or a stack or duct

Note 1 to entry: The rate at which the volume crosses the imaginary area is called the volumetric flow rate; and the rate at which the mass crosses the imaginary area is called either the mass flow rate or the volumetric flow rate at standard conditions.

[SOURCE: ISO 2889:2010, 3.33]

3.22
hydraulic diameter
type of equivalent duct diameter for ducts that do not have a round cross section

Note 1 to entry: Generally, it is four times the cross-sectional area divided by the perimeter.

[SOURCE: ISO 2889:2010, 3.38]

3.23
in-line system
system where the detector assembly is adjacent to, or immersed in, the *effluent* (3.18)

3.24
limits of the coverage interval
values which define a coverage interval

Note 1 to entry: It is characterized in this document by a specified probability $(1 - \gamma)$, e.g., 95 %, and $(1 - \gamma)$ represents the probability for the coverage interval of the measurand.

Note 2 to entry: The definition of a coverage interval is ambiguous without further stipulations. In ISO 11929-1 two alternatives, namely the probabilistically symmetric and the shortest coverage interval, are used. In this document only the probabilistically symmetric is used.

Note 3 to entry: The probabilistically symmetric coverage interval is the coverage interval for a quantity such that the probability that the quantity is less than the smallest value in the interval is equal to the probability that the quantity is greater than the largest value in the interval

[SOURCE: ISO 11929-1:2019, 3.16]

3.25
mixing element
device placed in a stack or duct that is used to augment mixing of both contaminant mass and fluid

[SOURCE: ISO 2889:2010, 3.47]

3.26
monitoring
continual measurement of a quantity (e.g. activity concentration) of the airborne radioactive constituent or the gross content of radioactive material continuously, at a frequency that permits an evaluation of the value of that quantity in near real-time, or at intervals that comply with regulatory requirements

[SOURCE: ISO 2889:2010, 3.48]

3.27
normal conditions
limits (or range) of use or operation under which a program or activity is able to meet its objectives and without significant changes that would impair this ability

3.28
nozzle
device used to extract a *sample* (3.38) from a stream of the gaseous *effluent* (3.18) and to transfer the sample to a transport line or a collector

[SOURCE: ISO 2889:2010, 3.49]

3.29
off-normal conditions
conditions that are unplanned and which present a gap with normal conditions

Note 1 to entry: Examples are accidents and equipment failure.

[SOURCE: ISO 2889:2010, 3.54]

3.30
positron emission tomography
PET
imaging technique that uses radioactive substances to reveal the operating function and metabolism of tissues and organs and allows the observation of malignant tissues

Note 1 to entry: The technic involves injection of a radioactive drug with the radionuclide being a positron emitter. Upon annihilation of the positron, two 511 keV photons are produced at 180° angle. These photons are used in the scanner to determine the point of annihilation and to develop an image.

3.31
probe
sometimes used colloquially to refer to the equipment inserted into a stack or duct for measurement of volumetric flow or amount of activity present

3.32
profile
distribution of gas velocity over the cross-sectional area of the stack or duct

[SOURCE: ISO 2889:2010, 3.62]

3.33
quality assurance
planned and systematic actions necessary to provide confidence that a system or component performs satisfactorily in service and that the results are both correct and traceable

[SOURCE: ISO 2889:2010, 3.63]

3.34
radionuclide
unstable isotope of an element that decays or converts spontaneously into another isotope or different energy state, emitting radiation

[SOURCE: ISO 2889:2010, 3.64]

3.35
reference method
apparatus and instructions for providing results against which other approaches may be compared

Note 1 to entry: Application of a reference method is assumed to define correct results.

[SOURCE: ISO 2889:2010, 3.66]

3.36
representative sample
sample (3.38) with the same quality and characteristics for the material of interest as that of its source at the time of sampling

[SOURCE: ISO 2889:2010, 3.67]

3.37
response time
time required after a step variation in the measured quantity for the output signal variation to reach a given percentage for the first time, usually 90 %, of its final value

[SOURCE: IEC 60761-1:2002, 3.15]

3.38
sample
portion of an air stream of interest, or one or more separated constituents from a portion of an air stream

[SOURCE: ISO 2889:2010, 3.68]

3.39
sample extraction location
location of extraction of a *sample* (3.38) from the *bulk stream* (3.8), also known as sampling location

[SOURCE: ISO 2889:2010, 3.69, modified — definition was reworded.]

3.40
sampling
process of removing a *sample* (3.38) from the *bulk stream* (3.8) and transporting it to a monitor

[SOURCE: ISO 2889:2010, 3.72]

3.41
sampling plane
cross sectional area where the *sample* (3.38) is extracted from the airflow

[SOURCE: ISO 2889:2010, 3.75]

3.42
sampling system
system consisting of an inlet, a transport line, a flow monitoring system and a monitor

[SOURCE: ISO 2889:2010, 3.76]

3.43
sensitivity
change in indication of a mechanical, nuclear, optical or electronic instrument as affected by changes in the variable quantity being sensed by the instrument

Note 1 to entry: The slope of a calibration curve of an instrument, where a calibration curve shows output values of an instrument as a function of input values.

[SOURCE: ISO 2889:2010, 3.78]

3.44
standard conditions
temperature of 25 °C and pressure of 101 325 Pa

Note 1 to entry: Used to convert air densities to a common basis. Other temperature and pressure conditions may be used and should be applied consistently.

[SOURCE: ISO 2889:2010, 3.82]

3.45
transport line
part of a *bypass system* (3.9) between the outlet plane of the *nozzle* (3.28) and the inlet plane of a detector chamber or a vessel

[SOURCE: ISO 2889:2010, 3.84]

3.46
turbulent flow
flow regime characterized by bulk mixing of fluid properties

Note 1 to entry: For example, in a tube, the flow is turbulent if the Reynolds number is greater than about 3 000 and laminar if the Reynolds number is below about 2 200. There is little mixing in the laminar flow regime.

[SOURCE: ISO 2889:2010, 3.86]

3.47
uncertainty
non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

Note 1 to entry: An analysis of uncertainty is a procedure for estimating the overall impact of estimated uncertainties in independent variables on the accuracy or precision of a dependent variable.

[SOURCE: ISO 11929-1:2019, 3.10]

3.48
vapour
gaseous form of materials that are liquid or solids at room temperature, as distinguished from non-condensable gases

Note 1 to entry: Vapours are gases but carry the connotation of having been released or volatilised from liquids or solids.

[SOURCE: ISO 2889:2010, 3.89]

3.49
velocity profile
distribution of the velocity values at a given cross section in a stack or duct

[SOURCE: ISO 2889:2010, 3.90]

4 Symbols

Symbols that are used in formulae in this document are defined below:

A	Cross sectional area of the stack or duct, in m^2;
A_R	Activity released over a period Δt_R, in Bq per time;
A_R^*	Decision threshold of the activity released over a period Δt_R, in Bq per time;
$A_R^\#$	Detection limit of the activity released over a period Δt_R, in Bq per time;
$A_R^\triangleleft$	Lower limit of the coverage interval of the released activity over a period Δt_R for a given probability $(1 - \gamma)$, in Bq per time;
$A_R^\triangleright$	Upper limit of the coverage interval of the released activity over a period Δt_R for a given probability $(1 - \gamma)$, in Bq per time;
C_{pt}	Velocity-averaging correction factor for determining the flow rate in a stack or duct with a Pitot tube from a single point reading, dimensionless;
c^*	Decision threshold of the activity concentration, in $Bq \cdot m^{-3}$;
$c^\#$	Detection limit of the activity concentration, in $Bq \cdot m^{-3}$;
$c_{g,i}$	Gross primary measurement of the activity concentration at a time $t_0 + i \cdot \Delta t$, in $Bq \cdot m^{-3}$;
$\overline{c_{g\,m,im}}$	Calculated gross average activity concentration over a time interval $m \cdot \Delta t$ at time $t_0 + i \cdot m \cdot \Delta t$, in $Bq \cdot m^{-3}$;
$\overline{\overline{c}}_{g_{\Delta t_R}}$	Calculated gross average activity concentration over a time interval $\Delta t_R = n \cdot m \cdot \Delta t$, in $Bq\ m^{-3}$;
c_i	Activity concentration at a time $t_0 + i \cdot \Delta t$, in $Bq \cdot m^{-3}$;
$\overline{c_0}$	Average value of n_{c_0} number of $c_{0,j}$, in $Bq \cdot m^{-3}$;
$\overline{\overline{c}}_0$	Average value of $n_{\overline{c_0}}$ number of $\overline{c}_{0\,m,jm}$, in $Bq \cdot m^{-3}$;
$c_{0,j}$	Gross primary measurement of the activity concentration which represents a background situation at a time $t_0 + j \cdot \Delta t$, in $Bq \cdot m^{-3}$;

$\overline{c_{0\,m,jm}}$ Calculated gross average activity concentration over a time interval $m \cdot \Delta t$, which represents a background situation at time $t_0 + j \cdot m \cdot \Delta t$, in Bq·m^{-3};

d_t Tube diameter, in m;

F_k Fluctuation constant, dimensionless;

NOTE 1 This is set at 1 for a meter whose readings do not fluctuate. If there are fluctuations, the parameter is set taken to be the average number of scales unit above and below the mean indicated value.

$I_{g,cd,i}$ Gross current of the compensating detector at time $t_0 + i \cdot \Delta t$, in A;

$I_{g,i}$ Gross current of the measuring detector at time $t_0 + i \cdot \Delta t$, in A;

I_{min} Minimum amount of current registered by the measuring detector with $I_{min} = \frac{Q_{min}}{t_C}$, in A;

$I_{0,cd,j}$ Background current of the compensating detector at a time $t_0 + j \cdot \Delta t$, in A;

$I_{0,j}$ Background current of the measuring detector at a time $t_0 + j \cdot \Delta t$, in A;

k Quantile of a standard normal distribution, if $k_{1-\alpha} = k_{1-\beta}$, dimensionless;

NOTE 2 The value of k is 1,96 for a coverage interval of 95 %.

$k_{1-\alpha}$ Quantile of a standard normal distribution for a probability $(1 - \alpha)$, dimensionless;

$k_{1-\beta}$ Quantile of a standard normal distribution for a probability $(1 - \beta)$, dimensionless;

$k_{1-\frac{\gamma}{2}}$ Quantile of a standard normal distribution for a probability $\left(1-\frac{\gamma}{2}\right)$, dimensionless;

m Number of times Δt to calculate $\overline{c_{g\,m,im}}$ and $\overline{c_{0\,m,jm}}$ from archived data;

n Number of times $m \cdot \Delta t$ to calculate $\overline{c}_{g_{\Delta t_R}}$ from archived data;

n_{c_0} Number of measurements of $c_{0,j}$ to determine $\overline{c_0}$, dimensionless;

$n_{\overline{c_0}}$ Number of measurements of $\overline{c_{0\,m,jm}}$ to determine $\overline{\overline{c_0}}$, dimensionless;

P Penetration, dimensionless;

NOTE 3 Penetration is the ratio between the activity concentration at the sampling system exit, including transport lines, and the activity concentration in the ventilation duct.

p Pressure, in Pa;

p_{std} Standard pressure, equal to 101 325 Pa;

Q_{min} Minimum amount of electric charge that induces a pulse registered by the measuring detector, in C;

Q_T Total volume of gas (air) sampled, in m^3;

q Volumetric flow rate, in m^3·s^{-1};

q_D Volumetric flow rate in the ventilation duct, in m^3·s^{-1};

q_{std} Volumetric flow rate at standard conditions, in m^3·s^{-1};

R_a Individual gas constant for air, equal to 287 J·kg^{-1}·K^{-1};

Re Reynolds number, dimensionless;

$r_{g,cd,i}$ Gross count rate of the compensating detector at time $t_0 + i \cdot \Delta t$, in s^{-1};

$r_{g,i}$ Gross count rate of the measuring detector at time $t_0 + i \cdot \Delta t$, in s^{-1};

r_0 Background noise measured by the probe, in s^{-1};

$r_{0,cd,j}$ Background count rate of the compensating detector at time $t_0 + j \cdot \Delta t$, in s^{-1};

$r_{0,j}$ Background count rate of the measuring detector at time $t_0 + j \cdot \Delta t$, in s^{-1};

s_{c_0} Standard deviation of n_{c_0} values of $c_{0,j}$, in Bq·m^{-3};

$s_{\overline{c_0}}$ Standard deviation of $n_{\overline{c_0}}$ values of $\overline{c_{0\,m,jm}}$, in Bq·m^{-3};

T Temperature, in K;

T_{std} Standard temperature, equal to 298 K;

t Time, in s;

t_0 Initial time, in s;

t_C Counting time of the measuring detector, s;

t_s Time period over which sampling is performed, in s;

t_{st} Time stamp, (e.g. in YYYY-MM-DD hh:mm:ss);

t_{st0} Initial time stamp, (e.g. in YYYY-MM-DD hh:mm:ss);

U_m Spatial mean velocity of gas (air) in a flow tube, in m·s^{-1};

$u(x)$ Standard uncertainty associated with x, units of x;

NOTE 4 As an approximation, the uncertainty associated with the calibration instrument may be used.

$u_{(rel)}$ Relative standard uncertainty in reading the flow meter scale, dimensionless;

NOTE 5 This can be estimated by dividing the value of the smallest scale division by the indicated flow rate and multiplying by a factor of 0,5.

v Velocity, in m·s^{-1};

v_{std} Velocity at standard conditions, in m·s^{-1};

w Calibration factor, in Bq·m^{-3}·s^{-1} in count rate mode or in Bq·m^{-3}·A^{-1} in current mode;

Δt Duration of acquisition, in s;

Δt_R Duration of the time interval over which the released activity is calculated, in s;

μ Dynamic viscosity of air, in Pa·s;

ρ Density, in kg·m^{-3};

ρ_{std} Density of air at standard conditions, equal to 1,184 kg·m^{-3}.

5 Factors impacting the design of the monitoring system

This document focuses on the mechanics of monitoring radioactive gases in facility emissions. Some of the factors that impact the design of the system are:

— purpose of monitoring;

— the type of conditions (normal or off-normal conditions);

— characteristics of the air stream and radioactive gases;

— desired measurement sensitivity;

— compensation for background radiation;

— concentrations or total emissions which trigger remedial action (action levels).

Informative guidance concerning these factors is given in Annexes A, B and C. The user may need to consider additional factors specific to a particular site, process, or environmental condition(s). The impact of these factors on the monitoring system should be assessed.

6 Types of monitoring systems

There are two general types of positron gas effluent monitoring systems in use; the first type, a bypass system, uses a sampling system to extract a representative sample from the duct and analyses the radioactive content in a detector away from the duct. The second type of system, an in-line system, uses detectors (or possibly probes) placed around or within the duct to directly analyse the activity concentrations of radioactive substances in the airstream.

In both types the response of the detectors to other sources of radiation shall be considered and minimized in order to accurately measure the activity concentration of radioactive gas in the airstream. For example, this minimization can be achieved by the use of shielding, or a compensation detector when a consequent ambient dose is involved and by the use of a compensation algorithm when radon gas influences the detector response.

General monitoring system requirements are provided in Table 1, which summarizes an adequate monitoring system as discussed in Clauses 7 to 9.

Table 1 — Summary of guidance for an adequate monitoring system

Adequate monitoring system criteria	Subclause
Detection system can meet the specified minimum detectable concentration.	7.2
The highest possible normal release condition can be measured.	7.2
Discharges following an incident can be quantified.	7.2
The detection range is compatible with those that may be present in the system.	7.2
Detector responses to outside sources of radiation, other than background, are considered and minimized.	7.3.1
Background effects are minimized.	7.3.1
System components are readily accessible for maintenance and calibration.	7.3.2, 8.2
Effects from environmental conditions are considered.	7.3.3, 9.3
Flow measurements are known and measured continuously.	7.4
Samples are extracted from a well-mixed location within the bulk stream.	8.2
Systems are designed in a way so that condensation of vapour is avoided.	8.3
Sample nozzles are maintained and checked periodically.	8.4
Leak checks are performed periodically.	8.5
Controls to prevent measurement readings from adjacent systems are in place.	9.2

7 General monitoring system requirements

7.1 General

Subclauses 7.2 to 7.4 provide guidance and requirements for the design of a monitoring system.

7.2 Detection range

The importance of the detection range (both low [~MBq] and high [~TBq]) originates from the requirement to be able to determine the activity concentration to a sufficient degree of certainty and with sufficient time resolution to subsequently allow the calculation and reporting of the total discharged activity.

In the low range, the detection system shall be adequate to meet a specified minimum detectable concentration (at the 95 % confidence level) with a reasonable counting time, taking into account the background at the location of installation, as discussed below.

The upper range of the system shall be capable of measuring up to the highest possible normal release condition, often requiring dead time correction in the detection system. Additional information on dead time is provided in A.4.4.2.

Discharges following an incident shall be quantified and taken into account in the total discharges of the facility (except in the event of a breakdown of ventilation).

In order to best evaluate discharges, it shall at first be ensured that the measuring range of the detection system is compatible with the levels of concentration that may be present. If a detection system saturates (overloads), it makes the evaluation of activity emitted (or released) during the incident impossible.

Isotope characteristics, including half-life, decay mode and energy of produced and parasitic radionuclides (e.g. ^{18}F, ^{11}C, ^{15}O, ^{13}N, ^{41}Ar) are provided in Annex A. Advantages and disadvantages of various types of detectors and associated operating principles are provided in Table A.3.

7.3 Detector location

7.3.1 Background

In both types of monitoring systems (in-line or bypass), the response of the detectors to other sources of radiation shall be considered and minimized in order to accurately measure the activity concentration of radioactive gas in the airstream. Therefore, any detector should be located such that the effects from background sources are minimised. Background sources could include:

— accelerators (cyclotron, linac);

— filter banks;

— target transfer lines;

— hot cells/fume cupboards;

— other effluent ducts;

— source stores;

— equipment;

— patient waiting areas;

— radon gas;

— radioactive waste storage.

The sensitive part of the monitoring system should be kept sufficiently far, sufficiently well shielded, or sufficiently well compensated from the above-mentioned sources of background interference to meet the system sensitivity requirements.

7.3.2 Ease of accessibility for maintenance

The detector, flow measurement system and associated equipment should be readily accessible for routine maintenance and calibration.

7.3.3 Environmental conditions

The effect of temperature, humidity, vibration, weather conditions and electromagnetic interference should be considered when deciding on system location and appropriate compensation applied where necessary.

7.4 Emission stream flow measurement

The flow measurements in the stack, duct, or vent are critical to both in-line and bypass monitoring systems because they directly impact the accuracy of the calculated emissions. The airflow of emission streams shall be continuously measured unless justified otherwise. Errors are introduced into the calculation of emissions if the emission and sample volumetric units are not based on the same gas density. Local regulations may specify the gas density conditions to use for reporting emissions and whether the activity concentration or the emitted activity is reported. In calculating the amount of effluent air, the user should either adjust for the density differences in the air or use measurements based on a standard density. For bypass systems, a correction factor to the ratio of sample to stack activity concentration may need to be applied, if the difference between the bulk and sample air densities exceeds 10 %.

The flow measurement device should be selected according to the duct shape. The device should be located in accordance with the manufacturer's recommendation. A shrouded probe is preferred when the main-stream velocity does not vary considerably over the cross-sectional area of the duct, while multi-point sampling may be necessary in situations where the main-stream velocity varies considerably over the cross-section. ISO 2889 provides additional details on the use of shrouded and multi-point nozzles for sampling. If there is no manufacturer recommendation, then the location should be a minimum of 10 hydraulic diameters downstream of a flow disturbance and a minimum of five hydraulic diameters upstream of the end of the stack or the next flow disturbance. The flow measurement device should be subject to minimum annual accuracy audits according to the recommendation of the manufacturer. Such checks can include, but are not limited to, comparison with manual measurements, routine calibration, or independent calibrated instrument verification.

8 Requirements specific to bypass systems

8.1 General

As noted in the definitions, a bypass system extracts a sample from the effluent stream and analyses it at a location remote from the region where the extraction takes place. The following should be considered when choosing to use a bypass system.

8.2 Sample extraction locations

A representative sample is best extracted from a location where the radioactive materials of interest are well mixed within the bulk stream. To establish a well-mixed location, the coefficient of variation, C_V, of the tracer gas concentration should be within ±20 % across at least the centre two thirds of the cross sectional area of the stack or duct. In addition, at none of the measurement points should the concentration of the tracer gas differ by more than 30 % from the mean value for all of the points (see Annex D). The designer should plan the ventilation system such as to provide a favourable location

where the sample may be extracted from a well-mixed stream. In this case, the sampling probe may contain a single inlet.

Following a careful evaluation, one or more of the following steps should be taken in circumstances where these criteria cannot be satisfied with respect to effluent systems designed and constructed prior to the publication of this document:

a) Select another location for the sampling probe;

b) Install features that promote mixing;

c) Perform in-situ tests at representative flow conditions, covering the expected range of flow rates, to demonstrate that there is no risk of under-sampling (ISO 2889); or

d) Apply appropriate correction factors.

The stack or duct geometry and the airflow within should be fully understood. The sample extraction location should not be so close to the stack exit that wind effects can significantly influence the velocity profile at the sampling location. Typically, in well mixed airflow, successful sample probe locations are in the range of 5 to 10 hydraulic diameters downstream of a flow disturbance and 3 or more hydraulic diameters upstream of a flow disturbance. There are instances where greater distances are needed. Particular attention should be given to the geometry surrounding the flow entry. Any addition of a small secondary air stream close to the wall of the stack or duct should be avoided. Bends, fans, duct junctions, and similar disturbances promote mixing, but may also produce distortions in velocity and contaminant concentration profile and angularity in the airflow in the first 2 to 3 hydraulic diameters downstream. Therefore, sampling locations too close to such disturbances should be avoided even at the cost of longer sampling lines.

In addition to the physics of obtaining a representative sample, there are other considerations in locating the probe and associated equipment. The location should be readily and safely accessible, it should not present a problem for sampler servicing and maintenance activities and it should be able to accommodate analysis or collection equipment that does not compromise the quality of the sample.

The sample should be extracted from a location where the gas constituents are well mixed in the bulk airflow. If side streams are present in the ventilation system, a uniform gas concentration should be validated. Features that enhance mixing do so by creating large scale turbulence. One or more 90° turns, converging airstreams, and mixing elements such as mixing boxes, perimeter rings, and commercial static mixers all enhance mixing. On the other hand, turning vanes and flow straighteners have the opposite effect. A summary of mixers and their test data can be found in Maiello and Hoover[40], NCRP Report 169[47] and ISO 2889:2010, Annex F[27]. The generic tests provide results of features that promote mixing. Previously tested configurations can be used and scaled. Many of these are summarised in Maiello and Hoover[40].

If particulate contaminants are present, then ISO 2889 also applies. Under conditions with particulates present, a well-mixed location also includes criteria for the flow angle, velocity and tracer concentration profile (see Annex D).

8.3 Condensation

Sample transport lines, collectors, and analysers should be designed to avoid condensation of vapour. Condensation takes place when the temperature of air in the sample transport line is less than the saturation temperature of the vapour of interest. Thermally insulating and in some cases heating, the sample transport line may be needed to prevent condensation. Experimental or numerical analyses may be performed to demonstrate the effectiveness of any design provisions that are intended to minimize or preclude the formation of condensation in sample transport systems.

8.4 Maintenance

The sampling nozzle should be checked periodically. The maintenance interval shall consider the presence of aerosol filters protecting the devices from aerosol deposits. Examples of proposed

maintenance intervals are three years for HEPA-filtered systems and one year for unfiltered systems for the presence of deposits of foreign materials and other factors that could degrade the performance of the monitoring system. If there are background aerosol particles that can produce deposits, a cleaning schedule should be established that does not allow over 5 % of the inlet area of a nozzle to be occluded. Where cleaning is not possible or desired the sampling nozzle should be replaced.

In case significant contamination is found on the sampling nozzle, consideration should also be given to cleaning or replacement of the sampling lines.

8.5 Leak checks

A leak in a bypass monitoring system would reduce the observed concentration relative to the true concentration. Leak checks shall be performed as a final step, prior to commissioning of the system following either installation or after carrying out significant maintenance or system modifications. The inspection or test methodology should be practical for the installation and shall be documented. Leak checks shall be performed periodically in line with operational experience. A leak rate of less than 5 % is considered acceptable; however, leakage should be minimized and justifiable with regards to the monitoring objectives.

9 Requirements specific to in-line systems

9.1 General

An in-line system is one where the detector assembly is adjacent to or immersed in the effluent. The items to be considered when designing this type of system are described below.

9.2 Location of the probe or detector

The probe or detector shall be located where the effluent stream in the duct or stack is well mixed. To establish a well-mixed location, the C_V of the tracer gas concentration should be within ±20 % across at least the centre two thirds of the cross sectional area of the stack or duct. In addition, at none of the measurement point should the concentration of the tracer gas differ by more than 30 % from the mean value for all of the points (see Annex D). A mixing element may be useful to establish appropriate mixing at the probe or detector location.

If two (or more) stacks or ducts are located close together, there is the potential for gaseous effluent in one to cause an elevated background reading in an adjacent system. This can lead to high background in the monitoring system, causing inaccuracies in the discharge results. This should be avoided by using the same techniques discussed in 7.3.1 to reduce the possibility of triggering a spurious alarm or control event. Additional information on factors that impact the monitoring is provided in Annex A.

9.3 Environmental conditions

Where detectors are placed on stacks that run external to buildings, or with no temperature control, temperatures can reach extreme highs and lows. This can cause damage to the monitoring system and inaccuracies in readings due to elevated backgrounds or changes in sensitivity. When using temperature sensitive detectors, the effect of temperature variations should be considered when selecting the detector type and location. Appropriate compensation should be applied where necessary.

10 Evaluation and upgrading of existing systems

If an existing air monitoring system was not designed according to the performance requirements and recommendations of this document, an evaluation of the performance of the system including the location and environment of the probe, detectors and other equipment is recommended. If deficiencies are discovered, the evaluation should determine if retrofit is recommended and possible. Arriving at a suitable solution requires optimisation among competing factors. Evaluation of existing systems

should be undertaken using proven techniques, for example the UK Environment Agency, Best Practice Techniques (BAT) guidance for environmental radiological monitoring[38].

Furthermore, there are instances when a performance verification of a monitoring system is advisable. These situations include:

— when the effluent stream being sampled is potentially not well mixed;

— when an existing system has just come under additional regulatory requirements;

— when the potential to emit contaminants has changed significantly;

— when an existing system has had significant changes, for example:

  — change of the stream flow beyond the original design limits;

  — addition of a new effluent stream in a manner that destroys the well mixed state at the nozzle (bypass system) or detector (in-line system) locations;

  — addition of new background sources close to the measurement system that may influence the measurement results; or

  — change of system operating parameters outside of the design range;

— when the supporting documentation is deficient.

11 Quality assurance and quality control

The purposes of a Quality Assurance (QA) program are to provide assurance to facility management teams, regulatory agencies and the public of the validity of air monitoring data and to identify any deficiencies in the monitoring system equipment and procedures so that corrective action can be taken. The tools used to accomplish these objectives include documentation, maintenance, inspection, and calibration. Information relevant for air sampling systems relating to these criteria is presented in Annex C.

Every facility that conducts radioactive air emissions monitoring shall have a QA Program that addresses the quality related activities of the air monitoring program. A specific QA Plan should be developed and implemented. As a minimum, it should address the quality aspects of the sampling and monitoring of effluent radioactive substances in the following areas:

a) organisation:

  — organisational responsibilities;

  — administrative controls;

  — reporting and notification system;

  — documentation;

  — personnel qualifications and training;

b) design of the monitoring system:

  — source terms;

  — selection of extraction or detector placement locations;

  — selection of monitoring devices;

c) operational procedures:

  — system operation procedures;

— calibration procedures;

— correction factors;

— data analysis and reporting;

— maintenance and check procedures;

— disposition of non-conformant items and conditions;

— corrective action program.

Annex A
(informative)

Factors impacting the monitoring system design

A.1 Introduction

The main radionuclide produced for radiopharmaceuticals and research is fluorine-18 (^{18}F), followed by carbon-11 (^{11}C), nitrogen-13 (^{13}N), and oxygen-15 (^{15}O). Their characteristics are recalled in Table A.1. The related activity values discharged annually in the form of gaseous effluents can vary between a few MBq and potentially be as high as a few TBq, depending on the facility.

Table A.1 — Characteristics of radionuclides produced

Radionuclide	Half-life min	β^+- energy (max) MeV	γ - energy keV
$^{18}_{F}$	110	0,634	511
$^{11}_{C}$	20	0,960	511
^{13}N	10	1,200	511
$^{15}_{O}$	2	1,732	511

These radionuclides emit β^+ particles, whose annihilation results in the emission of two 511 keV photons (γ) in opposite directions (see Figure A.1). It is this property that is used in nuclear medicine to perform PET (positron emission tomography) imaging.

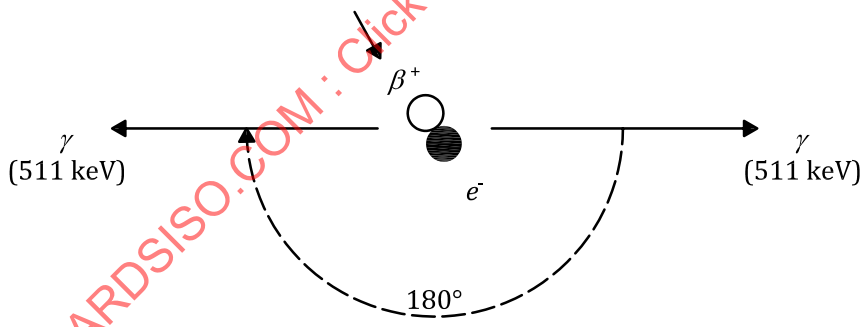


Figure A.1 — Annihilation of positrons

In addition to these radionuclides others "parasite" radionuclides, are produced when the target is irradiated by the cyclotron (by activating the air inside the shielded enclosure of the cyclotron, the contents of the target or certain materials). The main parasitic radionuclides most frequently identified by the operators are argon-41 (^{41}Ar) produced by activation of the air inside the shielded enclosure of the cyclotron and nitrogen-13 (^{13}N) produced by activation of the content of the target and released in the synthesis cell at the end of irradiation. Their characteristics are recalled in the Table A.2.

Table A.2 — Characteristics of "parasite" radionuclides

Radionuclide	Half-life min	β^+- energy (max) MeV	γ - energy keV	β^- - energy (max) MeV
$^{13}_{N}$	10	1,20	511	/
^{41}Ar	109	/	1 290	1,19

The first point to be solved is what type of detector is most suitable for measurements of gaseous effluents releases. The most common types of detectors are:

— ionisation chamber;

— proportional counter;

— Geiger-Müller (GM);

— scintillator detector;

— semiconductor detector.

They all generate either electrical current or electrical pulses which are then amplified, detected and counted by electronics.

Table A.3 shows the operating principle of each type of these detectors. The advantages and disadvantages (+/-) have different importance depending on the environment/working conditions.

Table A.3 — Type of detectors and operating principle

Type of detector	Operating principle	Advantages/Disadvantages
Ionization chamber (60 V to 300 V)	Ionization of a gas	— no saturation of the probe (+) — a very good detection limit and a minimum detectable activity (+) — a low detection yield (-) — good discrimination from background (+)
Proportional counter (1 kV to 4 kV)	Ionization of a gas	— a very good detection limit and a minimum detectable activity (+) — an average saturation of probe, detection limit (-) — sufficient discrimination from background depending on the gas used (-) — a low detection yield (-)
Geiger-Müller (GM)	Ionization of a gas	— a good detection limit and a minimum detectable activity (+) — a low detection yield (-) — sufficient discrimination from background (-) — a strong saturation of the probe (-)
Scintillator	Emission of fluorescence or phosphorescence photons	— a high detection yield (+) — a good detection limit and a minimum detectable activity (+) — an average saturation of the probe (-) — good discrimination from background (+)
Semi-conductor	Ionization of a solid	— a high detection yield (+) — a low minimum energy required to ionize the detector medium (+) — sufficient discrimination from background (-)

A.2 Monitoring purpose

There are many possible objectives for the gaseous effluent discharge monitoring program. The rationale in choosing a specific objective and approach should be well documented. Some possible air monitoring objectives are:

— meeting regulatory requirements;

— assessing the need for a permanent monitoring program;

— measuring the release of radioactive materials to the environment through monitoring;

— helping to ensure that people in the surrounding environment are not exposed to levels of radioactive releases exceeding established limits;

— helping to assess the possible consequences of the normal and off-normal releases of a facility and guiding the selection of appropriate corrective action. This can include the integration of radioactive contamination released to the environment over various time periods.

The design of a technically defensible monitoring program (in-line or bypass system) requires a clear understanding of these objectives.

Many objectives are related to worker or environmental protection and regulatory compliance. Failure to understand the monitoring objectives can lead to inappropriate or ineffective system design and implementation. The design and implementation of a monitoring plan in a particular facility involve matters of engineering judgement in which conflicting demands arise from consideration of obtaining the most accurate measure, ensuring worker and public safety, physical plant constraints, and other operational and safety factors that have to be balanced.

The various objectives for a monitoring system are not (or need not be) mutually exclusive in most effluents monitoring circumstances. A monitoring system designed to meet one objective may meet other objectives as well. Likewise, there can be a number of approaches taken to achieve a given objective.

A.3 Considerations for different monitoring conditions

A.3.1 General

Particular attention should be given to the potential interactions between the operating conditions of the facility, air contaminants, control and ventilation components, and environmental parameters that may impact the monitoring system.

The measurement system (including the probe, its positioning, the data analysis method) shall perform well in both normal and off-normal operation. It is therefore important to distinguish its role in both cases.

A.3.2 Monitoring under a normal condition

In general, normal operating conditions are those expected under normal operations and are associated with a certain expectable variability. These are usually the average operating conditions and their variance as defined in statistical terms. The normal operating conditions may have a large range of temperature and airflow rates depending on the processes in operation. The effluent monitoring system should be chosen to accommodate these conditions. The effluent discharge system may also operate with an effluent control (clean-up) system in place that reduces particle and gaseous emissions to an acceptable level. The effluent monitoring system should be designed to reliably function under these operating conditions.

The normal operation of a facility is defined as the operating situation for which the installation was designed, without taking into account potential situations of incident or accident. This involves avoiding any material or human failure that could lead to the unforeseen release of effluents into the environment.

Under normal conditions, the measurement system shall provide a good estimate of the discharged activity, in particular to ensure that it is within the permitted limits. The main requirement is therefore the ability of the system to measure a given level of discharge, characterized by the activity concentration of the effluents and by the airflow rate. In addition, the system shall provide real-time information useful for monitoring the current operation.

A.3.3 Monitoring under an off-normal condition

The main incidents that may lead to unusual releases in this type of installation are generally related to a rupture of a containment system. This loss of containment can cause leaks in the target, in the transfer system to the synthesis enclosures or in the synthesis equipment inside the enclosures.

In off-normal conditions (where discharges are higher than in normal operating conditions) the measuring device shall give early warning so that the appropriate measures can be implemented.

A.3.4 Action levels

An action level is an effluent contaminant concentration threshold at which an appropriate action is to be performed. The response (action) depends on the circumstances and can result in an alarm, the "diversion" of effluents by a longer transfer line or, for additional processing, it can also result in intervention at the process level (to remove incidental cause), work stoppage, or evacuation. Some actions have possible consequences (cost, damage to equipment, endangering people).

Careful consideration should be given to the setting of an action level for a monitoring system that considers all such consequences. The goal is to anticipate and avoid that:

— an operator's reaction to an alarm causes a stop and/or evacuation and unnecessary costs,

— an off-normal discharge is not investigated, which may be of consequence to facility operations and workers' safety.

Action levels related significant releases and potential risks to members of the public are generally established by the responsible authority following discussions with the operator. They correspond to Regulatory Alarm Levels. Releases above these Regulatory Alarm Levels require reporting to the responsible authority. In addition, the Licensee may set his own lower alarm levels (also called Administrative Levels or Limits). These may be set to avoid reaching the less stringent Regulatory Action Levels or they may be set for other technical or economic reasons. Administrative Levels are usually set somewhat above normal release levels. Alarms triggered by increasing release rates can be used in the operation of the surveillance system to warn operators that conditions of effluents releases have changed and that immediate action may be necessary to avoid exceeding an administrative level or action level.

The process of selection of an appropriate action level requires consideration of

— the physical and physicochemical characteristics of the contaminant,

— the characteristics of the sampling system, which is required to obtain a sample of the contaminant for analysis and counting (e.g. the nozzle design characteristics, the transport line design, or sampling location), and

— the type, intensity, and variability of interference with the measurement.

Each of these three factors can contribute uncertainty to the contaminant concentration estimate, and, therefore, affect the level of confidence that can be assigned to the decision. The selection of an appropriate action level is separate from and precedes considerations related to the required sensitivity of the monitoring systems.

In any case, in the context of discussing action levels it is useful to make distinctions among the following:

a) Control monitoring (i.e. continuous monitoring with alarm): monitoring for purposes of providing adequate warning so that an operator can take action to protect workers and the public from excessive exposure.

b) System availability: tracking the availability and response of monitoring systems so that the facility operators are alerted, if equipment failure takes a system off-line or seriously degrades its performance.

c) Performance monitoring: regulatory compliance monitoring that yields data of such quality and type that the facility operator can identify and quantify the most significant radionuclides present in the effluent, and demonstrate regulatory compliance by responding to all requirements of the monitoring system.

In order to resolve an off-normal situation it is essential to be able to identify it correctly via measurements of the radioactive releases.

To do this, an action level shall be defined beforehand. It corresponds to the value of the radioactive gaseous activity concentration from which the discharge can no longer be attributed to a normal operation of the system. The action level should be at least the "minimum detectable concentration" corresponding to an acceptable level of false alarm rate as defined in Annex B. Appropriate action shall then be taken to determine the cause of the discharge and to limit it. Generally, for these types of facilities, the action level is defined:

— from the airflow rate and the annual activity allowed for discharges, which can be expressed as activity per week, or per day, or per hour;

— from the application of the practical concentration limits in air, specific to each radionuclide. This method is based on the hypothesis of inhalation by a person, of concentration at the outlet and compliance with the annual limit of incorporation fixed as prescribed.

Indeed, the action level should not be defined according to the impact on the population. The action level should, however, make it possible to distinguish a normal from an off-normal situation related to gaseous discharges in order to alert the operators and allow them to remedy them.

It is therefore recommended to define the action level from the activity discharged during a conventional production taking into account a sufficiently large margin to avoid unwanted alarms. The value of this action level should be justified. Because each individual installation is different, the impact of the discharge and therefore action levels may also differ. Action levels should be re-evaluated in the event of a modification of the plant or of production parameters (synthesis of a new molecule, new production line).

A.4 Considerations for different monitoring systems

A.4.1 In-line monitoring system

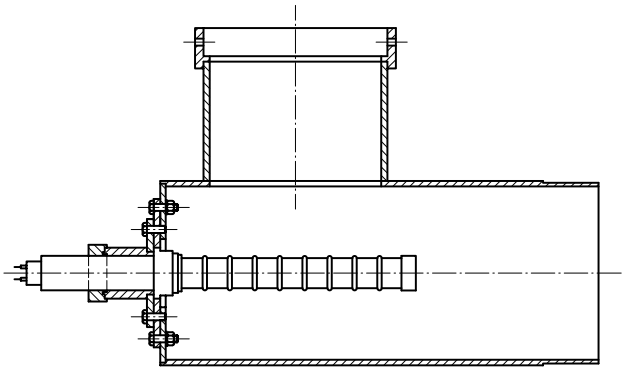
For in-line systems, the probe is positioned either directly within the duct (see Figure A.2) or on the duct (see Figure A.3). The geometry of the probe depends on its positioning: it is generally cylindrical when placed in the duct and rectangular when placed on it.

In the absence of special constraints, the installation of a live measurement with a probe positioned on or in the exhaust duct has the advantages that the flow is not disturbed as long as the probe is well positioned, that the response time is fast and that no additional parameters have to be taken into account.

When the probe is positioned in the exhaust duct it is essential to ensure that it is correctly positioned to avoid measuring in a dead or inhomogeneous zone.

The positioning of the probe on the duct makes it possible to overcome the disadvantages mentioned above, while allowing direct detection of all the discharges.

The advantages (+) and disadvantages (−) of the in-line monitoring system are presented in Figure A.2 (for a probe located in the exhaust duct) and Figure A.3 (for a probe located on the exhaust duct). These figures thus show the advantages and disadvantages of the positioning of the probe in the exhaust duct and on the exhaust duct.



(+) a strong reactivity

(+) a direct measurement

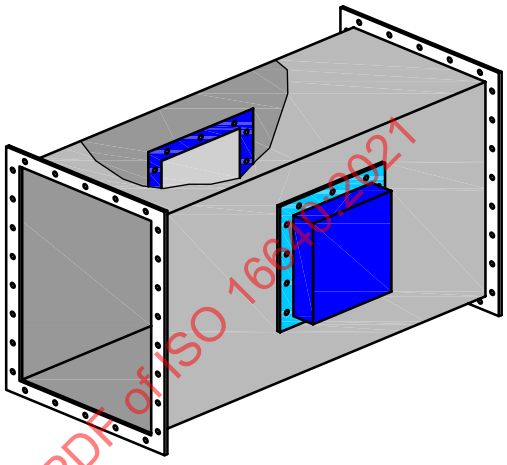
(−) low volume and detection surface

(−) an inhomogeneity of the flow

(−) difficulty of shielding from external sources

⇒ an alert probe is recommended

Figure A.2 — Probe positioned in the duct



(+) a direct measurement

(+) positioning of several probes

(+) large detection surface

(−) detection volume limited by the duct

(−) difficulty of shielding from external sources

⇒ may be reliable compromise

Figure A.3 — Probe positioned on the duct

A.4.2 Bypass monitoring system

For bypass systems, the probe is positioned in a container at a distance from the exhaust duct (see Figure A.4). The measurement is carried out on a sample taken from the main duct.

The capacity of the container can vary from less than one litre to several litres in volume. Several surface or cylindrical sensors can be positioned. Their detection surface is generally lower than that of the probes installed on the duct. For identical probes, the performance of this device is equivalent to that of the probes positioned on the extraction duct. However, this system is more effective when:

— the background radiation is too high near the measuring point in the duct;

— the probe cannot be installed in the exhaust duct under satisfactory conditions (congestion of the ventilation room, weight constraints, inadequate dimensions of the duct).

This solution, however, encounters some difficulties which need to be considered:

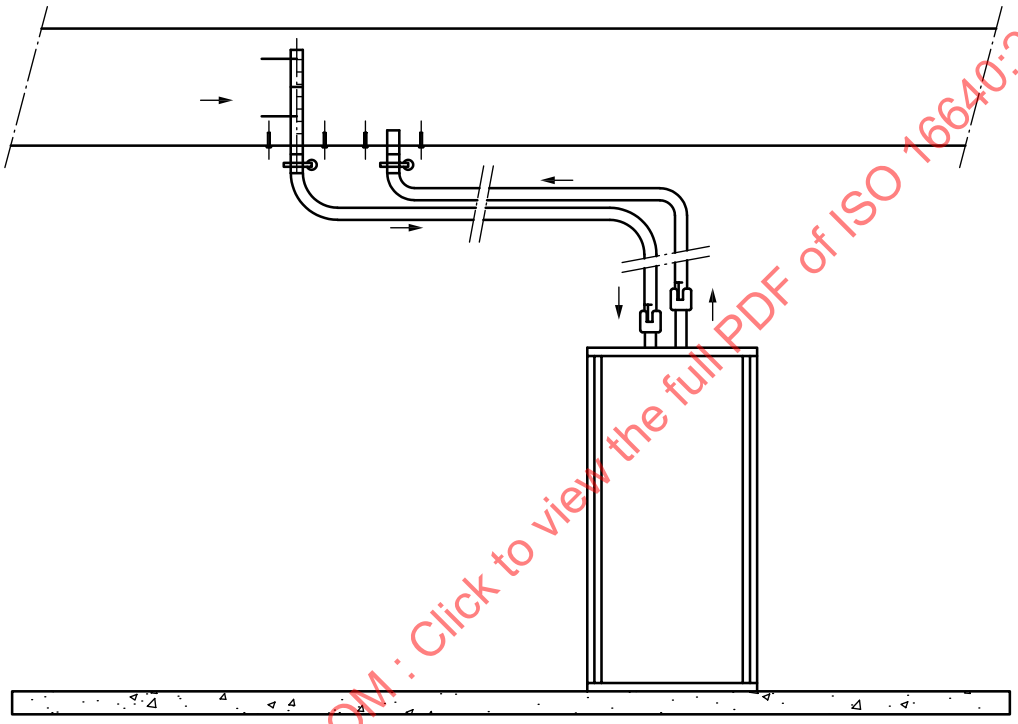
— the problem of representativeness of the sample taken;

— the installation of additional equipment (sampling pump, pipes, container), which shall be checked periodically and maintained.

The bypass measuring system may be acceptable under many conditions. The representativeness of the sample (sampling point, sampling rate) and the response time of the measurement shall be taken into consideration.

If the kinetics of this type of system is calculated to be slow, the bypass measuring system could be combined with a direct measurement (warning probe), thus allowing the rapid detection of any abnormal discharges. Otherwise, an alternative to achieve faster system kinetics may also be the use of a ring-line system with significantly higher sample flow and secondary extraction at the position of the detector. Other multi-point sampling probes or higher sample rate designs are described in ISO 2889.

The advantages (+) and disadvantages (−) of the bypass monitoring system are presented in Figure A.4.



(+) can be located in a lower background location

(+) easier to shield a smaller volume

(+) a low saturation of the probe

(−) representativeness of the sample

(−) additional material (pump, nozzle, pipe,) requires more maintenance

(−) delay of measurement: size and location of the container from the sampling point

→ Direction of flow.

⇒ Alternative solution if space is lacking.

Figure A.4 — Schematic of a bypass system

A.4.3 Environment of the monitoring system

A.4.3.1 General

In general, the environment of the monitoring system such as background noise, temperature, humidity, vibration, location, and accessibility should be carefully considered before being put in place. Such consideration of the environment serves to limit the impacts of these parameters. Compensatory provisions are implemented if necessary.

Whatever the technology used, the installation conditions influence the performance of the probes, in particular by promoting the homogeneity of the measured flux and by limiting the presence of parasitic radiation.

A.4.3.2 Radiation background noise

One of the main constraints in these installations is the proximity of the measuring systems to the production sites (cyclotron) and the handling and circulation of radioactive products (filtration systems, transfer lines, synthesis cells, other exhaust duct effluents, storage facilities for radioactive sources and waste). Under these conditions, the choice of a technology or a method to limit the impact of changes in the radiological environment on the measurement is necessary.

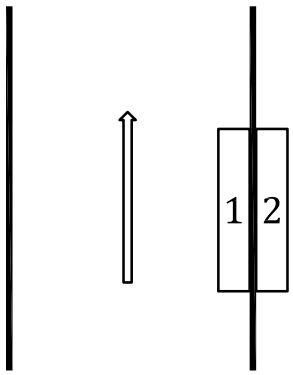
In order to avoid the risk of interference from background (interfering radiation) with the measurement results, the probe shall be positioned in such a way as to minimize this radiation. Ideally, the probe is positioned remotely from outside sources of radiation.

If this is not possible due to the configuration of the facility or to lack of space, the following solutions should be considered.

For a compensation measurement (see Figure A.5):

— Shielding of the probe or using a container for bypass systems.

— Implementing a second probe (guard probe: probe 2 in Figure A.5) contiguous to the main probe of measurement (probe 1 in Figure A.5). The guard probe is dedicated to the measurement of gamma parasitic radiation which can thus be subtracted in real time from the measurement results of the main probe. This method is called measurement by compensation. The probes used shall be identical and positioned back to back at the extraction duct (see Figure A.5).



Key

1 main probe: measurement of gamma and β^+ radiation

2 guard probe: measurement of γ radiation

NOTE When both probes are placed on the duct, it is necessary to ensure that the window between the main measurement probe and the duct is thin enough to allow the measurement of β^+ radiation.

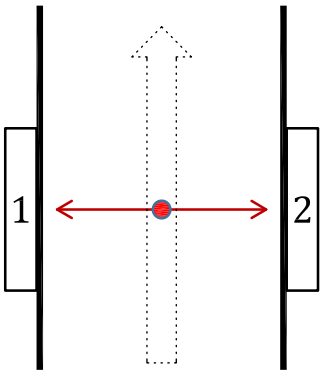
Figure A.5 — Guard probe – Compensation measurement

For a coincidence measurement (see Figure A.6):

— Choosing a bypass system to place the measurement away from any external radiation sources.

— Choosing a type of probe that is able to preferentially detect the β^+ radiation (depending on the filling gas) in order to minimize the proportion of gamma "parasite" radiation in the measurement result.

— Choosing a system allowing the detection of the γ radiation emitted in coincidence. With regards to PET, the probes are positioned in a way to detect the photons emitted simultaneously during the annihilation of β^+ (see Figure A.6).



Key

1 probe 1

2 probe 2

NOTE The probes are positioned on either side of the duct in order to detect the photons emitted simultaneously during the annihilation of β^+.

Figure A.6 — System of detection of the γ-radiation emitted in coincidence

It is important to note that the size of the probe influences its sensitivity to background radiation. This sensitivity increases with the volume and the detection surface of the probe. For proportional counters, for example, the sensitivity to background radiation increases with the number of anode wires. Therefore, it is necessary to find a balance between the detection efficiency of the probe and its sensitivity to background radiation.

A.4.3.3 Temperature

With respect to the ambient temperature, large variations are liable to disturb the measurement, in particular for probes of the NaI scintillator type probes. It is the luminous efficiency of the scintillator that increases with the increasing temperature (in particular in the case of the NaI scintillator). The temperature variations can also have an effect on the electronics associated with the probe.

It is recommended to use a measuring device that is insensitive to variations in ambient temperature and to preferably place it inside the facility in a temperature-controlled room. However, in justified cases, the sensitive device (e.g. scintillator) can still be used. Indeed, it is strongly advised not to locate the measuring device in places with large temperature variations (e.g. directly on the roof of a facility). An appropriate corrective factor shall be applied to the measurement result of this type of device.

In case of bypass monitoring, the expected temperature range at potential sampling points under normal operating conditions and credible accident conditions should be determined. Often the effluent temperature is very stable. However, any temperature changes could be important to the collection of a sample under off-normal conditions.

A.4.3.4 Effluent composition

The composition of a stack effluent under both normal and off-normal conditions should be taken into account when designing a ventilation system for that kind of installation. Radioactive and non-radioactive constituent characteristics should be identified. An important example is the presence of strong acid or caustic fumes that could cause rapid deterioration of a duct, a nozzle (see Figure A.7) or sample transport line unless suitable compensation is provided by the selection of appropriate materials for the construction of these elements. Moisture content of the effluent can also be a significant factor to be considered when designing these elements due to possible interactions with contaminant components and condensation.

Furthermore, the physicochemical forms of discharged radionuclides should be identified. While certain molecules discharged into the exhaust system as a gas may exit as a gas, others may become aerosols as they pass through the ventilation duct system and be discharged as particulates.

A.4.3.5 Accessibility and positioning

The equipment (probe, airflow sensor, sampling nozzle) shall be easily accessible, especially for maintenance and service operations.

With regards to the in-line system, the following is noted. In order to position the probe (e.g., shrouded probe or rake) in the exhaust duct, it shall be ensured that the airflow is well mixed in this place so that a homogeneous volume activity can be obtained. The positioning of the probe in a bent portion of the exhaust duct (see Figure A.2) is to be avoided due to the size of the probe compared to the size of the duct and due to the disturbance of the resulting airflow. However, this type of positioning, if carried out closer to the production or synthesis sites, has the advantage of allowing the rapid detection of an unusual discharge and of triggering an alert (warning probe).

For the bypass systems, the main difficulties concern the positioning of the sampling point and the representativeness of the sample taken (the volume activity of the sample shall be similar to that of the main stream). It is recommended to position the sampling point in a well-mixed flow in order to use a sampling probe with a single nozzle (see Figure A.7). In order to position the sampling point at a location where the flow is homogeneous, the sampling point should not be too close to the outlet of the duct, to limit the turbulence generated by the wind, nor too close to an element that can disturb the airflow (fan, elbow, duct junction).

Figure A.7 — Sampling probe with one nozzle

If the sampling is carried out in a non-homogeneous flow (for an existing facility), it is obviously advisable to choose another sampling point. If this is not possible, it is recommended to implement upstream devices to promote mixing or to perform an on-site test to demonstrate that the sample taken does not result in an underestimation of activity.

A.4.3.6 Effluent airflow rate

Knowledge of effluent flow is important in any final calculation of a release rate or total release. Knowing the range of gaseous effluent velocities is also important for the design and control of the monitoring (and sampling) system. Flow rates may change as processes increase or decrease, fans are turned on or off for maintenance, doors are opened or closed, and heating/cooling systems are operated.

It is important to address the issue of airflow measurement because it directly impacts the estimate of the activity discharged by the facility. Since the probe's measurement results are expressed in $Bq \cdot m^{-3}$, the estimate of the total activity discharged is in fact based on the value of the volumetric airflow rate, expressed in $m^3 \cdot h^{-1}$, considered during the measurement.

The airflow to be measured is that in the ventilation at the level of the discharge measurement system. The sensor, located on the terminal part of the ventilation system, is often close to the stack of the installation and therefore exposed to daily and annual variations in temperature and pressure. Therefore, it is recommended to set up an airflow measurement system that is insensitive to such variations. For this type of measurements there are a multitude of technologies that can be used in a well-mixed locations (thermal anemometer, Pitot tube). Devices such as airflow sensor, electronic module and user interface are associated with the probe (e.g. shrouded probe or rake) and can also influence the measurement results.

This document specifies the suitable positioning of the sensor to ensure that the airflow is measured from a homogeneous flow (see 8.2). If the positioning of the sensor cannot meet these criteria due to constraints related to the design of the ventilation system, it should be ensured that the airflow at the measuring point is homogeneous throughout the section of the duct.

For a bypass system, the density of the air in the duct shall be identical to the density of the air in the measurement chamber so that the results obtained from the measurement chamber can be extrapolated to the discharges of the duct. This document specifies the need for a correction factor if there is a deviation of more than 10 % between the two densities (see 7.4).

A.4.4 Characteristics of the monitoring system

A.4.4.1 Detection system capability

The detection limit of the probe indicates the smallest true quantity value of the measurand that can still be detected with the applied measurement procedure. This allows for a decision on whether or not the measurement procedure satisfies the requirements and is therefore suitable for the intended measurement purpose. Below this value, events are not counted. It is therefore important that the detection limit be as low as possible.

The decision threshold allows to decide whether the physical effect quantified by the measurand is present or not. It is the value from which a value measured by the monitoring system is counted in the cumulative releases of the facility. The decision threshold should not be set too low to limit the number of false positives. It shall also not be too high to ensure that all releases from the facility are accounted for and thus minimize false negatives. It could be the value of the minimum detectable activity of the monitoring system. Usually the value of the decision threshold is a half the value of the detection limit.

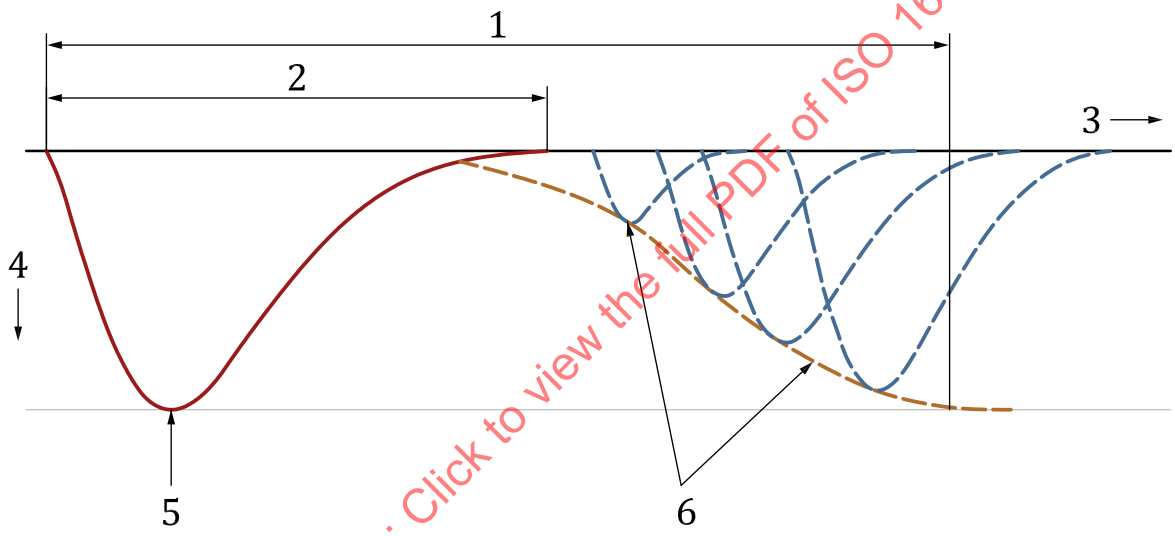
It can be noted that the decision threshold and the detection limit quantifying the metrological performance of the detection system depend on parameters such as the measurement time and the ambient radiological background in which the detector is immersed. In order to obtain a good metrological performance, the ambient radiological background shall be as low as possible and the measurement time shall be as long as possible while still providing a reasonable response time that allows the detection system to identify short-duration (e.g. puff, spike, or bolus) releases from the facility.

Generally, the manufacturer provides users with values of the detection limit associated with different values of measurement time for typical ambient radiological backgrounds. The operator can then make a preliminary evaluation of the measurement time to be set in order to be able to comply with the regulatory requirements related to released activities.

The notion of measurement time is important, because the longer it is, the more it is possible to measure low activity releases. The gaseous discharges are typically released in puffs (also called spikes or boluses) of about 10 min (during the transfer of the contents of the target and during certain phases of the synthesis, principally those in which the solution is heated). Therefore, the operator shall balance the detection limit values, requiring long averaging times, with those of measuring actual puff releases of short duration, requiring fast response. Also noteworthy is the fact that if the response time set up is longer than the puff release duration, the peak of the measured activity concentration can be underestimated even though the activity release over that period which is calculated by the integration of measured activity concentrations over that same period is correct.

A.4.4.2 Saturation of the probe

The count rate of the probe is limited by the dead time, which is related to the technology of the probe, the materials that compose it and to the associated electronics. It corresponds to the minimum (incompressible) duration before another event can be detected (see Figure A.8). A low dead time thus makes it possible to detect a large number of events.



Key

1 recovery time
2 dead time
3 time
4 output voltage
5 initial discharge (red line)
6 level of possible events after the initial discharge (orange and blue dashed lines)

Figure A.8 — Detection duration cycle of the γ-radiation emitted in coincidence

Beyond the maximum count of the probe, some of the events can no longer be detected. This is called saturation of the probe (e.g. a paralysable [GM tube] detector). Generally, the type of probe chosen shall be adapted to this constraint. For low count rates, both a paralysable and non-paralysable detector system give virtually the same result, but their behaviour is very different at higher count rates. The count loss in a paralysable model is predicted to be much higher than in non-paralysable model. At the extremely high count rates the paralysable detector, which in addition to saturating, gives results falsely lower than the value actually measured[61]. Therefore, it is recommended to adapt the geometry of the probe in order to limit the phenomenon of saturation in case of a high activity concentration. A second probe, shielded, should be placed near the main probe, to keep the count in case of saturation. The first probe is thus dedicated to the measurement of low and medium activity concentrations, while the second probe is dedicated to the measurement of larger activity concentrations.

A.4.4.3 Detector calibration factor

A.4.4.3.1 The probe-specific calibration factor

The probe-specific calibration factor is determined by the manufacturer. One method of doing this is to place the probe in a closed box with a known volume and activity of ^{18}F together with an air stirrer. The contents of the enclosure are suspended in the form of micro-droplets with a system of nebulization by compressed air. Some manufacturers have also conducted on-site experiments to confirm the values obtained by this method. The physicochemical characteristics of the calibration gas (^{18}F, ^{11}C, ^{13}N, or ^{15}O) should be known and may include its chemical form, wall losses and materials not nebulized.

Knowing its emissions characteristics, it is also possible to calculate by modelling and simulation the calibration factor for a given radionuclide.

The conversion factor takes into account the calibration factor and the other parameters of influence such as penetration and the detection volume inside the duct. The conversion factor directly impacts the measurement of released activity.

The calibration factor varies depending on the energy of the β^+ particle. For installations producing several radionuclides (^{18}F, ^{11}C, ^{13}N and ^{15}O), the value of the calibration factor is usually manually selected. In this case, the calibration factor should be known for the specific isotopes that are potentially present and the most pessimistic value (i.e. the calibration factor for the isotope that the detector is least sensitive to) used. This addresses the most critical calibration factor being selected for the type of detector utilized and its operating mode (e.g. scintillator in plateau mode, or a GM tube).

A.4.4.3.2 In situ correction factor

The in-situ correction factor integrates both the calibration factor of the probe determined by the manufacturer and another factor that is related to the geometry of the installation and the environment of the probe. Various parameters such as ambient temperature, background noise, diameter of the duct, homogeneity and velocity of the flow in the extraction duct influence the response of the probe. A difference can occur between the measurements made in static condition (closed box) and those carried out in a dynamic airflow (real conditions). It is therefore probable that for the same type of probe this factor varies from one installation to another.

Annex B
(informative)

Evaluating uncertainty of effluent measurement

B.1 Introduction

Real-time gaseous monitoring systems measure the activity concentration within a ventilation duct before discharge. The use of these systems is primarily driven by demonstrating compliance to regulations, activity concentration discharge limits, total activity discharges, and dose equivalent from discharges to a receptor with an acceptable accuracy. These systems generally include a time-stamped archiving of the raw signals measured by the detector (number of pulses, amount of electric charge) associated with a software interface allowing a retrospective restitution of a radiological event as well as the calculation of the average gross activity on a given time interval by the sum of these raw signals over this time interval.

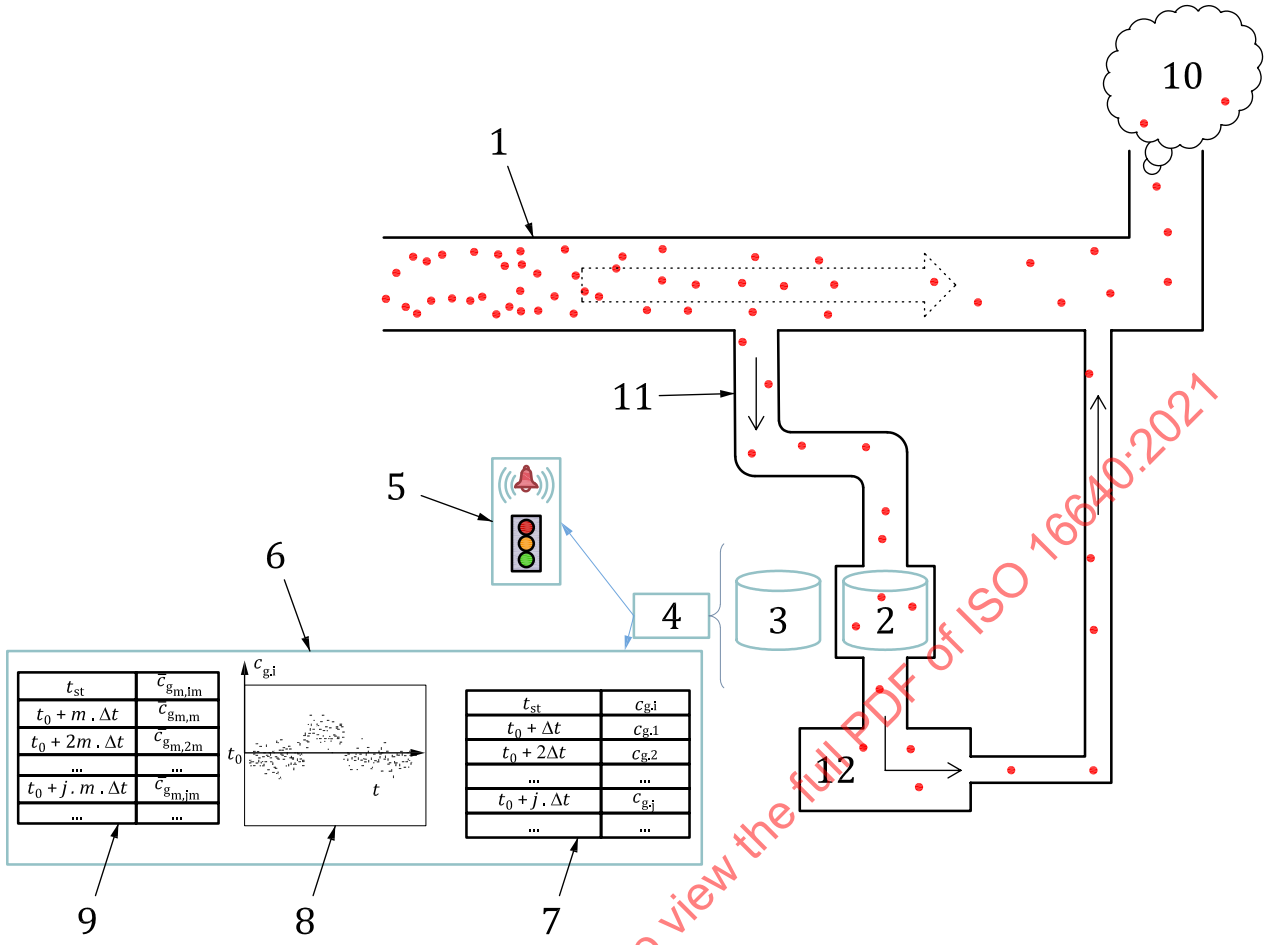
The objective of this annex is to describe how to determine, a posteriori, from the restitution of archived data, the released activity over a given period and the associated characteristic limits (decision threshold, detection limit, limits of the coverage interval).

Additional information on evaluating the performance of continuous air monitors may be found in ISO/TR 22930-2. It provides details on air monitoring based on flow-through sampling techniques without accumulation.

B.2 Description of real-time measurement systems

B.2.1 General Description

For measuring the activity concentration in a ventilation duct, there are two types of measurements. The first one involves continuously sampling of air from the ventilation duct by means of a bypass system and then measuring this sample (see Figure B.1).



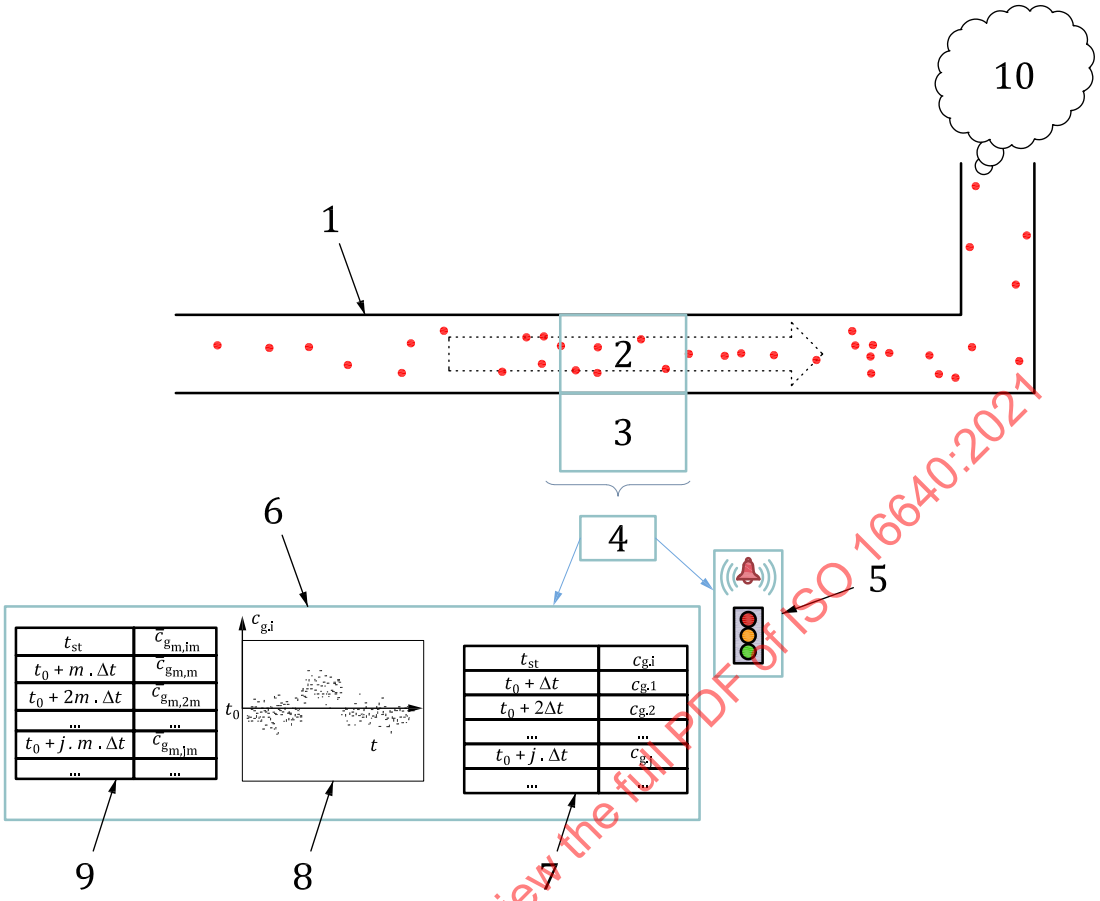
Key

1 ventilation duct
2 measuring detector
3 compensating detector (option)
4 processing algorithm
5 alarm processing unit
6 unit for displaying and processing data
7 visualization of the real-time acquisition results of the activity concentration in the ventilation duct
8 graphic display
9 archiving of average measurements
10 released activity
11 line of sampling
12 sampling pump

Figure B.1 — Bypass measurement system

For a bypass system (see Figure B.1), the sample return may be either downstream of the sample location or just as well upstream of the sample location. When the sample return is downstream, the sampled stream exits the stack with the other non-sampled exhaust. It is important to place the downstream return far enough downstream so as not to impact the sample location. While returning the sampled stream upstream of the sample location, it may be possible that a portion of the sampled stream be sampled a second time thereby adding to the overall emission calculation.

The second method consists of directly measuring in-line the activity concentration by means of detector(s) placed around or inside the ventilation duct (see Figure B.2).

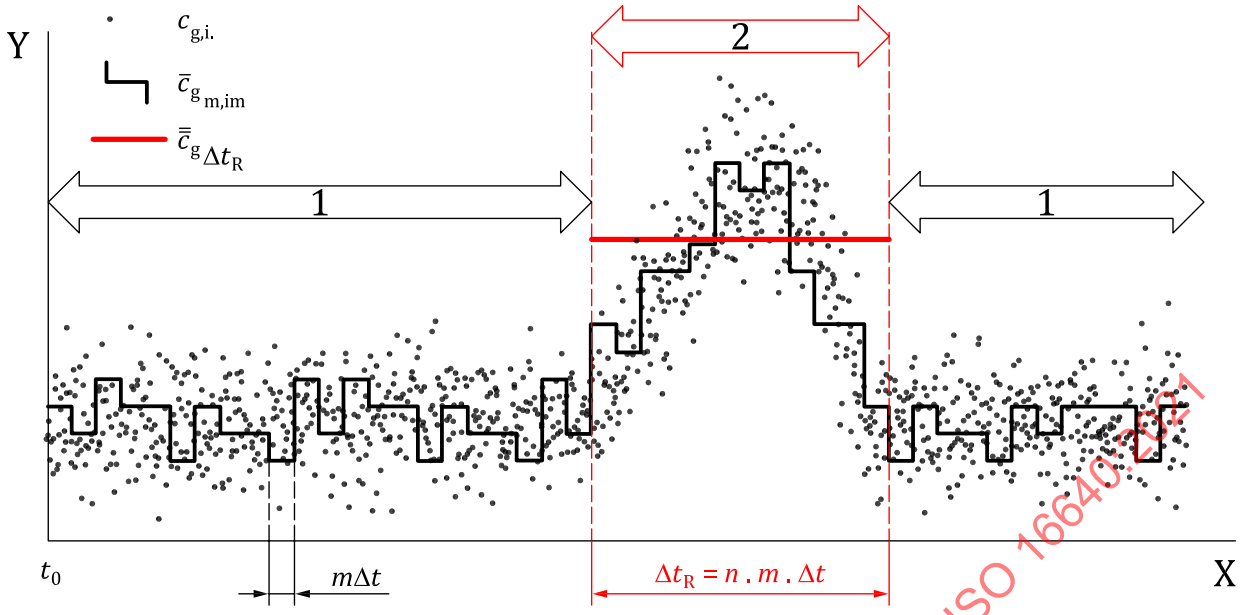


Key

1 ventilation duct
2 measuring detector
3 compensating detector (option)
4 processing algorithm
5 alarm processing unit
6 unit for displaying and processing data
7 visualization of the real-time acquisition results of the activity concentration in the ventilation duct
8 graphic display
9 archiving of average measurements
10 released activity

Figure B.2 — In-line measurement system

In both cases, there is a unit for displaying and processing data comprising a visualization of the real-time acquisition results of the activity concentration in the ventilation duct and the possibility to restitute average activity concentrations over specified periods from the archived data. Figure B.3 illustrates the different displayed activity concentrations.



Key

X time stamp
Y activity concentration
1 background period in absence of released activity
2 period of released activity

Figure B.3 — Illustration of the different displayed activity concentrations

B.2.2 Real-time activity concentration

B.2.2.1 Definition of the model of evaluation

The activity concentration c_i at a time $t_0 + i \cdot \Delta t$ is given by

$$c_i = c_{g,i} - \overline{c_0} \tag{B.1}$$

with

$$\overline{c_0} = \frac{1}{n_{c_0}} \cdot \sum_{j=1}^{n_{c_0}} c_{0,j} \tag{B.2}$$

And expressions of $c_{g,i}$ and $c_{0,j}$ are given in Table B.1

Table B.1 — Expressions of the activity concentrations $c_{g,i}$ and $c_{0,j}$

Compensation detector	Mode	$c_{g,i}$	$c_{0,j}$
NO	Count rate	$\frac{r_{g,i} \cdot w}{P}$ (B.3)	$\frac{r_{0,j} \cdot w}{P}$ (B.4)
	Current	$\frac{I_{g,i} \cdot w}{P}$ (B.5)	$\frac{I_{0,j} \cdot w}{P}$ (B.6)
NOTE In the case of in-line measurement (see Figure B.2), the penetration, P, is 1.			

Table B.1 *(continued)*

Compensation detector	Mode	$c_{g,i}$	$c_{0,j}$
YES	Count rate	$\frac{(r_{g,i}-r_{g,cd,i})\cdot w}{P}$ (B.7)	$\frac{(r_{0,j}-r_{0,cd,j})\cdot w}{P}$ (B.8)
	Current	$\frac{(I_{g,i}-I_{g,cd,i})\cdot w}{P}$ (B.9)	$\frac{(I_{0,j}-I_{0,cd,j})\cdot w}{P}$ (B.10)
NOTE In the case of in-line measurement (see Figure B.2), the penetration, *P*, is 1.			

In general $r_{g,i}, r_{0,j}, r_{g,cd,i}, r_{0,cd,j}, I_{g,i}, I_{0,j}, I_{g,cd,i}$ and $I_{0,cd,j}$ are input data for processing algorithm and are not usually accessible to the user who only has pre-processed values of $c_{g,i}$ and $c_{0,j}$ at their disposal.

B.2.2.2 Standard uncertainty

Table B.2 gives the expressions of $u^2(c_i)$.

Table B.2 — Expressions of standard uncertainty $u^2(c_i)$

Compensation detector	Mode	$u^2(c_i)$
YES or NO	Count rate	$\frac{w}{P\cdot t_C}\cdot c_i + u^2(c_i=0) + \left[\frac{u^2(w)}{w^2}+\frac{u^2(P)}{P^2}\right]\cdot c_i^2$ (B.11)
	Current	$\frac{I_{min}\cdot w}{P}\cdot c_i + u^2(c_i=0) + \left[\frac{u^2(w)}{w^2}+\frac{u^2(P)}{P^2}\right]\cdot c_i^2$ (B.12)
NOTE Usually the parameter $I_{min}=\frac{Q_{min}}{t_C}$ is given by the manufacturer of the ionization detector.		

With according to Reference [34]:

$$u^2(c_i=0)=s_{c_0}^2\left[1+\frac{n_{c_0}-1}{n_{c_0}\cdot(n_{c_0}-3)}\right] \quad \text{(B.13)}$$

and

$$s_{c_0}=\sqrt{\frac{1}{n_{c_0}-1}\cdot\sum_{j=1}^{n_{c_0}}(c_{0,j}-\overline{c_0})^2} \quad \text{(B.14)}$$

under the condition that n_{c_0} is greater than 3.

B.2.2.3 Decision threshold and detection limit

The decision threshold is given by the expression

$$c^*=k_{1-\alpha}\cdot u(c_i=0) \quad \text{(B.15)}$$

then according to (B.13)

$$c^* = k_{1-\alpha} \cdot s_{c_0} \cdot \sqrt{1+\frac{n_{c_0}-1}{n_{c_0} \cdot \left(n_{c_0}-3\right)}} \tag{B.16}$$

NOTE 1 The determination of c_i according to Formula (B.1) implies to check periodically that there is not significant variation of $\overline{c_0}$.

NOTE 2 The determination of the decision threshold c^* according to Formula (B.16) implies to check periodically that there is not significant variation of s_{c_0}.

Table B.3 gives the expressions of the detection limit.

Table B.3 — Expressions of the detection limit $c^{\#}$

Compensation detector	Mode	$c^{\#}$
YES or NO	Count rate	$\dfrac{2 \cdot c^* + \dfrac{k^2 \cdot w}{P \cdot t_C}}{1-k^2 \cdot \left[\dfrac{u^2(w)}{w^2} + \dfrac{u^2(P)}{P^2}\right]}$ (B.17)
	Current	$\dfrac{2 \cdot c^* + \dfrac{k^2 \cdot I_{\min} \cdot w}{P}}{1-k^2 \cdot \left[\dfrac{u^2(w)}{w^2} + \dfrac{u^2(P)}{P^2}\right]}$ (B.18)
with $k = k_{1-\alpha} = k_{1-\beta}$ and the condition $k^2 \cdot \left[\dfrac{u^2(w)}{w^2} + \dfrac{u^2(P)}{P^2}\right] < 1$.		

B.3 Determination of released activity

B.3.1 Definition of the model of evaluation

The calculated released activity A_R over a duration Δt_R is given by

$$A_R = \Delta t_R \cdot q_D \cdot \left(\overline{\overline{c}}_{g_{\Delta t_R}} - \overline{\overline{c}}_0\right) = n \cdot m \cdot \Delta t \cdot q_D \cdot \left(\overline{\overline{c}}_{g_{\Delta t_R}} - \overline{\overline{c}}_0\right) \tag{B.19}$$

With

$$\overline{\overline{c}}_0 = \frac{1}{n_{\overline{c}_0}} \cdot \sum_{j=1}^{n_{\overline{c}_0}} \overline{c}_{0\,m,jm} \tag{B.20}$$

and

$$\overline{\overline{c}}_{g_{\Delta t_R}} = \frac{1}{n} \cdot \sum_{i=1}^{n} \overline{c}_{g\,m,im} \tag{B.21}$$

NOTE 1 $\overline{\overline{c}}_{g_{\Delta t_R}}$ is calculated from the sum of the time-stamped archived raw signals (number of pulses, amount of electric charge) provided by a software interface. This sum is made over a specified time interval of $\Delta t_R = n \cdot m \cdot \Delta t$ duration which is equivalent to having a counting time of Δt_R or a minimum amount of current registered by the measuring detector of $I_{\min} = \dfrac{Q_{\min}}{\Delta t_R}$.

NOTE 2 The determination of A_R according to Formula (B.19) implies to check periodically that there is not significant variation of $\overline{\overline{c_0}}$ over time.

B.3.2 Standard uncertainty

The variance is given by

$$u^2(A_R) = (\Delta t_R \cdot q_D)^2 \cdot \left[u^2\left(\overline{\overline{c}}_{g_{\Delta t_R}}\right) + u^2\left(\overline{\overline{c_0}}\right)\right] + u^2_{rel}(q_D) \cdot A_R^2 \quad \text{(B.22)}$$

Since no other information is available, the $\overline{c}_{0\,m,im}\left(i=1,\ ...,n_{\overline{c_0}}\right)$ is assumed to be samples from Gaussian distributions with unknown expectations and variances. According to Reference [34] the arithmetic means $\overline{\overline{c_0}}$ is the best estimate and the standard uncertainties associated with $\overline{\overline{c_0}}$ is

$$u\left(\overline{\overline{c_0}}\right) = \left(\frac{n_{\overline{c_0}} - 1}{n_{\overline{c_0}} - 3}\right)^{1/2} \cdot \frac{s_{\overline{c_0}}}{\sqrt{n_{\overline{c_0}}}} \quad \text{with } n_{\overline{c_0}} \geq 4 \quad \text{(B.23)}$$

With

$$s_{\overline{c_0}} = \sqrt{\frac{1}{n_{\overline{c_0}} - 1} \sum_{j=1}^{n_{\overline{c_0}}} \left(\overline{c}_{0\,m,jm} - \overline{\overline{c_0}}\right)^2} \quad \text{(B.24)}$$

and from (B.21)

$$u^2\left(\overline{\overline{c}}_{g_{\Delta t_R}}\right) = \frac{1}{n^2} \cdot \left[\sum_{i=1}^{n} u^2\left(\overline{c}_{g\,m,im}\right)\right] \quad \text{(B.25)}$$

It is recalled that in the absence of the phenomenon to be measured (period B in Figure B.3) it is assumed that $u^2\left(\overline{c}_{g\,m,im}\right) = u^2\left(\overline{c}_{0\,m,im}\right) = s^2_{\overline{c_0}}$ then

$$u^2(A_R = 0) = (\Delta t_R \cdot q_D)^2 \cdot \left[\frac{s^2_{\overline{c_0}}}{n} + u^2\left(\overline{\overline{c_0}}\right)\right] = (\Delta t_R \cdot q_D)^2 \cdot s^2_{\overline{c_0}} \cdot \left[\frac{1}{n} + \frac{n_{\overline{c_0}} - 1}{n_{\overline{c_0}} \cdot \left(n_{\overline{c_0}} - 3\right)}\right] \quad \text{(B.26)}$$

Table B.4 gives the expressions of $u^2(A_R)$.

Table B.4 — Expressions of the variance of the released activity $u^2(A_R)$

Compensation detector	Mode	$u^2(A_R)$
YES or NO	Count rate	$\frac{q_D \cdot w}{P} \cdot A_R + u^2(A_R = 0) + \left[\frac{u^2(w)}{w^2} + \frac{u^2(P)}{P^2} + \frac{u^2(q_D)}{q_D^2}\right] \cdot A_R^2$ (B.27)
	Current	$\frac{I_{min} \cdot q_D \cdot \Delta t_R \cdot w}{P} \cdot A_R + u^2(A_R = 0) + \left[\frac{u^2(w)}{w^2} + \frac{u^2(P)}{P^2} + \frac{u^2(q_D)}{q_D^2}\right] \cdot A_R^2$ (B.28)
NOTE 1 In Formula (B.28) $I_{min} = \frac{Q_{min}}{\Delta t_R}$.		
NOTE 2 $u^2(A_R = 0)$ is given by (Formula B.26).		

B.3.3 Decision threshold and detection limit

The decision threshold is given by the expression

$$A_{\mathrm{R}}^{*} = k_{1-\alpha} \cdot u\left(A_{\mathrm{R}} = 0\right) \tag{B.29}$$

Then according to Formula (B.26)

$$A_{\mathrm{R}}^{*} = k_{1-\alpha} \cdot \Delta t_{\mathrm{R}} \cdot q_{\mathrm{D}} \cdot \overline{s}_{c_0} \cdot \sqrt{\frac{1}{n} + \frac{\overline{n}_{c_0} - 1}{\overline{n}_{c_0} \cdot \left(\overline{n}_{c_0} - 3\right)}} \tag{B.30}$$

NOTE The determination of the decision threshold, A_{R}^{*}, according to Formula (B.30) implies to check periodically that there is not significant variation of $\overline{s}_{c_0}$.

The detection limit, $A_{\mathrm{R}}^{\#}$ is given in Table B.5.

Table B.5 — Expressions of $A_{R}^{\#}$

Compensation detector	Mode	$A_{R}^{\#}$
YES or NO	Count rate	$\dfrac{2 \cdot A_{\mathrm{R}}^{*} + \dfrac{k^2 \cdot w \cdot q_{\mathrm{D}}}{P}}{1 - k^2 \cdot \left[\dfrac{u^2(w)}{w^2} + \dfrac{u^2(P)}{P^2} + \dfrac{u^2(q_{\mathrm{D}})}{q_{\mathrm{D}}^2}\right]}$ (B.31)
	Current	$\dfrac{2 \cdot A_{\mathrm{R}}^{*} + \dfrac{k^2 \cdot w \cdot I_{\min} \cdot q_{\mathrm{D}} \cdot \Delta t_{\mathrm{R}}}{P}}{1 - k^2 \cdot \left[\dfrac{u^2(w)}{w^2} + \dfrac{u^2(P)}{P^2} + \dfrac{u^2(q_{\mathrm{D}})}{q_{\mathrm{D}}^2}\right]}$ (B.32)
With $k = k_{1-\alpha} = k_{1-\beta}$ and the condition $k^2 \cdot \left(\dfrac{u^2(w)}{w^2} + \dfrac{u^2(P)}{P^2} + \dfrac{u^2(q_{\mathrm{D}})}{q_{\mathrm{D}}^2}\right) < 1$.		
NOTE: In (Formula B.32) $I_{\min} = \dfrac{Q_{\min}}{\Delta t_{\mathrm{R}}}$.		

B.3.4 Limits of the coverage interval

The limits of the coverage interval are provided when $A_{\mathrm{R}} \geq A_{\mathrm{R}}^{*}$ in such a way that the coverage interval contains the true value of A_{R} with a specified probability $(1-\gamma)$.

The lower limit, $A_{R}^{\triangleleft}$, and the upper limit, $A_{\mathrm{R}}^{\triangleright}$, of the coverage interval are provided by:

$$A_{\mathrm{R}}^{\triangleleft} = A_{\mathrm{R}} - k_{1-\frac{\gamma}{2}} \cdot u\left(A_{\mathrm{R}}\right) \tag{B.33}$$

and

$$A_{\mathrm{R}}^{\triangleright} = A_{\mathrm{R}} + k_{1-\frac{\gamma}{2}} \cdot u\left(A_{\mathrm{R}}\right) \tag{B.34}$$

With $u\left(A_{\mathrm{R}}\right)$ given in Table B.4.

B.4 Application examples

B.4.1 Description of the measurement equipment and its display and archiving principles

This is an in-line measurement system (see Figure B.2), with a compensated measurement in count rate mode. The parameters are given in Table B.6.

Table B.6 — Compensated measurement parameters in count rate mode inputs

Quantity	Value	Unit	Relative standard uncertainty %
w[a]	3 100	Bq·s·m^{-3}	10
P	1		
q_D	0,2	m^3·s^{-1}	10
$\alpha = \beta$	2,5	%	
γ	5	%	
$k = k_{1-\alpha} = k_{1-\beta} = k_{1-\gamma/2}$	1,96		
a $^{18}_{F}$			

B.4.2 Released activity characteristic limits and results

The gross average activity concentrations $\overline{c_{0\,m,jm}}$ which represent a background situation are given in Table B.7. $\overline{c_{0\,m,jm}}$ is calculated from the archived data over a time interval $m \cdot \Delta t = 1 \times 3\ 600 = 3\ 600$ s.

Table B.7 — Mean gross activity concentrations representing a background situation inputs

t_{st} in DD/MM/YYYY hh:mm	$\overline{c_{0\,m,jm}}$ in Bq·m^{-3}	t_{st} in DD/MM/YYYY hh:mm	$\overline{c_{0\,m,jm}}$ in Bq·m^{-3}
12/08/2017 02:00	6,47E+02	13/08/2017 02:00	3,44E+02
12/08/2017 03:00	5,26E+02	13/08/2017 03:00	4,01E+02
12/08/2017 04:00	1,39E+02	13/08/2017 04:00	5,01E+02
12/08/2017 05:00	5,07E+02	13/08/2017 05:00	2,75E+01
12/08/2017 06:00	4,15E+02	13/08/2017 06:00	3,14E+02
12/08/2017 07:00	4,01E+02	13/08/2017 07:00	4,16E+02
12/08/2017 08:00	1,74E+02	13/08/2017 08:00	3,52E+02
12/08/2017 09:00	4,36E+02	13/08/2017 09:00	1,29E+02
12/08/2017 10:00	4,55E+02	13/08/2017 10:00	4,59E+02
12/08/2017 11:00	4,47E+02	13/08/2017 11:00	2,45E+02
12/08/2017 12:00	5,41E+02	13/08/2017 12:00	4,39E+02
12/08/2017 13:00	5,79E+02	13/08/2017 13:00	3,27E+02
12/08/2017 14:00	7,34E+02	13/08/2017 14:00	2,30E+02
12/08/2017 15:00	5,02E+02	13/08/2017 15:00	5,16E+02
12/08/2017 16:00	3,98E+02	13/08/2017 16:00	2,96E+02
12/08/2017 17:00	4,46E+02	13/08/2017 17:00	3,01E+02
12/08/2017 18:00	3,34E+02	13/08/2017 18:00	2,34E+02
12/08/2017 19:00	4,51E+02	13/08/2017 19:00	4,95E+01

Table B.7 *(continued)*

t_{st} in DD/MM/YYYY hh:mm	$\overline{c_{0\,m,jm}}$ in Bq·m^{-3}	t_{st} in DD/MM/YYYY hh:mm	$\overline{c_{0\,m,jm}}$ in Bq·m^{-3}
12/08/2017 20:00	2,06E+02	13/08/2017 20:00	1,96E+02
12/08/2017 21:00	2,61E+02	13/08/2017 21:00	4,64E+02
12/08/2017 22:00	4,91E+01	13/08/2017 22:00	5,49E+02
12/08/2017 23:00	2,15E+01	13/08/2017 23:00	6,14E+02
13/08/2017 00:00	5,75E+02	14/08/2017 00:00	1,80E+02
13/08/2017 01:00	4,62E+02	14/08/2017 01:00	3,09E+01

$\overline{\overline{c_0}}$ is calculated with $n_{\overline{c_0}}=48$ values of $\overline{c_{0\,m,jm}}$.

A_R^* is calculated with $n=\frac{\Delta t_R}{m\cdot\Delta t}=\frac{86\ 400}{3\ 600}=24$.

$\overline{\overline{c_0}}$, A_R^*, $A_R^\#$ are given in Table B.8.

Table B.8 — Decision threshold, and detection limit outputs

Quantity	Value	Unit	Reference Formula
$\overline{\overline{c_0}}$	3,6E+02	Bq·m^{-3}	(B.20)
A_R^*	1,5E+06	Bq·d^{-1}	(B.29)
$A_R^\#$	3,3E+06	Bq·d^{-1}	(B.31)

The gross average activity concentrations $\overline{\overline{c}}_{g_{\Delta t_R}}$ is calculated from the archived data over a time interval $\Delta t_R = n\cdot m\cdot\Delta t = 24\times 3\ 600 = 86\ 400$ s, from 15/08/2017 01:00 to 16/08/2017 00:00, by the use of a software interface and is given in Table B.9.

A_R, $A_R^\triangleleft$ and $A_R^\triangleright$ are calculated from the n = 24 values of $\overline{c_{g\,m,i}}$ and are also given in Table B.9.

Table B.9 — Released activity, lower and upper limits of the coverage interval outputs

Quantity	Value	Unit	Reference Formulae
$\overline{\overline{c}}_{g_{\Delta t_R}}$	6,9E+02	Bq·m^{-3}	Extracted from archived data
A_R	5,7E+06	Bq·d^{-1}	(B.19)
$A_R^\triangleleft$	4,1E+06	Bq·d^{-1}	(B.33)
$A_R^\triangleright$	7,3E+06	Bq·d^{-1}	(B.34)

Table B.9 shows that the $A_R^\triangleright$ does not exceed the value of L1 given in B.4.2.

Annex C
(informative)

Quality assurance

C.1 Introduction

Documentation, maintenance, inspection and calibration are key components of ensuring the quality of air samples.

C.2 Documentation

C.2.1 General

The quality assurance program should assure that the activity concentration detection system and its components are characterized and documented.

C.2.2 Source term

The nature of the processes serving each stack should be identified, including information about the identity of the radionuclides as well as their chemical and physical forms. It includes changes to the ventilation system or changes to processes that might affect the airborne effluent discharged. The air cleaning systems associated with each stack should be identified as well as the probable nature of releases resulting from the possible failure of these systems.

C.2.3 Effluent flow characterization

The results of studies to characterize the flow conditions of the effluents should be documented, e.g. spatial and temporal variations in velocity across the stack or duct, determination of cyclonic flow, gas mixing. In some cases, modelling may be used to supplement the characteristics of the flow conditions[5],[6],[52]. The documentation should include or list all procedures employed, times and dates of the measurements, individuals involved, equipment used, and any pertinent information regarding facility operations.

C.2.4 Design and construction

Documentation that describes the objectives of each stack sampling system, and includes or lists all radionuclides and their potential physical and chemical forms, should be available. If a particular component is present but not sampled, the reasons should be discussed.

The rationale and any supporting evidence for sampling at a particular location along the duct or stack should be documented. Similarly, the rationale for sampling at a particular point(s) within (across) the stack or duct should be documented. Documentation that explains the rationale for the design of the sampling system should be available. This includes documentation regarding the choice of the transport system, the material, diameter and configuration of the sampling lines, the choice of filters or absorbers, the selection of flow meters.

Also, there should be a means for allowing verification that the installed sampling equipment is that described in the documentation. This can be accomplished by identification marks on the installed components. An evaluation of sample losses in the sampling lines should be documented. Other design documents that should be maintained include engineering change control documents, equipment manuals and vendor supplied information.

Further to this, the key characteristics of the monitoring system should also be documented. This should, as a minimum, include:

— the technical data of the detection system (e.g. CAM) – energy response, sensitivity, range, limit of detection. The type test report for the detection system should also be available, and would detail most of these key characteristics;

— the alarm setup characteristics – levels, units, logging intervals, response time;

— the properties of the archived data, how they are managed and how they can be post-processed for release calculation;

— The user manual and maintenance procedures.

C.3 Maintenance and inspection

C.3.1 General

The requirements for maintenance and inspection depend upon the nature of the sampling equipment. Routine maintenance may be performed as described in the manufacturer's equipment manuals. Non-routine maintenance should also be performed as indicated by the results of inspections. The guidance provided here can be used as appropriate, such as when manufacturer recommendations are absent.

Inspection and maintenance activities should be described in procedures. Checklists should be employed as part of inspection protocols, and, after use, a checklist should become a part of the inspection record. The inspection and maintenance records should include the nature of the inspection or maintenance, reasons for the inspection or maintenance, names of the individuals involved, times and dates, identity of the equipment employed, and a description of any replaced parts or materials. All deficiencies identified during scheduled and unscheduled inspections should be recorded. Recommended maintenance and inspection guidelines are given below. Regularly scheduled inspections should be performed at least once a year, possibly concurrent with calibrations. Ideally, the same individuals responsible for the calibrations would also be responsible for the inspections.

C.3.2 Inspections

Inspections should be performed routinely, quarterly or annually as appropriate and practicable, possibly concurrent with other maintenance. Inspections should include but not be limited to:

— position and orientation of sampling nozzles or inlets;

— condition of nozzle or inlet openings;

— dust accumulation in the sampling nozzles, inlets, and transport lines;

— corrosion, physical damage or dust loading to the transport lines and equipment;

— leakage in the overall sample transport system;

— tightness of all fittings and connections;

— condition of flow sensors;

— condition of temperature and pressure sensors;

— calibration of flow meters (the value of the flow rate determined by the test should not deviate from the nominal value more than 10 %).

C.3.3 Sampling system flow meter inspections

Mass flow meters should be checked at least annually with a secondary or transfer standard, where a transfer standard is typically a calibrated mass flow meter placed in series with the unit to be tested. Unscheduled calibrations may be needed if any maintenance to the sampling system has been conducted that could affect the performance of the flow meter. The flow rate at which the mass flow meter is checked should be at a level that is within ±25 % of the nominal design sampling rate of the system. If the flow rate, q_{std}, of the flow meter being tested differs by more than 10 % from the value indicated by a secondary standard, the flow meter should be removed from service for maintenance and calibration. Rotameters may not need to be checked in the field with secondary standards unless any maintenance or changes have been made to the sampling system that could affect their accuracy. A rotameter should be inspected at the start of each sampling interval for assurance that no foreign matter has been deposited on inside surfaces in the measurement tube. If foreign matter is visible, the rotameter should be removed from service, cleaned, and re-calibrated.

C.3.4 Continuous effluent flow measurement apparatus

On an annual basis, response checks should be made of the flow rate readings from in-stack equipment through use of a reference Prandtl-type pitot tube. If a thermal anemometer or pitot tube is used in the stack or duct, the reference pitot tube should be placed in the vicinity of the in-stack device at a point where, based on previous measurements (see Annex E), the velocity reading is either the same as that of the in-stack device or a known correction factor can be applied to provide a ratio of the two velocity readings. If the in-stack sensor is a pitot tube, the velocities calculated from use of the two tubes should be within ±10 % (after taking into account any correction factors). If the in-stack sensor is a thermal anemometer, the velocity determined from use of the reference pitot tube, v, should be converted using temperature, T and T_{std}, and pressure, p and p_{std}, to the equivalent velocity at standard conditions, v_{std}, through use of:

$$v_{std} = v \cdot \frac{T_{std}}{T} \cdot \frac{p}{p_{std}} \tag{C.1}$$

The ratio of the velocity at standard conditions indicated by the in-stack sensor and the reference sensor should be within ±10 %.

If the velocity value from either an in-stack pitot tube or thermal anemometer is outside of the specified range, the cause of the difference should be determined. The device may need to be recalibrated. Also, if a sensor requires maintenance that could affect the calibration, the device should be recalibrated.

If the flow sensor is a pitot tube, response checks should be made at least quarterly to verify the functionality of any pressure gauges used in conjunction with the pitot tube readout. This check may be a simple test to show the application of a pressure differential causes an appropriate output of the gauge.

If an acoustic flow meter is used as the in-stack equipment, at least quarterly performance checks should be made by comparing the average velocity determined with the acoustic flow meter to the velocity at a reference point determined with a Prandtl-type pitot-static tube. Based on the Reference method measurements (see Annex E) taken during calibration of the acoustic flow meter, a ratio can be established between the average velocity and the velocity at the selected reference point. The velocity measured with the acoustic flow meter should agree within ±10 % of the single point pitot tube measurement when the latter is corrected with the velocity ratio.

C.4 Calibration verification

C.4.1 General

Measurement and test equipment should be calibrated using standards whose calibration is traceable to the governing national institute of standards and measurements or derived from accepted values of natural physical constants. The principal calibration activities on a sampling system involve the verification of sample flow rate, sampling time, and effluent flow rate. The suggested calibration