BS ISO 2889:2021

BSI Standards Publication

Sampling airborne radioactive materials from the stacks and ducts of nuclear facilities

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National foreword

This British Standard is the UK implementation of ISO 2889:2021. It supersedes BS ISO 2889:2010, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee NCE/2, Radiation protection and measurement.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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INTERNATIONAL STANDARD

ISO 2889

Third edition
2021-08

Sampling airborne radioactive materials from the stacks and ducts of nuclear facilities

Échantillonnage de substances radioactives en suspension dans l'air dans les émissaires de rejet et les conduits des installations nucléaires

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

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

This third edition cancels and replaces the second edition (ISO 2889:2010), which has been technically revised. The main changes are:

— clarification of the circumstances where numerical modelling may be used to perform or assist with meeting the qualifications for sample extraction locations;

— clarification of passages allowing the use of alternate aerosol particle sizes for the purpose of testing to meet various performance criteria described in this document;

— changes for the discussion of standard uncertainty with regard to setting action levels (Annex I).

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.

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Introduction

This document focuses on monitoring the activity concentrations and activity releases of radioactive substances in air in stacks and ducts. Other situations for monitoring the activity concentrations and activity releases of radioactive substances in air (environmental or workplace monitoring) are being addressed in subsequent standards. This document provides performance-based criteria for the use of air-sampling equipment, including probes, transport lines, sample collectors, sample monitoring instruments and gas flow measuring methods. This document also provides information covering sampling programme objectives, quality assurance, development of air monitoring control action levels, system optimization and system performance verification.

ISO 2889 was first published in 1975 as a guide to sampling airborne radioactive materials in the ducts, stacks, and working environments of installations where work with radioactive materials is conducted. Since then, an improved technical basis has been developed for each of the major sampling specialities. The focus of this document is on the sampling of airborne radioactive materials in ducts and stacks.

The goal of achieving an unbiased, representative sample is best accomplished where samples are extracted from airstreams in which potential airborne contaminants are well mixed in the airstream. This document sets forth performance criteria and recommendations to assist in obtaining valid measurements of the concentration of airborne radioactive materials in ducts or stacks.

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Sampling airborne radioactive materials from the stacks and ducts of nuclear facilities

1 Scope

This document sets forth performance-based criteria and recommendations for the design and use of systems for sampling of airborne radioactive materials in the effluent air from the ducts and stacks of nuclear facilities.

The requirements and recommendations of this document are aimed at sampling that is conducted for regulatory compliance and system control. If existing air-sampling systems are not designed to the performance requirements and recommendations of this document, an evaluation of the performance of the system is advised. If deficiencies are discovered, a determination of whether or not a retrofit is needed and practicable is recommended.

It can be impossible to meet the requirements of this document in all conditions with a sampling system designed for normal operations only. Under off-normal conditions, the criteria or recommendations of this document still apply. However, for accident conditions, special accident air sampling systems or measurements can be used.

This document does not address outdoor air sampling, radon measurements, or the surveillance of airborne radioactive substances in the workplace of nuclear facilities.

NOTE Reference [1] addresses the instrumentation that is frequently used in nuclear air monitoring. Reference [5] addresses air sampling in the workplace of nuclear facilities. References [6] and [7] describe the performance characteristics of air monitors.

2 Normative references

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

ISO 10780:1994, *Stationary source emissions — Measurement of velocity and volume flowrate of gas streams in ducts*

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 https://www.electropedia.org/

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

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3.2
absorbent
material that takes up a constituent through the action of diffusion, allowing the constituent to penetrate into the structure of the absorbent (if a solid) or dissolve in it (if a liquid)

Note 1 to entry: When a chemical reaction takes place during absorption, the process is called chemisorption.

3.3
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

3.4
accuracy
closeness of agreement between a measured quantity and the true quantity of the measurand

3.5
action level
threshold concentration of an effluent contaminant at which it is necessary to perform an appropriate action

3.6
adsorbent
material, generally a solid, that retains a substance contacting it through short-range molecular forces that bind the adsorbed material at the surface of the material

3.7
aerodynamic diameter
D_a
for a particle of arbitrary shape and density, the diameter of a sphere with density 1 000 kg/m^3 that has the same sedimentation velocity in quiescent air as the arbitrary particle

3.8
aerosol
dispersion of solid or liquid particles in air or other gas

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

3.9
aerosol, monodisperse
aerosol (3.8) comprised of (solid or liquid) particles that are all of approximately the same size

Note 1 to entry: In general, the geometric standard deviation of the particle-size distribution of a monodisperse aerosol is less than or equal to 1,1.

3.10
aerosol, polydisperse
aerosol (3.8) comprised of particles with a range of sizes

Note 1 to entry: In general, the geometric standard deviation of the particle-size distribution of a polydisperse aerosol is greater than 1,1.

3.11
aerosol particle
solid or liquid particle constituents of an *aerosol* (3.8)

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3.12
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: An analyser usually evaluates the concentration of radionuclides in a sampled air stream. However, some analysers are mounted directly in or outside a stack or duct.

3.13
aspiration ratio
ratio of particle mass or number concentration in the nozzle inlet to the concentration in the free stream

3.14
bend
gradual change in direction of a sample transport line

Note 1 to entry: The radius of curvature of a bend should be at least three times the inside diameter of the tubing.

3.15
bulk stream
air flow in a stack or duct, as opposed to the sample flow rate

3.16
burial
imbedding of a particle into a filter medium or the masking of a particle by subsequent deposits of particulate matter

3.17
calibration
operation that, under specified conditions, initially establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and then uses this information to establish a relation for obtaining a measurement result from an indication

3.18
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.

3.19
collector
component of a sampling system that is used to retain radionuclides for analysis

EXAMPLE A filter that is used to remove from a sample stream aerosol particles that carry alpha-emitting transuranic radionuclides or other radionuclides.

3.20
conditioning system
apparatus that can be used to purposefully, in a controlled manner, change the *aerosol particle* (3.11) concentration, gas composition, *particle-size distribution* (3.53), temperature or pressure in a *sample stream* (3.68)

3.21
continuous air monitor
CAM
near-real-time sampler and associated detector that provide data on radionuclides [e.g. concentration of alpha-emitting *aerosol particle* (3.11)] in a *sample stream* (3.68)

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3.22
continuous monitoring
continuous near-real-time measurements of one or more sampling characteristics

3.23
continuous sampling
either uninterrupted sampling or sequential collection of samples obtained automatically at intervals short enough to yield results that are representative for the entire sampling period

Note 1 to entry: The sample may be analysed in near-real-time (i.e. equivalent to monitoring) or it may be analysed post-sample-collection in a remote laboratory.

3.24
curvature ratio
ratio of bend radius to the tube diameter

3.25
depositional loss
loss of constituents of the sample on the internal walls of a sampling system

Note 1 to entry: See also 3.84.

3.26
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 that the true value of the measurand is zero is less or equal to a chosen probability for a wrong decision, α.

[SOURCE: ISO 11929-1:2019, 3.12 modified – definition identical, but Note 1 to entry changed and Note 2 to entry not included here.]

3.27
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* (3.26), 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, when, in fact, the true value of the measurand is not zero.

[SOURCE: ISO 11929-1: 2019, 3.13 modified – definition identical, but last sentence of Note 1 to entry not included here as well as Note 2 to entry.]

3.28
droplet
liquid *aerosol particle* (3.11)

3.29
effective dose
sum of the products of the dose absorbed by an organ or a tissue and the factors relative to the radiation and to the organs or tissues that are irradiated

3.30
effluent
waste stream flowing away from a process, plant, or facility to the environment

Note 1 to entry: This document applies to the effluent air that is discharged to the atmosphere through stacks and ducts.

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3.31
emission
contaminants that are discharged into the environment

3.32
emit
discharge contaminants into the environment

3.33
extractive sampling
diverting a part of the airflow from a stack or duct for the purpose of the collection of a sample of the air

Note 1 to entry: See 3.69 and 3.72.

3.34
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.

3.35
geometric mean of a variable
x_g
value for N observations of a random variable x_i given by

$$\ln x_g = \frac{1}{N}\sum_{i=1}^{N} \ln x_i$$

3.36
geometric standard deviation
s_g
the geometric standard deviation for N observations of a random variable, x_i, calculated from:

$$\ln^2 s_g = \frac{1}{N-1}\sum_{i=1}^{N}\left(\ln x_i - \ln x_g\right)^2$$

where x_g is the geometric mean of the random variable

3.37
high-efficiency particulate air filter
HEPA filter
high-efficiency filter used for removing *aerosol particles* (3.11) from an air stream

Note 1 to entry: A HEPA filter usually collects aerosol particles at the most penetrating particle size (between 0,1 µm and 0,3 µm diameter) with a high efficiency and is designed to collect greater fractions of aerosol particles with diameters either larger or smaller. The minimum efficiency of a HEPA filter is not defined in this document.

3.38
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.

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3.39
impaction
process by which *aerosol particles* (3.11) are removed from an air stream by striking an object in the air stream

Note 1 to entry: Curvature of air streamlines, principally on the front side of the object, causes particles with sufficient inertia to strike the object while the airflow passes around it.

3.40
in-line system
system where the detector assembly is adjacent to, or immersed in, the *effluent* (3.30) stream or stream in the duct or stack

3.41
interception
process by which *aerosol particles* (3.11) are removed from an air stream by an object in the flow, where the trajectory of the particle's centre of gravity misses the object but the body of the particle strikes the object

3.42
isokinetic
condition that prevails when the velocity of air at the inlet plane of a nozzle is equal to the velocity of undisturbed air in a stack or duct at the point where the nozzle inlet is located

Note 1 to entry: Anisokinetic is the antonym of isokinetic. Sub-isokinetic refers to the condition where the nozzle inlet velocity is less than the free-stream velocity. Super-isokinetic refers to the condition where the nozzle inlet velocity is greater than the free-stream velocity.

3.43
laminar flow
flow regime in stacks or ducts associated with Reynolds numbers less than about 2 200

Note 1 to entry: This regime is not usually encountered in effluent air flows. Mixing in laminar flow results from molecular diffusion, which is a much slower process than mixing in turbulent flow.

3.44
membrane filter
filter medium consisting of thin, organic-based films having a range of selectable porosities and controlled composition

Note 1 to entry: Thin, porous metallic filters are sometimes also called membrane filters.

3.45
mixing element
device placed in a stack or duct that is used to augment the mixing of the contaminant mass with the fluid

3.46
monitoring
continual measurement of a quantity (e.g. activity concentration) of the airborne radioactive constituent or the gross content of radioactive material, 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

3.47
nozzle
device used to extract a sample from an *effluent* (3.30) stream and transfer the sample to a transport line or collection device

Note 1 to entry: Within the nozzle, there is a transition zone where the sample stream adjusts to the conditions in the transport line.

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3.48
nozzle exit (plane)
imaginary plane across the cross-section of a transport system that divides the nozzle region from the transport line

Note 1 to entry: The nozzle is frequently a separate component and the nozzle exit plane is clearly defined as the downstream end of that component. If there is no separate component, the nozzle exit is the end of the transition zone of the nozzle flow.

3.49
nozzle inlet (plane)
imaginary cross-sectional inlet plane of a nozzle where the flow first enters the transport system

Note 1 to entry: In the special case of a shrouded nozzle, the inlet is referenced to the inner nozzle rather than the shroud.

3.50
number size distribution
representation of the number of particles associated with intervals of particle size, over the full size range encountered in a sample

Note 1 to entry: For samples consisting of aerosol particles, it is a representation of the relative number of particles (measured number of particles in a size interval divided by the total number of particles in the sample) associated with intervals of aerodynamic diameter.

3.51
off-normal condition
condition that is unplanned and which presents a gap with normal conditions

EXAMPLE Accidents and equipment failure.

3.52
particle
aggregate of molecules, forming a solid or liquid, ranging in size from a few molecular diameters to several millimetres

3.53
particle-size distribution
distribution of *particle* (3.52) size as a function of mass or activity rather than number

3.54
penetration
ratio of the concentration at the outlet of the sampling system, transport lines included, to that in the duct or at the stack

3.55
potential emission
radionuclides that can be released to the environment from a facility in the absence of control equipment

3.56
precision
closeness of agreement between indications obtained by replicate measurements on the same or similar objects under specified conditions.

Note 1 to entry: A value of precision is obtained by repetitive testing of a homogenous sample under specified conditions. The precision of a method is expressed quantitatively as either the standard deviation computed from the results of a series of controlled determinations or as the coefficient of variation of the measurements.

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3.57
probe
tubing or apparatus inserted into a stack or duct through which a sample of the stream is withdrawn

Note 1 to entry: A probe usually refers to one or more nozzles and part of the transport line.

3.58
profile
distribution of air velocity, of gas concentration or of *particle* (3.52) concentration over the cross-sectional area of the stack or duct

3.59
quality assurance
QA
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

3.60
radionuclide
unstable isotope of an element that decays or converts spontaneously into another isotope or different energy state, emitting radiation

3.61
record sample
sample that is collected for reporting purposes

Note 1 to entry: Record samples are often analysed off-line.

3.62
reference method
apparatus and instructions for providing results against which other approaches may be compared

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

3.63
representative sample
sample with the same quality and characteristics for the material of interest as that of its source at the time of sampling

3.64
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

3.65
sample
portion of an air stream of interest or one or more separated constituents from a portion of an air stream

3.66
sample-extraction location
location in a stack or duct that coincides with the *sample* (3.65) *nozzle inlet* (3.49)

Note 1 to entry: By extension from the nozzle inlet, the entire plane that is perpendicular to the longitudinal axis of a stack or duct.

3.67
sampler
device that collects or analyses constituents of the air *sample* (3.65)

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3.68
sample stream
air that flows through a sampling system

3.69
sampling
process of removing a *sample* (3.65) from the free air and transporting it to a *collector* (3.19) or an *analyser* (3.12) (monitor)

3.70
sampling environment
conditions of the air flow and gas within a stack or duct that can influence the sampling process

Note 1 to entry: Factors to take into account include pressure, temperature and molecular composition of the gas.

3.71
sampling plane
cross-sectional area where the *sample* (3.65) is extracted from the air flow

3.72
sampling system
system consisting of a nozzle, an inlet, a transport line, a flow *conditioning system* (3.20) and a *collector* (3.19) or monitor

Note 1 to entry: A flow conditioning system may be used to change concentration, temperature, humidity, or other characteristics. Depending upon the application, a flow conditioner might not be used in the sampling system.

3.73
sedimentation velocity
terminal (maximum) velocity an *aerosol particle* (3.11) attains in quiescent fluid (air) as a result of the gravitational force

3.74
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: This is 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.

3.75
shroud
aerodynamic decelerator placed around and extending beyond a sampling nozzle to reduce sampling biases

3.76
standard conditions
temperature of 25 °C and a pressure of 101,325 kPa

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

3.77
transmission ratio
ratio of the *aerosol particle* (3.11) concentration at the nozzle outlet to that in the free stream

Note 1 to entry: It is stated whether a mass or activity basis is used.

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3.78
transport line
part of a transport system between the *nozzle exit plane* (3.48) and the entrance plane of a *collector* (3.19) or *analyser* (3.12)

3.79
transport system
all components of a *sampling system* (3.72), excluding the *collector* (3.19) or *analyser* (3.12)

3.80
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.

3.81
uncertainty
parameter characterizing the dispersion of the value of a measurand, based on the true value of a quantity

Note 1 to entry: The uncertainty is typically stated at a given statistical level of confidence (e.g. 95 %).

3.82
uncertainty analysis
procedure for estimating the overall impact on the *accuracy* (3.4) or *precision* (3.56) of a dependent variable as a result of the estimated uncertainties of the independent variables

3.83
vapour
gaseous form of materials that are liquids 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 volatilized from liquids or solids.

3.84
velocity profile
distribution of the velocity values at a given cross-section in a stack or duct

3.85
volatile
having a high *vapour* (3.83) pressure, which allows significant quantities of material to become gaseous at the prevailing temperature

Note 1 to entry: In this document, the stack or duct temperature is generally considered as the reference.

3.86
wall loss
loss of *sample* (3.65) constituents to the internal walls of a *sampling system* (3.72)

Note 1 to entry: Quantitatively, it is the equivalent concentration lost to the walls of a nozzle, transport line, conditioning system, or transport system divided by the concentration at the inlet plane of the nozzle, transport line, or transport system.

4 Symbols

For the purposes of this document, the following symbols apply.

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A	cross-sectional area of a stack or duct, (m^2)
$\bar{A}$	average radionuclide stack or duct emission rate over the period of integration, expressed in in $Bq \cdot s^{-1}$
A_e	aspiration efficiency of a sampling nozzle (dimensionless)
A_i	cross-sectional area of the ith element, in m^2
C	Cunningham's slip correction for aerosol particles (dimensionless)
c_A	effluent activity concentration, expressed in in $Bq \cdot m^{-3}$
$C_{cal,pt}$	Pitot calibration factor, dimensionless
c_e	activity or mass or aerosol particle concentration at the exit plane of a transport system, in $Bq \cdot m^{-3}$ or $kg \cdot m^{-3}$ or m^{-3}, respectively
$c_{e,j}$	activity or mass or aerosol particle concentration at the exit plane of a component j, in $Bq \cdot m^{-3}$ or $kg \cdot m^{-3}$ or m^{-3}, respectively
$c_{i,j}$	activity or mass or aerosol particle concentration at the inlet plane of a transport system component j, in $Bq \cdot m^{-3}$ or $kg \cdot m^{-3}$ or m^{-3}, respectively
c_∞	activity or mass or aerosol particle concentration in the undisturbed free stream at the nozzle location, in $Bq \cdot m^{-3}$ or $kg \cdot m^{-3}$ or m^{-3}, respectively
c^*	decision threshold of the activity concentration
$c^\#$	detection limit of the activity concentration
$C_{v,pt}$	velocity-averaging correction factor for a Pitot tube, dimensionless
$C_{v,ta}$	velocity-averaging correction factor for a single point thermal anemometer, dimensionless
$C_{v,af}$	velocity-averaging correction factor for a line average velocity taken with an acoustic flow meter, dimensionless
D_a	aerodynamic particle diameter, expressed in µm
De	Dean number of a flow bend, $De = Re/R_o^{1/2}$ (dimensionless)
d_t	inside diameter of a transport system component (e.g. tube), expressed in m
f_c	ratio of the activity concentration in the sample volume to the effluent activity concentration in the free stream, dimensionless
f_{cu}	curvature ratio ($f_{cu} = r_{cu}/d_t$) (dimensionless)
F_k	fluctuation constant (dimensionless)
L	length of a section of tubing, expressed in m
l_W	wall losses of aerosol particles in transport system components (dimensionless)
M	mean molar mass of a gas, expressed in $kg \cdot mol^{-1}$
M_P	mixing of radioactive contaminant in the total effluent gas volume, determined as the ratio of the concentration in the sample volume to the concentration in the free stream (dimensionless)

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N	number of points or observations
n	number of components in a transport system, dimensionless
P	overall penetration of a sample through a transport system (dimensionless)
P_j	penetration of a sample through the jth component of a transport system (dimensionless)
p_a	actual pressure in the stack or duct, expressed in Pa
p_{std}	standard pressure, equal to 101,325 kPa
P_s	penetration through a straight tube, dimensionless
q_a	volumetric flow rate at actual temperature and pressure conditions, expressed in $m^3 \cdot s^{-1}$
q_{std}	volumetric flow rate at standard conditions, equal to 25 °C and 101,325 kPa, expressed in in $m^3 \cdot s^{-1}$
R	individual gas constant for a particular gas, equal to R_u/M, expressed in $J \cdot kg^{-1} \cdot K^{--1}$
r_{cu}	radius of curvature of a pipe bend, expressed in m
R_u	universal gas constant, equal to 8,314 J/(mol·K)
Ra	surface roughness, expressed in µm
Re	Reynolds number of flow in a tube, equal to $\rho U_m d_t/\mu$ (dimensionless)
r	resuspension rate, expressed in s^{-1}
r_n	net count rate (gross minus background) of the sample, expressed in s^{-1}
S	signal
St	Stokes number, equal to $(C\rho_w D_a{}^2 U_m)/(9\mu d_t)$ (dimensionless)
s	standard deviation
T	temperature, expressed in K
T_a	temperature in stack or duct, expressed in K
T_{std}	standard temperature, equal to 298 K
t	time, expressed in s
t_s	time period over which sampling is performed, expressed in s
U(Cal)	uncertainty associated with determining the calibration factor (dimensionless)
$U(V)$	total uncertainty in the volume of air (dimensionless)
$u(\bar{A})$	standard uncertainty of the activity emission rate of a radionuclide, in $Bq \cdot s^{-1}$
u_c	uncertainty associated with determining the calibration factor, i.e. correcting the indicated flow, dimensionless
$u(F_k)$	standard uncertainty of the fluctuation constant, which is set at 1 for a meter whose readings do not fluctuate, dimensionless

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$u(r_n)$	standard uncertainty of the net count rate, in s^{-1}
u_s	uncertainty in reading the flow meter scale, dimensionless
$u(t_s)$	standard uncertainty associated with the measurement of the sampling time, dimensionless
$u(V_T)$	standard uncertainty of the total volume sampled, in m^3
$u(w)$	standard uncertainty of the calibration factor, in s^{-1}
$u_r(w)$	relative standard uncertainty of the calibration factor, dimensionless
$u_r(A)$	relative standard uncertainty of the cross-sectional area, dimensionless
$u_r(\bar{A})$	relative standard uncertainty of the activity emission rate of a radionuclide, dimensionless
$u_r(C_{cal,pt})$	relative standard uncertainty of the Pitot calibration factor, dimensionless
$u_r(p)$	relative standard uncertainty of the pressure, dimensionless
$u_r(\rho)$	relative standard uncertainty of the gas density, dimensionless
$u_r(V_a)$	relative standard uncertainty of the volume at actual conditions, dimensionless
$u_r(P)$	relative standard uncertainty of the overall penetration in a transport system, dimensionless
$u_r(f_c)$	relative standard uncertainty of the ratio of the activity concentration in the sample volume to the effluent activity concentration in the free stream, dimensionless
$u_r(\varepsilon_f)$	relative standard uncertainty of the collection efficiency of the collection medium, dimensionless
$u_r(\varepsilon_d)$	relative standard uncertainty of the detection efficiency, dimensionless
$u_{r,k=2}(\bar{A})$	relative standard uncertainty of the activity emission rate of a radionuclide representing the coverage interval at 95 % (k = 2), dimensionless
v_m	spatial mean velocity of gas (air) in a flow tube, expressed in $m \cdot s^{-1}$
v	velocity, expressed in $m \cdot s^{-1}$
V_a	volume of effluent that produced the sample at stream temperature, pressure, and gas composition, expressed in m^3
V_a	total volume of gas (air) sampled, expressed in m^3
v_{af}	line-average velocity obtained from an acoustic flow meter, in $m \cdot s^{-1}$
$v_{a,pt}$	velocity at actual conditions determined from use of the reference Pitot tube, in $m \cdot s^{-1}$
v_d	deposition velocity due to Brownian diffusion or turbulent inertial deposition on the wall of a transport tube, expressed in in $m \cdot s^{-1}$
v_e	effective deposition velocity of contaminant at the wall of a transport tube, expressed in $m \cdot s^{-1}$
v_g	sedimentation velocity of an aerosol particle, expressed in $m \cdot s^{-1}$
v_{ge}	cross-stream component of gravitational settling velocity, expressed in $m \cdot s^{-1}$
V_i	velocity at the midpoint of the *ith* element, expressed in metres per second

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V_{std}	equivalent velocity at standard conditions (25 °C and 101,325 kPa), expressed in m·s^{-1}
$v_{std,ta}$	velocity obtained from a single-point thermal anemometer at standard conditions, in m·s^{-1}
$v_{std,ta,i}$	velocity measured with a properly calibrated thermal anemometer at the centroid of the ith element of area, in m·s^{-1}
w	calibration factor, dimensionless
α	angular coordinate of a tube cross-section, expressed in degrees or radians
u	standard uncertainty
εd	detection efficiency, expressed in reciprocal becquerel-seconds
ε_f	collection efficiency (dimensionless)
ε_{Ts}	transport efficiency
λ	decay constant, expressed in s^{-1}
μ	dynamic viscosity of a gas, expressed in pascal-seconds
θ	flow angle, expressed in degrees or radians
ρ	gas density in the stack or duct, in kg·m^{-3}
ρ_a	gas density in the stack or duct at actual conditions, expressed in kg/m^3
ρ_{std}	density of air at standard conditions of 25 °C and 101,325 kPa, equal to 1,184 kg/m^3
ρ_w	density of water at 4 °C, equal to 1 000 kg/m^3
σ	standard deviation
τ	transmission ratio of a nozzle (dimensionless)
τ_L	transmission through the transport line
τ_p	transmission through the nozzle
ϕ	angle of inclination of a tube axis relative to horizontal, expressed in degrees or radians

5 Factors impacting the sampling program

This document focuses on the mechanics of obtaining a sample of airborne radioactive constituents in facility ducts and stacks. However, there are important factors that impact the design of sampling systems, in particular the following:

— the purpose of sampling;

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

— the characteristics of the air stream and radioactive constituents;

— the desired measurement sensitivity;

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

The impact of these factors on the sampling system should be assessed. Informative guidance concerning the first three of these factors is given in Annexes G and L. Information relevant to the last two is given in Annex I.

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For off-normal conditions, the performance of the sampling system can be affected by the modification of several parameters (temperature, flow rate in ducts or stacks, type of airborne particles). Thus, acceptance criteria introduced in this document for normal conditions should be considered as recommendations for off-normal conditions.

6 Sample extraction locations

6.1 General

The sample extraction location shall provide the possibility to extract a representative sample.

A representative sample is best extracted from a location where the radioactive materials of interest are well mixed within the free stream. The term "well-mixed" includes the several criteria that are given in 6.3. In a well-mixed stream the sampling probe may contain a single nozzle. In circumstances where the well-mixed criteria are not achieved, a multi-nozzle probe may be necessary to get a representative sample. The design and operation of sampling probes are described in 7.3 and Annex M. Tools to determine if the criteria for well-mixed sample extraction locations are described in Annex F. These tools include

— physical testing on the actual ventilation stack,

— physical tests with scale models or geometrically similar stacks, and

— numerical methods validated against physical test data.

6.2 General requirements for sample extraction locations

The stack or duct geometry and the airflow within should be fully understood. The sample extraction probe should be located where the potential radioactive constituents are well mixed with the airflow. To meet the recommendations of the following paragraphs the accommodation for effluent sampling is addressed early in the design of the ventilation system for discharging the airborne effluent.

Usually, for a stack, the sample extraction location should be situated between the discharge of the fan(s) and the discharge to the atmosphere, with the provision that the location should not be so close to the final exit that wind effects can significantly influence the velocity profile at the sampling location. Typically, in a 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 can be instances where greater distances are needed.

Particular attention should be given to the geometry of flow-entry conditions. 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 can also produce distortions in the velocity and the 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.

NOTE 1 Features that enhance mixing do so by creating large-scale turbulence. One or more 90° turns, converging airstreams, mixing boxes, perimeter rings and commercial static mixers all enhance mixing. On the other hand, turning vanes and flow straighteners have the opposite effect. The generic tests of References [50], [77], [80] and [100] provide tests of features that promote mixing. These are also summarized in Chapter 15 of Reference [79]. Previously tested configurations can be used and scaled.

NOTE 2 If the user is interested in adopting a previously tested configurations, there are several documented tests in published literature and technical reports: for example References [17], [19], [46], [47] and [93], (or other publicly available test reports such as can be found on OSTI.gov). There are the constraints in F.1.2.5 for adopting the results of previously tested stack or duct configurations.

6.3 provides criteria which describe a satisfactorily well-mixed location in the stack or duct system. These criteria shall be met generally in the centre two-thirds of the cross-sectional area of the duct. Consequently, sampling probes should be located within the centre half of the cross section of the duct

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where the mixing is optimal. This enables the use of a single nozzle sampling probe, simplifying the probe design and improved sample transport. Modern shrouded nozzles or automatic velocity matching nozzles are accommodating of changes in free stream air velocity.

There are other considerations in locating the sample extraction 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 accommodate analysis or collection equipment that does not compromise the quality of the sample. High radiation fields under post-accident conditions can present a problem with respect to worker safety at the sample-extraction location. High ambient temperatures or humidity can also be a problem in some cases. Either of these situations can dictate the requirement for transport lines longer than normally required to accommodate installation of the sample collection and analysis equipment.

Following a careful evaluation (see 7.8), one or more of the following steps should be taken in circumstances where these criteria cannot be satisfied in 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 an in situ test demonstrating that a representative sample is being collected.

6.3 Criteria for the homogeneity of the air stream at sampling locations

6.3.1 General

The values of the properties that signify a well-mixed location for sample extraction can be characterized by certain criteria which are given in 6.3.2 to 6.3.6 and in Annex F. Achieving the criteria can be demonstrated using a program of physical tests and computation modelling. Measurements of these parameters are made at the in the sampling plane. Physical test results on constructed systems are unambiguous because all hidden construction details and their effects are accounted for. Physical test results from scale models or computational modelling are more ambiguous without accounting for damper construction, damper settings, turning vanes, fan construction, uneven velocity profiles at the discharge of fans and the many hidden construction details.

6.3.2 Angular or cyclonic flow

The presence of a swirl can adversely affect the mixing of particles in the airflow and degrade the performance of sampling nozzles. The mean flow angle between the flow axis and nozzle axis should not exceed 20°.

6.3.3 Air velocity profile

Air velocities are measured at the grid of points described in ISO 10780. The coefficient of variation, C_V, of the measurements is calculated. The C_V should be less than or equal to 20 % across an area that includes at least the centre two-thirds of the area of the stack or duct.

6.3.4 Gas concentration profile

A tracer gas (e.g. alcohol, sulfur hexafluoride, nitrous oxide, helium) is introduced into the airflow upstream of the sampling location. The tracer concentration is measured at the same grid of measurement points used for the velocity uniformity determination. The C_V of concentration at the measurement points is calculated. The C_V of the tracer gas concentration should be ≤20 % across at least the centre two-thirds of the cross-sectional area of the stack or duct. Also, at no measurement point should the concentration of the tracer gas differ by more than 30 % from the mean value for all of the points.

NOTE Reference [116] provides a comparison of the use of sulfur hexafluoride and nitrous oxide tracers.

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6.3.5 Particle concentration profile

Suitable test aerosol particles are introduced into the airflow upstream of the sampling location. The tracer concentration is measured using the same grid of measurement points as used for the velocity uniformity determination. The C_V of concentration at the measurement points is calculated. The C_V should be ≤20 % across at least the centre two-thirds of the cross-sectional area of the stack or duct.

Test aerosol particles with a D_a of about 10 µm are recommended. This kind of test particle should be used because of the requirement for test aerosol particles whose aerodynamic behaviour clearly exhibits the inertial effects that can adversely influence mixing. They can be relatively easily generated in either monodisperse (single particle size) or polydisperse forms and released into stack or duct flow. Advice on test aerosol injection points is given in Annex F. Favourable results with this particle size result in even better results with aerosol particles of smaller size. See also Annexes F and G for further discussion of aerosol particles in different types of facilities.

In cases where additional data about the relevant size distribution (e.g. activity size distribution) under normal, off-normal and anticipated accident conditions are available, the test aerosol particle size may be selected accordingly.

6.3.6 Summary of recommendations for locations to extract samples from a well-mixed air stream

The recommended characteristics for locations from which to extract samples from a well-mixed air stream are summarized in Table 1.

Table 1 — Summary of recommendations for a sampling location

Characteristic	Methodology	Recommendations
Measurement to determine if flow in a or duct is cyclonic	ISO 10780	The average resultant angle should be less than 20°.
Velocity profile	Selection of points across a section based on the guidance in ISO 10780 for the centre 2/3 of the area of the stack or duct. Additional points or area may be added to adequately cover the region.	C_V should not exceed 20 % over the centre region of the stack or duct that encompasses at least 2/3 of the stack or duct cross-sectional area.
Tracer gas concentration profiles	Selection of points across a section based on the guidance in ISO 10780 for the centre 2/3 of the area of the stack or duct. Additional points or area may be added to adequately cover the region.	C_V should not exceed 20 % over the centre region of the stack or duct that encompasses at least 2/3 of the stack or duct cross-sectional area.
Maximum tracer gas concentration deviations	Selection of points across a section based on the guidance in ISO 10780 for the entire cross-sectional area. Additional points or area may be added to adequately cover the region.	At no point on the measurement grid should the tracer gas concentration differ from the mean value by more than 30 %.
Aerosol particle concentration profile	Selection of points across a section based on the guidance in ISO 10780. Additional points or area may be added to adequately cover the region.	C_V should not exceed 20 % over the centre region of the stack or duct that encompasses at least 2/3 of the stack or duct cross-sectional area.

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7 Sampling system design

7.1 General

The penetration of aerosol particles, gases and vapours of concern from the free stream to the collector or analyser shall be determined.

Performance criteria introduced in this document for monitoring of effluents may be considered as recommendations for sampling systems designed for control monitoring only.

The performance of the sampling system for aerosol particles shall be considered sufficient for normal conditions and for most off-normal conditions if a test under normal conditions with near-monodisperse particles having a D_a of 10 µm yields a penetration value above 50 %. In cases where additional data about the relevant size distribution (e.g. activity size distribution) are available, the test aerosol particle size may be selected accordingly.

The discussion in 7.2 to 7.9 does not cover all possible situations and may be adjusted for particular situations where testing is neither appropriate nor practicable and for local regulations. A risk-based graded approach may be used in the design of systems for sampling radionuclides in stacks and ducts of the nuclear industry. However, formulating such an approach is beyond the scope of this document.

7.2 Volumetric flow measurement

7.2.1 General

Accurate measurements of airflow in both the air sampling system and in the stack or duct being sampled should be provided because they directly impact the accuracy of emissions estimates. Errors are introduced into the calculation of emissions if the emission and sample flow rate units are not based on the same gas density. This becomes significant where airflow is at either elevated or depressed temperature or pressure, for example if the facility is at an elevation of more than 300 m above sea level or if the sample flow meter is on the vacuum side of the air mover. Local regulations may specify the gas density conditions to use for reporting emissions.

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. Typical conditions for standard density flow measurements are a pressure of 101 325 Pa and a temperature of 298 K (25 °C). Flow measurements at these conditions are represented by the symbol q_{std}. The use of so-called mass flow meters in both the emission and sampler airflows, calibrated, can eliminate the need to make density adjustments.

7.2.2 Emission stream flow measurement

The airflow of sampled emission streams should be continuously measured if the flow rate is anticipated to vary by more than 20 % per year (if historical data are available, the 20 % value can be approximated by the standard deviation of the measurements.) Factors such as fan maintenance, the opening of doors and the variations in the number of fans should be taken into account in determining if continuous flow rate is implemented.

If continuous measurement of flow rate is not implemented, then measurements of flow rate should be performed at least annually in accordance with ISO 10780. This standard method, as modified in Annex A, is denoted hereafter as the reference method.

For stacks and ducts where continuous sampling is necessary , the flow measurement and recording system should be capable of determining the mass or volumetric flow rate of the effluent stream with an accuracy that is within 10 % of that measured with the reference method.

Any continuous flow measurement device should be subjected to minimum annual accuracy audits. If the sensor of the continuous flow measurement device is based on electronic or acoustical principles, periodic checks of the instrument zero and span (or linearity) should be made.

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7.2.3 Sample air flow rate and volume measurement

The relative accuracy of the sample flow rate measurement and recording system should be within 10 % of a traceable flow standard. The sample flow sensor should be placed in the sampling system so that it does not cause losses of aerosol particles or reactive radioactive gases. As a consequence, the flow sensor is generally located downstream of the sample collector or analyser. Therefore, the gas density at the flow meter differs from the gas density in the stack or duct.

The sample flow rate should be displayed. If a mass flow meter is not used, pressure and temperature instrumentation should be added to enable calculation of the gas density at the sensor.

If the sampling flow rate does not vary by more than 20 % over the sampling period, as a minimum it should be recorded at the start and the end of a sampling period. For such a case, the total volume sampled, V_T, may be calculated using Formula (1):

$$V_T = \frac{q_1 + q_2}{2} \cdot t_s \tag{1}$$

where

V_T is the total volume sampled, in m^3;

q_1 is the volumetric flow rate indicated by the flow meter at the start of the sampling period, in $m^3 \cdot s^{-1}$;

q_2 is the volumetric flow rate at the end of the sampling period, in $m^3 \cdot s^{-1}$;

t_s is the sampling period, in s.

Continuous flow measurement should be used if the flow rate can vary by more than 20 % during the sampling period. When continuous flow measurement is employed, the flow rate should be recorded at intervals not exceeding 10 min. The total volume of sampled air is based on integration of flow over the entire sampling period. If the time interval between recordings is Δt, expressed in seconds, and the flow rate during the interval (either the true average in the interval, the average of the initial and final values in the interval, or the value at the interval midpoint) is q_i, expressed in cubic metres per second, the total volume of air sampled, V_T, expressed in cubic metres, is calculated using Formula (2):

$$V_T = \sum_{i=1}^{N} q_i \cdot \Delta t \tag{2}$$

where

V_T is the total volume of air sampled, in m^3;

q_i is the volumetric flow rate during the ith interval, in $m^3 \cdot s^{-1}$;

N is the number of intervals, dimensionless;

Δt is the time interval between recordings, in s.

Other integration schemes may be used if the numerically induced errors do not exceed those implicit in the Formula above. The total sample volume, V_T, is based on the flow rate indicated by the flow meter.

If a controller is used to maintain a constant flow rate, the controller should maintain the flow rate within 15 % over conditions that correspond to an initial pressure drop across the collector (usually a filter) or analyser to a value that is twice the initial pressure drop.

If the emission flow rate can vary more than 20 % over a sampling interval, automatic control of the sample flow rate should be used and the sample flow rate should be varied in proportion to the flow rate through the stack or duct. The ratio between sample flow rate and effluent flow rate should be maintained within 20 % of the sample fraction at normal operating conditions.

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An exception may be made for that part of the air monitoring system containing a real-time contamination sensor if its operation depends on a constant internal flow rate.

The flow controller should be tested at conditions similar to the operating conditions.

7.2.4 Leak checks

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

Leakage under flowing conditions into a sample collector, measured with apparatus such as that discussed in Notes 1 or 2, below, should not exceed 1 % of the operational flow rate when the pressure level across the filter or collector is as recommended in NOTE 1.

NOTE 1 Visual inspection and the observation of foreign materials on samples can identify large leaks. If the sampling system is strategically equipped with full-bore ball valves, then parts of the system can be isolated for vacuum or pressure decay measurements or by observing or measuring flow through a blocked system. An explanation of the latter approach is to block flow through the nozzle(s) (or at a transport line connection close to the sampling probe), then apply vacuum to the transport line and measure the leakage rate. For example, a mass flow meter could be attached downstream of the collector or monitor and the vacuum source connected to downstream side of the mass flow meter. The pressure level in the tubing between the collector or monitor and vacuum source would be adjusted to the nominal value encountered during sampling (typically about 4 kPa for sampling systems that involve use of collection filters) by bleeding air into the line downstream of the flowmeter.

NOTE 2 Reference [59] illustrates the use of a chamber and tracer gas method for leak testing of filter holders and continuous monitors under flowing conditions.

NOTE 3 The recommendations of this subclause do not apply to collectors internal to continuous air monitoring instruments.

7.3 Nozzle design and operation for extracting aerosol particles

7.3.1 General

The information in 7.3.2 to 7.3.7 is applicable to sampling from stacks and ducts that have the potential to emit aerosol particles. Extracting the air sample with a properly designed nozzle from a location where the potential contaminants are well mixed in the airflow provides a representative sample during normal conditions and an adequate sample during accident conditions. Background information on the design parameters of sampling nozzles is given in Annex M. Performance recommendations for nozzles are given in 7.3.2 to 7.3.7.

7.3.2 Nozzle performance

M.1 provides a discussion of the relationships of the nozzle performance factors. Performance characteristics of sampling nozzles are tested with liquid aerosol particles with a recommended D_a of about 10 µm. This kind of test particle should be used because of the requirement for test aerosol particles whose aerodynamic behaviour clearly exhibits the inertial effects that can adversely influence mixing. They can be relatively easily generated in either monodisperse (single particle size) or polydisperse forms and released into stack or duct flow. Comparable behaviour should be demonstrated to provide similar transmission values, because liquid particles adhere to walls, while solid particles can rebound or be re-entrained from a surface.

The test aerosol D_a of about 10 µm is recommended because the results should be conservative in most situations as discussed in Annex G. Because radioactivity bearing particles commonly change size as a facility ages or events occur, favourable test results with this particle size means even better performance with reduced uncertainty for smaller aerosol particles size. In cases where additional

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data about the relevant size distribution (e.g. activity size distribution) under normal, off-normal and anticipated accident conditions are available, the test aerosol particle size may be selected accordingly.

The presence of a nozzle should not disturb the aerosol particle concentration in the stack or duct. Accordingly, the frontal area of a nozzle, including the shrouds if so equipped, should not be excessive (e.g. not greater than 15 % of the stack or duct cross-sectional area) and the inlet diameter should not be too small.

7.3.3 Application and performance considerations

7.3.3.1 General

The factors in 7.3.3.2 to 7.3.3.5 should be considered in the selection and use of a sampling nozzle.

7.3.3.2 Location

Sampling should take place at a location where both the aerosol particle concentration and fluid momentum (velocity) are well mixed and thus meet the performance criteria of 6.3.

7.3.3.3 Orientation

For aerosol particle sampling, the nozzle axis should be aligned parallel to the temporal mean flow direction.

7.3.3.4 Transmission and aspiration ratios

A sampling nozzle shall have a transmission ratio within the range of 0,80 to 1,30 over the anticipated range of normal and abnormal conditions for an aerosol with a particle size of 10 µm D_a. Also, the aspiration ratio of a sampling nozzle shall be within the range of 0,80 to 1,50 for the anticipated range of operating conditions. The transmission and aspiration ratios of the selected nozzle design should be traceable to experimental verification of performance for conditions that include the nominal sampling flow rate and range of anticipated sampling flow rates, the nominal free stream velocity and the range of anticipated free stream velocity, and a particle size, D_a, of about 10 µm. In cases where additional data about the relevant size distribution (e.g. activity size distribution) are available, the test aerosol particle size may be selected accordingly. If actual testing is used, the means for determining the transmission and wall-loss ratios should be documented. If reference to previous testing is employed, the equivalency of the selected design and the design that was tested should be documented.

7.3.3.5 Nozzle configuration

The leading edge of the nozzle inlet should have a sharp edge and the external cone angle should not exceed 30°. Other configurations may be used if experimental data show either equivalent or superior performance to the sharp-edged nozzle. If the sampling nozzle is shrouded, the shroud should not have a sharp leading edge. For sharp-edged nozzles, the leading edge of the nozzle should be inspected for damage following installation and subsequent to any maintenance procedures in which the nozzle could be damaged. Studies (e.g. References [50], [85] and [86]) have shown that single-nozzle, shrouded probes have reduced wall losses for particles having an aerodynamic diameter, D_a, greater than 5 µm, in high-velocity streams (velocity greater than 10 m/s) when compared to isokinetic nozzles.

7.3.4 Sampling probes with multiple-inlet nozzles

The previous edition of this document recommended selecting a sampling location where both fluid momentum and contaminants are well mixed with the airflow. The concept of “well mixed” was loosely defined and the deployment of multiple nozzles in circular ducts larger than 201 mm in diameter, or in rectangular ducts with cross-sectional areas greater than 0,093 m^2, was recommended to ensure the possibility of extracting a representative sample. However, it is now recommended that in place of multiple-point sampling, single-point representative sampling should be used, with the requirement

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that potential contaminants be "well mixed" at the sample-extraction location, as specified in the performance criteria of 6.3.

If the effluent stream cannot be adequately mixed and sampled at a single point, probes with multiple inlets have been a solution in the past. Now, in this case, an in-place demonstration of the system providing a representative sample is recommended.

Now it is required that a multi-nozzle probe be capable of the same performance as a single-nozzle probe. A multi-nozzle probe shall, then, in principle, consist of a number of acceptable nozzles. The total sample flow is then increased. Nozzles with an internal diameter smaller than about 10 mm are usually not an option because they have a lower flow and higher losses. It is necessary, in fact, that a nozzle on a multi-nozzle probe perform as well as, or better than, a single nozzle because of particle losses in additional bends and joints.

Multi-nozzle probes may be used where they can be demonstrated, with in-place testing, to provide a representative sample. Some designs of multi-nozzle samplers are discussed in Annex M.

7.3.5 Materials of construction

Nozzles should be constructed of materials that do not react with either the aerosol particles or the vapour constituents of the gas stream. The average surface roughness of the internal regions of nozzle that contact the sampled stream should not exceed 0,8 µm. The average surface roughness of the external region of the sampling nozzle from the inlet plane to a distance of two nozzle inlet diameters from the inlet plane should not exceed 1,6 µm. A shroud should have an average surface roughness that does not exceed 3,2 µm.

7.3.6 Maintenance

The sampling nozzle should be checked periodically for alignment, presence of deposits of foreign materials and other factors that can degrade the performance of the sampling system. If there are background aerosol particles that can produce deposits, a cleaning schedule should be established that does not allow the occlusion of over 5 % of the inlet area of a nozzle. For nozzles that are used to sample air, filtered by a high efficiency particulate air filter (HEPA), the nozzle should be cleaned if there are visible deposits of material on either the internal or external regions of the nozzle, although visible deposits would not be expected if the filters were performing satisfactorily.

7.3.7 New concepts

When new approaches are developed for design and operation of nozzles, such designs may be used in ducts and stacks if it can be demonstrated experimentally that the designs meet or exceed the performance specifications given in 7.3. The test conditions should include experiments to determine the wall losses and aerosol particle transmission under the following conditions:

a) particle sizes, D_a, of about 3 µm, 10 µm and 20 µm at the nominal free-stream velocity and nominal flow rate;

b) maximum and minimum operational or anticipated free-stream velocities for a particle size, D_a, of 10 µm at the nominal sampling flow rate;

c) maximum and minimum anticipated sampling flow rates for a particle size, D_a, of 10 µm at the nominal free-stream velocity.

7.4 Sample transport for particles

7.4.1 General

The transport of aerosol particles from a sampling nozzle to a collector or analyser should take place in such a manner that changes in concentration and size distribution of airborne radioactive materials are minimized within the constraints of current technology.

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7.4.2 Depositional losses

In general, there are some losses of aerosol particles in transport lines due to particle deposition, and any design entails compromises. The design parameters should be carefully chosen to optimize the utility of the overall system. Annex B provides guidance on assessing particle penetration.

The deposition of particles inside the transport lines from the extraction point to the filter should be determined experimentally using test aerosol particles or by the use of documented computer codes or documented and referenced hand calculations.

The performance of the sampling system is considered sufficient under normal, off-normal and anticipated accidental conditions, if a test with near monodisperse particles of 8 µm to 12 µm (D_a) yields a penetration value above 50 %.

A D_a of 10 µm is mentioned when no information on aerosol size distribution is available. In cases where additional data about the relevant size distribution (e.g. activity size distribution) are available, the test aerosol particle size can be selected accordingly.

Particles with a D_a smaller than 10 µm have a higher penetration due to lower deposition rates. Particles with a D_a larger than 10 µm can be expected to have smaller penetrations. On the other hand, for dry particles, the penetration can increase with particle size due to resuspension. Therefore, penetration measurements with test aerosol particles having a D_a of 10 µm can be considered to address the penetration minimum.

In cases where additional data about the relevant size distribution (e.g. activity size distribution) are available, the test aerosol particle size may be selected accordingly.

Documented computer codes or documented and referenced hand calculations, based on verified experimental data, may also be used to assist in the design of the sampling line and selection of test aerosol particles. The computations may be used to extrapolate measured penetration values to other particle sizes, and may be used also in the case of a modification of the flow rate or changes in sampling-line geometry. Annex B describes such calculation methods.

The straight sections of transport tubes, particularly horizontal tubing sections, should be kept as short as possible, and the number of bends should be minimized within the geometrical constraints of the application. There should be no inward-facing steps at the tubing connections that cause more than a 1 % reduction in tube diameter. The tubing ends should be free of burrs and crimping. Bends should have a curvature ratio of at least 3. Flattening, which is defined as the ratio of the minimum tube diameter to the original tube diameter, should not be less than 0,85. The user should note that special fabrication techniques can be needed to meet these specifications.

7.4.3 Corrosion

The internal walls of the transport system should be constructed of materials that are minimally reactive to inadvertently deposited aerosol particles or to reactive vapour compounds that can be present in the sample. The materials of construction for external walls and seals between sampling system components should also be compatible with the environment to which they are exposed. Materials recommended for the nuclear industry are stainless steel for general applications and polytetrafluoroethylene for radioiodine.

7.4.4 Electrostatic effects and flexible tubes

If plastic is used in aerosol-particle transport systems, internal electric fields can cause particle losses[27]. In particular, plastic tubing that has been flexed can show abnormally high wall deposits as seen in Reference [77]. A transport system should be constructed of materials, such as metals or conductive plastics, that do not maintain internal electrostatic fields. In many applications, it is useful or convenient to employ flexible, non-metallic tubing to connect a sampler or analyser to a transport line, particularly if it is necessary to isolate an analyser from mechanical vibrations in the sample transport line. The inside diameter of the plastic line should not be smaller than the inside diameter of the components with which it is connected and the bend curvature ratio should not be less than three.

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nor may the curvature of a bend cause more than a 15 % change in the inside diameter of the tube. If non-conductive, flexible tubing is used, the line length should be kept as short as practicable and should not exceed 0,5 m.

Of the flexible tubes that can be categorized as non-conductors, neoprene and natural rubber are recommended to minimize electrostatic deposition of particulate matter[27]. If radioiodine is present in the effluent stream, the materials suggested in Annex C should be used.

7.4.5 Smoothness of internal surfaces

To minimize aerosol-particle depositional losses and to facilitate decontamination, the internal surfaces of transport lines should be as close to hydraulically smooth as practical. Drawn tubing or other types of tubes with Ra/d_t less than approximately 5×10^{-5} are acceptable, where Ra represents the height of surface roughness of the internal tube walls and d_t is the tube diameter. This criterion requires an average surface roughness of approximately 1,6 µm or less for tube sizes that are in the order of 25 mm in diameter.

7.4.6 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. It can be necessary to thermally insulate, and in some cases heat, the sample transport line to prevent condensation. For situations in which heating of the sampling line can result in unacceptably high temperatures at a collector or analyser, a dilution system should be considered. However, care should be exercised to ensure that the dilution process does not produce condensation at the mixing location. Experimental or numerical analyses should 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.

7.4.7 Cleaning transport lines

An additional consideration at some facilities is the necessity to clean transport lines. For applications in which the sampled air is HEPA-filtered, cleaning might not be necessary within the expected lifetime of the installation. However, for applications where background aerosol particles are present, it can be necessary to periodically remove deposits from the internal walls of the transport system. If, after inspection, there is an indication of deposits inside the nozzle inlet, the transport line should be inspected and, if deposits are visible inside the transport line, the line should be cleaned or replaced. For systems that sample non-HEPA-filtered air containing background aerosol particles, regular inspections are recommended. If an estimate can be made of the rate of deposition of all aerosol particles on the internal walls of the system, the system should be cleaned when the mean mass of deposited material exceeds 1 g/m^2. Measuring the mass of material deposited is possible only in systems designed to allow it. Alternatively, a cleaning schedule can be set up based on performance of the transport system. The interval between cleanings should be such that accumulations of wall losses cause a reduction of no more than 10 % in the overall penetration of aerosol particles with a D_a of 10 µm through the sampling system.

In cases where additional data about the relevant size distribution (e.g. activity size distribution) are available, the test aerosol particle size may be selected accordingly.

In addition, if there are indications of re-entrainment of deposits from the walls of the sampling system or if there has been sampling of easily re-entrainable aerosol particles (e.g. flakes), either of which can cause anomalous radiological data to be gathered, the system should be cleaned. Decontamination and waste-production should be taken into account for any cleaning procedure.

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7.5 Gas and vapour sample extraction and transport

Much of the discussion in 7.4 applies generally for sampling particles and gases. However, consideration should be given to extracting and transporting vapour and gases to determine where special system design can be required.

When non-reactive gases and vapour are the only species being sampled, the sampling recommendations are considerably simpler than those for aerosol particles. The recommendations for minimizing particle line-loss are irrelevant. Deposition in long transport lines and condensation due to temperature changes in the line should be avoided. If the flow can contain only gaseous contaminants, the nozzle design is not critical, but the sampling should take place at a location where the flow is well mixed and meets the criteria of 6.3. The nozzle design can be simply an open-ended or perforated tube. The extraction and transport requirements that apply include extracting the sample from a well-mixed location and avoiding water and vapour condensation in the transport and collection system (except where condensation is used as the collection method).

When non-reactive gases, vapour and particles are being simultaneously sampled, the particle sample extraction and transport requirements should apply, which also ensures adequate delivery of the gas and vapour sample. The remaining consideration, then, is the selection of suitable collection devices. The gas or vapour-collection device should be located downstream of a particle filter to eliminate potential radionuclide interferences by particulate matter. The minimum penetration for vapour or gas samples from the free stream to the collector or analyser should be 50 %.

When working with reactive gases and vapour, particular attention should be paid to the sampling-system construction materials and to avoiding condensation. The construction material should have minimum reactivity with the gas. Consideration should be given to the advantages of providing a separate sampling system for the gases whenever the construction materials that are for the transport of the particle and gas samples are incompatible. In situations where even a low level of reactivity cannot be avoided, the length of the transport line should be kept to a minimum. The penetration of the gas or vapour through the complete extraction and transport system should be documented. The minimum penetration for vapour or gas samples from the free stream to the collector or analyser should be optimized, with the objective of achieving 50 %. If long transport lines are unavoidable, consideration should be given to the effect of transport and detection delay time caused by deposition, chemical transformation and subsequent resuspension. Consideration should also be given to how significant the effect the delay has on the timeliness, interpretation and usefulness of the resulting data. Although rapid changes in the emission can become attenuated over a long time interval relative to the change in emission, the data can still be useful and quantitative when interpreted in that light. Annexes C, H and K provide guidance on the sampling of radioiodine, tritium and carbon-14, respectively. Annex B provides guidance on verifying the transport of sampled constituents.

7.6 Collection of particle samples

7.6.1 General

Depending on the purpose of the sample, a wide range of techniques is available for monitoring or collecting airborne particles. Particles can be collected on filters for retrospective determination of total mass, radionuclide activity, or chemical form, in cyclones or cascade impactors for determination of particle size distribution, on electron microscope substrates for determination of particle morphology or they can be observed using light-scattering or time-of-flight techniques for measuring the number, concentration and size. Near-real-time devices, such as alpha continuous air monitors (CAMs), typically collect particles on a filter or impaction substrate and monitor the accumulation of radioactive substance with time. Critical issues for selection and operation of particle collection devices are as follows:

— appropriate presentation of the sample for real-time analyses or preservation of the sample for retrospective analyses;

— adequate flow rates and detection efficiencies to meet sensitivity requirements;

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— minimal in-leakage within the collector;

— minimal particle loss within the collection zone.

7.6.2 Filter media

Selection of a particle-collection filter should be based on careful consideration of collection efficiency for the typical particle size in the duct, the area of the filter, the pore size, the filter's resistance to air flow, the background radioactive material of the filter, filter fragility, cost, self-absorption within the filter and chemical solubility. If the performance characteristics of the front and back surfaces of the filter are not within 5 % of each other for the intended purpose of the sample, there should be a clear means of identifying the appropriate surface for particle collection. The filter should be strong enough to maintain its integrity at the required sample flow rates and during handling activities.

When filter media are used, a backup support that produces a negligible pressure drop should be used behind the filter to prevent filter distortion or deterioration. The filter holder should provide adequate structural support while not damaging the filter, should prevent sampled air from bypassing the filter, should facilitate changing the filter and should facilitate decontamination. If gaskets are used to seal the filter to the backing plate, the gasket should be in contact with the filter along the entire circumference to ensure a good fit. The gasket should be periodically inspected to detect degradation and eliminate build-up of dust or filter material, which can result in sampled air bypassing the filter.

To reduce the uncertainty associated with collection efficiency, filters that are used for sampling airborne radioactive particles should have a minimum efficiency of 95 %. Efficiency values should be applicable to the conditions of use, for example, the collection efficiency depends on the face velocity[72].

If published or manufacturer's data on filter collection efficiency are not available for the particle sizes of interest, then the efficiency should be determined by the user. This can be done by placing a highly efficient membrane or glass fibre filter behind the filter of interest and then comparing the mass penetrating to the backup filter to the total mass collected on both filters (see Reference [51]). If a filter with an efficiency lower than 95 % is required to meet the overall sampling objectives, then a correction for efficiency should be made. Because filter efficiency is a function of air flow rate, care should be taken to maintain a sample flow rate that is adequate to achieve the desired collection efficiency.

If penetration of radioactive material into the collection media or self-absorption of radiation by the material collected can reduce the count rate by more than 5 %, a correction factor should be used. A dual filter method can also be used to measure the absorption efficiency in the filter medium[51]. Evaluation of self-absorption in the material collected may require separate radiochemical analyses.

Annex D illustrates the type of information that is useful in selecting an appropriate filter for sampling airborne radioactive particles. This includes physical and performance characteristics of a number of typical coarse-fibre, fine-fibre and membrane-type filters.

7.7 Collection of gas and vapour samples

7.7.1 General

Airborne radioactive volatile materials and noble gases (e.g. krypton) are frequently present in nuclear facility effluents. Their sampling and collection require techniques and methods that are different from those used in particle sampling. This topic may be divided into two general methods of sampling:

a) sampling with retention of specific constituents of the air stream, and

b) sampling without constituent separation. Annexes C, H, K and N provide further guidance specific to radioiodine, tritium, carbon-14 and ruthenium-106, respectively.

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7.7.2 Sampling with retention of specific constituents

Sampling with removal and collection of specific constituents requires a detailed knowledge of the chemical and physical properties of the radioactive material of interest, including possible interfering materials, such as particulate matter and accompanying non-radioactive gases (e.g. acids and organic chemicals). The many possible combinations of the properties of the constituents being measured and the accompanying airborne materials require careful study to select the optimum collector. Gases and vapour components can be soluble in water, can be highly reactive with certain solutions, can dissolve in specific non-aqueous solvents, or can be retained on specific solid adsorbents or other specifically prepared media. In general, continuous or extended samples are taken when separation and removal of a constituent is required. Sampling rates should be established to ensure adequate sensitivity for the selected radioassay method and should be compatible with the collector performance characteristics. Avoiding sample breakthrough should also be considered when choosing the sampling rate and duration. The principal collection methods include solid absorbents (such as carbon, zeolites, silica gel and metal beds), condensation, gas absorption and catalytic or chemical reaction (see Reference [23]).

The retention of certain sampled gaseous or vaporous constituents are specifically addressed in the annexes. Annex H discusses Tritium, Annex K discusses ^{14}C and Annex N covers ^{106}Ru.

7.7.3 Sampling without constituent separation

In some instances, a sample of air containing gaseous radioactive constituents can be desired for measurement of the activity concentration of airborne materials and its trend. Examples are noble gas isotopes, tritium and activated gases near a reactor. Volume collection and flow-through detectors are the two principal methods for total gas sampling or monitoring.

Because the constituent radioactive materials of interest might not be concentrated with a particular flow-through or volumetric collection device, insufficient sensitivity of detection can limit or preclude their use. It is necessary to evaluate each situation individually to determine the feasibility of the gross sample measurement.

Volume collection methods include the following:

— using an evacuated container that can be valved open to the stream of interest, then sealed and returned to a laboratory for measurement of all the activity or the activity of individual constituents;

— passing the stream through the sample vessel until the vessel is completely purged, then closing the inlet and outlet valves;

— pumping the sample stream into deflated bags (of a non-adsorbing material) for subsequent compression and analysis;

— compressing the sample stream into a vessel for real-time or subsequent analysis.

A flow-through sample vessel may also be an ion chamber whose ion current reflects the activity concentration of material in the gas. Care should be taken to keep the gas well above its dew point in the sampling system and ionization chamber. A gradual build-up of contamination in the chamber usually occurs, which increases the observed activity rates.

Flow-through chamber samplers can be similarly monitored by gamma-ray scintillation crystal counters or other detector held adjacent to or inserted in a well in the chamber wall. An increased background from contamination can be expected in these samplers, and the chamber should be periodically decontaminated to avoid errors from this source. Prior filtration of the air stream can assist in keeping the chamber clean when gaseous constituents alone are being measured. A flow-through sampling system, which is frequently used at power reactors for accident monitoring, involves placement of a high- or wide-range detector mounted directly inside or outside the effluent stack or duct.

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7.8 Evaluation and upgrading of existing systems

If an existing air sampling system was not designed to the performance requirements and recommendations of this document, an evaluation of the performance of the system, including the location of the probe, is recommended. If deficiencies are discovered, an evaluation study should be performed to determine if a retrofit is recommended and possible. Arriving at a suitable solution requires optimizing among competing factors. Guidance on the process of optimization for radiological protection has been described in Reference [10]. Evaluation of existing systems should be undertaken using proven techniques.

7.9 Summary of performance criteria and recommendations

Throughout this document, performance criteria for various elements have been included in the discussion of each element. For convenience, they are summarized in Table 2. These criteria cover aspects of system design and operation. The approach followed in this document is to give performance criteria and recommendations according to guidance values when no information is available on the type of stream being measured. When information is available on the stream being measured (e.g. aerosol particle size distribution), then these specific values should be used.

A facility sets action levels for a particular radionuclide in an aerial discharge in response to the authorization discharge levels for that facility set by the regulator of that facility. Action levels can be either a control mechanism used by the facility itself, or levels that, if reached, necessitate official notification to the regulator.

Performance criteria for the sampling and measurement of a specific radionuclide are determined by the facility, in consultation with the regulator and Table 2, in order to provide accurate monitoring of the specific radionuclide.

Table 2 — Summary of performance criteria and recommendations

Performance criteria and recommendations[a]	Reference
The performance of the sampling system for aerosol particles shall be considered sufficient for normal, off-normal and anticipated accidental conditions, if a test under normal conditions with monodisperse particles with a D_a of 10 µm yields a penetration value ≥50 %.	Clause 7 and 7.4.2
The penetration of the gases and vapours of concern from the free stream to the collector or analyser should be considered sufficient if it is ≥50 %.	Clause 7 and 7.5
The nozzle should have a transmission ratio ≥80 % and ≤130 % for particles with a D_a of 10 µm.	7.3.2
Recommendations for a suitable sampling location are as follows: a) coefficients of variation over the central 2/3 by area of the cross-section within 20 % for with a D_a of 10 µm, gaseous tracer, aerosol particle tracer and gas velocity; b) the tracer gas concentration should not vary from the mean by >30 % at any point on the measurement grid (see 6.3.4). c) Flow angle ≤20° relative to the long axis of the stack or duct and the nozzle inlet	6.3
Effluent flow rate continuous measurement recommended if flow variation is greater than ±20 % in a year.	7.2.2

NOTE 1 A D_a of 10 µm is mentioned when no information on aerosol size distribution is available. In cases where additional data about the relevant size distribution (e.g. activity size distribution) are available, the test aerosol particle size can be selected accordingly.

NOTE 2 This table is based on presence of aerosol particles in the stack or duct. If no particles are emitted, criteria can be based on gas characteristics only.

[a] The criteria given in this table are recommendations based on user experience in actual testing. These recommendations for individual uncertainties and biases result in a satisfactory overall uncertainty.

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Table 2 *(continued)*

Performance criteria and recommendations[a]	Reference
Effluent and sample flow rate should be measured within ±10 %.	7.2.2 and 7.2.3
Continuous sample flow rate measurement and control are recommended if the stack or duct flow varies by more than ±20 % during a sample interval. Flow control should be within ±15 %.	7.2.3

NOTE 1 A D_a of 10 µm is mentioned when no information on aerosol size distribution is available. In cases where additional data about the relevant size distribution (e.g. activity size distribution) are available, the test aerosol particle size can be selected accordingly.

NOTE 2 This table is based on presence of aerosol particles in the stack or duct. If no particles are emitted, criteria can be based on gas characteristics only.

[a] The criteria given in this table are recommendations based on user experience in actual testing. These recommendations for individual uncertainties and biases result in a satisfactory overall uncertainty.

8 Quality assurance and quality control

Every facility that conducts sampling and monitoring of effluent radioactive substances should have a quality assurance (QA) programme. The purposes of a QA programme are to provide assurance to facility management, regulatory agencies and the public of the validity of the data from the sampling and monitoring of released radioactive substances, and to identify any deficiencies in the sampling equipment and procedures in order to take corrective action. The tools used to accomplish these objectives include documentation, calibration, maintenance and inspection. As a minimum, the QA programme should address the quality aspects of the sampling of effluent radioactive substances in the following areas:

a) organization:

— organizational responsibilities;

— administrative controls;

— reporting and notification system;

— documentation;

— personnel qualifications;

b) design of the sampling system:

— source terms;

— selection of extraction locations;

— selection of sampling and monitoring devices;

— selection of collection procedures;

c) operating procedures:

— sample extraction procedures;

— sample collection procedures;

— system operation procedures;

— calibration procedures;

— data analysis;

— maintenance and check procedures;

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— maintenance procedures;

— check and test procedures;

— status;

— disposition of non-conformant items and conditions;

— corrective action programme.

Additional information relating to inspections and calibrations particularly relevant to air sampling systems is presented in Annex J.

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