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

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

Reference number
ISO 2889:2010(E)

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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.

ISO 2889 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiation protection*.

This second edition cancels and replaces the first edition (ISO 2889:1975), which has been technically revised.

Introduction

This International Standard 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 International Standard 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 International Standard 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 International Standard 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 International Standard sets forth performance criteria and recommendations to assist in obtaining valid measurements of the concentration of airborne radioactive materials in ducts or stacks.

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

1 Scope

This International Standard 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 International Standard 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 International Standard, 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 International Standard in all conditions with a sampling system designed for normal operations only. Under off-normal conditions, the criteria or recommendations of this International Standard still apply; however, for accident conditions, special or separate accident air sampling systems can be necessary.

2 Normative references

The following referenced documents are indispensable for the application 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.

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

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 When a chemical reaction takes place during absorption, the process is called chemisorption.

3.3
accident (conditions)
upset conditions that can lead to the release of abnormal amounts of radionuclides

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 An aerosol is not only the aerosol particles.

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

NOTE 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 comprised of particles with a range of sizes

NOTE 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

3.12
analyser
device that provides for near real-time data on radiological characteristics of the gas (air) flow in a sampling system or duct

NOTE 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 efficiency
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 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
COV
quantity that is the ratio of the standard deviation of a variable to the mean value of that variable

NOTE 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 concentration, gas composition, particle-size distribution, temperature or pressure in a sample stream

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 particles) in a sample stream

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 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 See also 3.92.

3.26
detection limit
minimum input signal to an instrument that can be said, with a predetermined confidence level, to exceed the inherent noise of the instrument

3.27
droplet
liquid aerosol particle

3.28
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

3.29
effluent
waste stream flowing away from a process, plant, or facility to the environment

NOTE This International Standard applies to the effluent air that is discharged to the atmosphere through stacks and ducts.

3.30
emission
contaminants that are discharged into the environment

3.31
emit
discharge contaminants into the environment

3.32
extractive sampling

NOTE See 3.72.

3.33
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 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.

3.34
geometric mean of a variable
x_g
value given by Equation (1) for N observations of a random variable x_i:

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

3.35
geometric standard deviation

s_g

the geometric standard deviation for N observations of a random variable, x_i, calculated from Equation (2):

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

where x_g is the geometric mean of the random variable

3.36
high-efficiency particulate air filter
HEPA filter

high-efficiency filter used for removing aerosol particles from an air stream

NOTE 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 an International Standard.

3.37
humidifier

device for adding water vapour to a sample stream

3.38
hydraulic diameter

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

NOTE Generally, it is four times the cross-sectional area divided by the perimeter.

3.39
impaction

process by which aerosol particles are removed from an air stream by striking an object in the air stream

NOTE 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 stream or stream in the duct or stack

3.41
interception

process by which aerosol particles 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 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 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
LLD
lower limit of detection

3.45
may
in regulatory applications, indicates that an action is permissible but not mandatory

3.46
membrane filter
filter medium consisting of thin, organic-based films having a range of selectable porosities and controlled composition

NOTE Thin, porous metallic filters are sometimes also called membrane filters.

3.47
mixing element
device placed in a stack or duct that is used to augment the mixing of the contaminant mass with the fluid

3.48
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

3.49
nozzle
device used to extract a sample from an effluent stream and transfer the sample to a transport line or collection device

NOTE Within the nozzle, there is a transition zone where the sample stream adjusts to the conditions in the transport line.

3.50
nozzle exit (plane)
imaginary plane across the cross-section of a transport system that divides the nozzle region from the transport line

NOTE 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.

3.51
nozzle inlet (plane)
imaginary cross-sectional inlet plane of a nozzle where the flow first enters the transport system

NOTE In the special case of a shrouded nozzle, the inlet is referenced to the inner nozzle rather than the shroud.

3.52
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 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.

3.53
off-line system
system whereby a sample is withdrawn from the effluent stream and analysed at a location that is remote from the region where extraction takes place

3.54
off-normal condition
condition that is unplanned and which presents a gap with normal conditions

EXAMPLES Accidents and equipment failure.

3.55
particle
aggregate of molecules, forming a solid or liquid, ranging in size from a few molecular diameters to several millimetres

3.56
particle, large
particle that has an aerodynamic diameter greater than 10 µm

3.57
particle-size distribution
distribution of particle size as a function of mass or activity rather than number

3.58
penetration
ratio of the concentration at the outlet of the sampling system, transport lines included, to that in the duct or at the stack

3.59
potential emission
radionuclides that can be released to the environment from a facility in the absence of control equipment

3.60
precision
closeness of agreement between indications obtained by replicate measurements on the same or similar objects under specified conditions.

NOTE 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.

3.61
probe
tubing or apparatus inserted into a stack or duct through which a sample of the stream is withdrawn

NOTE A probe usually refers to one or more nozzles and part of the transport line.

3.62
profile
distribution of air velocity, of gas concentration or of particle concentration over the cross-sectional area of the stack or duct

3.63
quality assurance
planned and systematic actions necessary to provide confidence that a system or component performs satisfactorily in service and that the results are both correct and traceable

3.64
radionuclide
unstable isotope of an element that decays or converts spontaneously into another isoptope or different energy state, emitting radiation

3.65
record sample
sample that is collected for reporting purposes

NOTE Record samples are often analysed off-line.

3.66
reference method
apparatus and instructions for providing results against which other approaches may be compared

NOTE The application of a reference method is assumed to define correct results.

3.67
representative sample
sample with the same quality and characteristics for the material of interest as that of its source at the time of sampling

3.68
sample
portion of an air stream of interest or one or more separated constituents from a portion of an air stream

3.69
sample-extraction location
location of extraction of a sample from the air

NOTE Location of inlet of the sampling system.

3.70
sampler
device that collects or analyses constituents of the air sample

3.71
sample stream
air that flows through a sampling system

3.72
sampling
process of removing a sample from the free air and transporting it to a collector or an analyser (monitor)

3.73
sampling environment
conditions of the air flow and gas within a stack that can influence the sampling process

NOTE Factors to take into account include pressure, temperature and molecular composition of the gas.

3.74
sampling location

NOTE See 3.69.

3.75
sampling plane
cross-sectional area where the sample is extracted from the air flow

3.76
sampling system
system consisting of an inlet, a transport line, a flow conditioning system and a collector or monitor

NOTE Depending upon the application, a flow conditioner might not be used in the sampling system.

3.77
sedimentation velocity
terminal (maximum) velocity an aerosol particle attains in quiescent fluid (air) as a result of the gravitational force

3.78
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 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.

3.79
shall
in regulatory compliance, indicates that an action is mandatory

3.80
should
in regulatory compliance, indicates that an action is desirable but not mandatory

3.81
shroud
aerodynamic decelerator placed around and extending beyond a sampling nozzle to reduce sampling biases

3.82
standard conditions
temperature of 25 °C and a pressure of 101,325 kPa

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

3.83
transmission ratio
ratio of the aerosol particle concentration at the nozzle outlet to that in the free stream

NOTE It is stated whether a mass or activity basis is used.

3.84
transport line
part of a transport system between the nozzle exit plane and the entrance plane of a collector or analyser

3.85
transport system
all components of a sampling system, excluding the collector or analyser

3.86
turbulent flow
flow regime characterized by bulk mixing of fluid properties

NOTE 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.

3.87
uncertainty
parameter characterizing the dispersion of the value of a measurand, based on the true value of a quantity

NOTE The uncertainty is typically stated at a given statistical level of confidence (e.g. 95 %).

3.88
uncertainty analysis
procedure for estimating the overall impact on the accuracy or precision of a dependent variable as a result of the estimated uncertainties of the independent variables

3.89
vapour
gaseous form of materials that are liquids or solids at room temperature, as distinguished from non-condensable gases

NOTE Vapours are gases but carry the connotation of having been released or volatilized from liquids or solids.

3.90
velocity profile
distribution of the velocity values at a given cross-section in a stack or duct

3.91
volatile
having a high vapour pressure, which allows significant quantities of material to become gaseous at the prevailing temperature

NOTE In this International Standard, the stack temperature is generally considered as the reference.

3.92
wall loss
loss of sample constituents to the internal walls of a sampling system

NOTE 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 are used.

A	Cross-sectional area of a stack or duct, expressed in square metres
A_e	Aspiration efficiency of a sampling nozzle (dimensionless)
B	Bias (dimensionless)
B_CAL	Calibration bias (dimensionless)
B_L	Overall bias limit (dimensionless)
B_PAR	parameter estimate bias (dimensionless)
B_TST	design and test bias (dimensionless)
C	Cunningham's slip correction for aerosol particles (dimensionless)

C_{af}	Velocity-averaging correction factor for determining flow rate in a stack or duct from a line average velocity taken with an acoustic flow meter (dimensionless)
C_{P}	Pressure coefficient for a Pitot tube (dimensionless)
C_{pt}	Velocity-averaging correction factor for determining flow rate in a stack or duct from a single-point reading with a Pitot tube (dimensionless)
C_{ta}	Velocity-averaging correction factor for determining flow rate in a stack or duct from a single-point reading with a thermal anemometer (dimensionless)
c_{A}	Effluent activity concentration, expressed in becquerel per cubic metre
c_{e}	Activity or aerosol particle concentration at the exit plane of a transport system component (activity or particle mass or particle count per cubic metre)
c_{i}	Activity or aerosol particle concentration at the inlet plane of a transport system component (activity or particle mass or particle count per cubic metre)
c_8	Activity or aerosol particle concentration in the undisturbed free stream at the nozzle location (activity or particle mass or particle count per cubic metre)
D_{a}	Aerodynamic particle diameter, expressed in micrometres
De	Dean number of a flow bend, $De = Re/R_{\mathrm{o}}^{1/2}$ (dimensionless)
d_{t}	Inside diameter of a transport system component (e.g. tube), expressed in metres
E	Average radionuclide stack emission rate over the period of integration, expressed in becquerel per second
E_{average}	Stack emission rate, expressed in becquerel per second
E_{c}	Uncertainty associated with determining the calibration factor (dimensionless)
E_{QT}	Total uncertainty in the volume of air (dimensionless)
E_{s}	Uncertainty in reading the flow-meter scale (dimensionless)
E_{t}	Uncertainty associated with the measurement of the sampling time (dimensionless)
F_{k}	Fluctuation constant (dimensionless)
L	Length of a section of tubing, expressed in metres
L_{c}	Confidence limit
L_{LD}	Lower limit of detection, LLD
l_{W}	Wall losses of aerosol particles in transport system components (dimensionless)
M	Mean molar mass of a gas, expressed in kilograms per mole

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)
N	Number of points or observations
P	Overall penetration of sample through a transport system (dimensionless)
P_j	Penetration of sample through the jth component of a transport system (dimensionless)
p	Pressure, expressed in pascals
p_{std}	Standard pressure, equal to 101,325 kPa
Q	Volume of effluent that produced the sample at stream temperature, pressure, and gas composition, expressed in cubic metres
Q_T	Total volume of gas (air) sampled, expressed in cubic metres
q	Volumetric flow rate, expressed in cubic metres per second
q_a	Volumetric flow rate at actual temperature and pressure conditions, expressed in cubic metres per second
q_{std}	Volumetric flow rate at standard conditions, equal to 25 °C and 101,325 kPa, expressed in cubic metres per second
R	Individual gas constant for a particular gas, equal to R_u/M, expressed in kilojoules per kilogram-kelvin
R_c	Radius of curvature of a pipe bend, expressed in metres
R_o	Curvature ratio ($R_o = R_c/d_t$) (dimensionless)
R_u	Universal gas constant, equal to 8,314 J/(mol·K)
Ra	Surface roughness, expressed in micrometres
Re	Reynolds number of flow in a tube, equal to $\rho U_m d_t/\mu$ (dimensionless)
r	Resuspension rate, expressed in reciprocal seconds
r_n	Net count rate (gross minus background) of the sample, expressed in counts per second
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 kelvin
T_a	Temperature in stack or duct, expressed in kelvin
T_{std}	Standard temperature, equal to 298 K

t	Time, expressed in seconds
t_{samp}	Time period over which sampling is performed, expressed in seconds
U_{m}	Spatial mean velocity of gas (air) in a flow tube, expressed in metres per second
V	Velocity, expressed in metres per second
V_i	Velocity at the midpoint of the *ith* element, expressed in metres per second
V_{std}	Equivalent velocity at standard conditions (25 °C and 101,325 kPa), expressed in metres per second
v_{d}	Deposition velocity due to Brownian diffusion or turbulent inertial deposition on the wall of a transport tube, expressed in metres per second
v_{e}	Effective deposition velocity of contaminant at the wall of a transport tube, expressed in metres per second
v_{g}	Sedimentation velocity of an aerosol particle, expressed in metres per second
v_{ge}	Cross-stream component of gravitational settling velocity, expressed in metres per second
α	Angular coordinate of a tube cross-section, expressed in degrees or radians
δ	Uncertainty
ε_{d}	Detection efficiency, expressed in reciprocal becquerel-seconds
ε_{f}	Collection efficiency (dimensionless)
$\varepsilon_{\mathrm{Ts}}$	Transport efficiency
λ	Decay constant, expressed in reciprocal seconds
μ	Dynamic viscosity of a gas, expressed in pascal-seconds
θ	Flow angle, expressed in degrees or radians
ρ	Density, expressed in kilograms per cubic metre
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	Variance
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 vertical, expressed in degrees or radians

5 Factors impacting the sampling program

This International Standard 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.

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 International Standard for normal conditions should be considered as recommendations for off-normal conditions.

6 Sample extraction locations

The sampling 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” addresses several criteria that are given in 6.2. The designer should design the ventilation system to provide a favourable location where the sample can be extracted from a well mixed stream (see 6.3). In this case, the sampling probe may contain a single nozzle. In circumstances where the well mixed criteria are not achieved, a multi-nozzle probe may be used or can be required to get a representative sample. The design and operation of sampling probes are described in 7.2 and Annex M.

Following a careful evaluation (see 7.7), 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 International Standard.

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.

6.1 General requirements for sample extraction locations

The stack or duct geometry and the airflow within should be fully understood. Usually, for a stack, the sample extraction location should be situated between the discharge of the fan(s) and the stack exit point, with the provision that the location should not be so close to the stack exit that wind effects can significantly influence the velocity profile at the sampling location. Typically, in 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.

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

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

The values of the properties that signify a well mixed location for sample extraction can be characterized by certain parameters that shall be determined through the series of tests, examples of which are given in 6.2.1 to 6.2.5 and in Annex F. These measurements are made in the sampling plane.

6.2.1 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°.

6.2.2 Air velocity profile

Air velocities are measured at the grid of points described in ISO 10780. The coefficient of variation, COV, of the measurements is calculated. The COV 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.

6.2.3 Gas concentration profile

A tracer gas (e.g. alcohol, sulfur hexafluoride, 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 COV of concentration at the measurement points is calculated. The COV of the tracer gas concentration should be $\leqslant 20$ % 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.

6.2.4 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 COV of concentration at the measurement points is calculated. The COV should be $\leqslant 20$ % 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 flow.

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.

6.2.5 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 stack 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.	COV should not exceed 20 % over the centre region of the stack that encompasses at least 2/3 of the stack 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.	COV should not exceed 20 % over the centre region of the stack that encompasses at least 2/3 of the stack 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.	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.	COV should not exceed 20 % over the centre region of the stack that encompasses at least 2/3 of the stack cross-sectional area.

6.3 Designing effluent discharge systems for sampler placement

Extracting a representative sample from a stack or duct is best accomplished where the potential radioactive constituents are well mixed with the airflow. When designing new emission units, or remodelling old units, the designer should incorporate design features that promote mixing downstream of the fans, abatement equipment and all additions to the bulk flow.

NOTE 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 McFarland, *et al.* (1999a), McFarland, *et al.* (1999b), Seo, *et al.* (2006), and Han *et al.* (2007) provide tests of features that promote mixing. Previously tested configurations can be used and scaled. There are documented tests in published literature and technical reports: Rodgers, *et al.* (1996); Ballinger, *et al.* (2004); Glissmeyer (2001); Glissmeyer and Maughan (2001); Glissmeyer and Maughan (1998a); Glissmeyer and Maughan (1999); Glissmeyer and Maughan (1998b); Glissmeyer, *et al.* (2002); and Glissmeyer (2006).

7 Sampling system design

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 International Standard 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 7.1 to 7.8 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 International Standard.

7.1 Volumetric flow measurement

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 kPa and a temperature of 298 K (25 °C). Flow measurements at these conditions are reported in units of m^3_{std}/s (or m^3_{std}/min) and 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.

7.1.1 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 the requirement for continuously measuring flow rate.

If continuous measurement of flow rate is not needed, then periodic manual 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 that it is necessary to monitor continuously, 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.

7.1.2 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, Q_T, may be calculated using Equation (3):

$$Q_T = \frac{q_1 + q_2}{2}(t_2 - t_1) \tag{3}$$

where

q_1 is the volumetric flow rate indicated by the flow meter at the start of the sampling period, t_1, expressed in cubic metres per second;

q_2 is the volumetric flow rate at the end of the period t_2, expressed in cubic metres per second.

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, Q_T, expressed in cubic metres, is calculated using Equation (4):

$$Q_T = \sum_{i=1}^{N} q_i \Delta t \tag{4}$$

where N is the number of intervals.

Other integration schemes may be used if the numerically induced errors do not exceed those implicit in the equation above. The total sample volume, Q_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.

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.

7.1.3 Leak checks

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

Leakage under flowing conditions should not exceed 1 % of the nominal sampling flow rate. Bypass around a sample collector should be less than 0,1 %.

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 for a measuring flow through a blocked system. A method of carrying out the latter approach is to block the flow through the nozzle, then apply vacuum to the transport line and measure the leakage rate. For example, a mass flow meter can be attached downstream of the collector or monitor and the vacuum source connected to the downstream side of the mass flow meter. The pressure level in the tubing between the collector or monitor and vacuum source is adjusted to the nominal value encountered during sampling (typically about 4 kPa for sampling systems that involve the use of collection filters) by bleeding air into the line downstream of the flow meter.

NOTE 2 Karthik and McFarland (2004) illustrate the use of a chamber and tracer method of leak-testing small assembled items.

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

7.2 Nozzle design and operation for extracting aerosol particles

The information in 7.2.1 to 7.2.6 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 on the design parameters of sampling nozzles is given in Annex M. Performance recommendations for nozzles are given in 7.2.1 to 7.2.6.

7.2.1 Nozzle performance

A sampling nozzle itself should have a transmission ratio within the range of 0,80 to 1,30 over the anticipated range of normal operational or accidental conditions for an aerosol with a particle size, D_a, of 10 µm. If information is available on the activity distribution as a function of particle size for a particular stack or duct, additional tests with aerosol particle sizes in this range should be considered at the design stage of the nozzle or at the manufacturer's facilities, particularly if larger particles are present.

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.

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 presence of a nozzle should not disturb the aerosol particle concentration in the stack or duct. Accordingly, the frontal area of a nozzle 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.

7.2.2 Application and performance considerations

The factors in 7.2.2.1 to 7.2.2.5 should be considered in the selection and use of a sampling nozzle.

7.2.2.1 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 6.2.

7.2.2.2 Orientation

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

7.2.2.3 Transmission and aspiration ratios

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 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.

7.2.2.4 Sampling flow rate and free stream velocity

During operation of a nozzle, the sampling flow rate may be varied to accommodate changes in the free stream velocity, or it may be held constant to accommodate the functionality of a particular collector or analyser. Where the emission stream flow rate can vary by more than 20 % over a sampling period, the sampling flow rate should be varied in proportion to the flow rate through the stack or duct in order to permit an accurate assessment of the quantities of any release. If the sample flow rate is varied, the ratio of the sampling flow rate to the stack flow rate should be established for nominal operational conditions of the stack or duct. Over the range of operational flow rates that is based on either historical records or *a priori* considerations, the ratio should not vary by more than 20 %. To determine the starting point for proportional control, the nominal design velocity for the nozzle should be matched to the nominal stack velocity.

7.2.2.5 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. Some studies (e.g. Reference [71]) have shown that single-nozzle, shrouded probes can reduce wall losses for particles having an aerodynamic diameter, D_a, greater than 5 µm, in high-velocity streams (velocity greater than 10 m/s).

7.2.3 Sampling probes with multiple-inlet nozzles

Where the airflow-mixing criteria of Clause 6 cannot be met, multi-nozzle probes may be used where they can be demonstrated, with in-place testing, to provide a representative sample.

Table 2 suggests a rationale for selecting the number of nozzles. The table assumes that the sample extraction location is at a minimal distance corresponding to 5 hydraulic diameters downstream of any bends, junctions or other flow disturbances. The number of sampling points is known, taken from the earlier version of this International Standard. The nozzles should be located in the duct or stack such that each covers an equal fraction of the sampling plane area.

Table 2 — Number of nozzles for multi-nozzle sampling probes

Stack or duct diameter mm	Number of nozzles
< 300	2
300 to 1 000	3 to 5
> 1 000	6 or more

Particular attention should be paid to the design of sample delivery when sampling with a very high number of nozzles (e.g. more than 10). The performance of the installation shall be demonstrated as for single-point samplers; see 7.2.1. Each of the nozzles should then meet the requirements of 7.2, with an added margin to allow for the losses in additional bends and joints.

Uneven velocity distribution is a special problem for multi-nozzle sampling. It is necessary that the flow through each nozzle be proportional to the local velocity, so as to make the combined sample representative, and to make sampling nearly isokinetic. However, internal flows can develop from nozzles in high-velocity zones to nozzles in zones with less velocity, depending on the design of nozzles and manifold.

Some designs of multi-nozzle samplers are discussed in Annex M.

7.2.4 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.

7.2.5 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 HEPA-filtered air, 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.

7.2.6 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 7.2. 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 to about 10 µm to 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.

7.3 Sample transport for particles

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.

7.3.1 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 shall be determined experimentally using test aerosol particles.

The performance of the sampling system shall be 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 smaller 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 may 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.

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.

7.3.2 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.

7.3.3 Electrostatic effects and flexible tubes

If plastic is used in aerosol-particle transport systems, internal electric fields can cause particle losses (Charuau 1982); in particular, plastic tubing that has been flexed can show abnormally high wall deposits (Liu *et al*. 1985). 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, 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, not exceeding 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 (Charuau 1982). If radioiodine is present in the effluent stream, the materials suggested in Annex C should be used.

7.3.4 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.

7.3.5 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.

7.3.6 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.

7.4 Gas and vapour sample extraction and transport

Much of the discussion in 7.3 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 6.2. 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.

7.5 Collection of particle samples

7.5.1 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;
- minimal in-leakage within the collector;
- minimal particle loss within the collection zone.

7.5.2 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 (Liu *et al*., 1983).

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 Hickey *et al*., 1991). 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 (Hickey *et al.*, 1991). 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.

7.6 Collection of gas and vapour samples

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: 1) sampling with retention of specific constituents of the air stream; and 2) sampling without constituent separation. Annexes C, H, K and N provide further guidance specific to radioiodine, tritium, carbon-14 and ruthenium-106, respectively.

7.6.1 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 Brown and Woebkenberg, 1989).

7.6.2 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.

7.7 Evaluation and upgrading of existing systems

If an existing air sampling system was not designed to the performance requirements and recommendations of this International Standard, 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 provided by the International Commission on Radiological Protection (ICRP, 1989). Evaluation of existing systems should be undertaken using proven techniques.

7.8 Summary of performance criteria and recommendations

Throughout this International Standard, performance criteria for various elements have been included in the discussion of each element. For convenience, they are summarized in Table 3. These criteria cover aspects of system design and operation. The approach followed in this International Standard 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 3, in order to provide accurate monitoring of the specific radionuclide.

Table 3 — 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 $\geqslant$ 50 %.	Clause 7 and 7.3.1
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 $\geqslant$ 50 %.	Clause 7 and 7.4
The nozzle should have a transmission ratio $\geqslant$ 80 % and $\leqslant$ 130 % for particles with a D_a of 10 µm.	7.2.1
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, and gas velocity; b) the tracer gas concentration should not vary from the mean by > 30 % at any point on the measurement grid (see 6.2.3).	6.2
Effluent flow rate continuous measurement recommended if flow variation is greater than ± 20 % in a year.	7.1.1
Effluent and sample flow rate should be measured within ± 10 %.	7.1.1 and 7.1.2
Continuous sample flow rate measurement and control are recommended if the stack flow varies by more than ± 20 % during a sample interval. Flow control should be within ± 15 %.	7.1.2

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.

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:

1) organization:

   - organizational responsibilities,
   - administrative controls,
   - reporting and notification system,
   - documentation,
   - personnel qualifications;

2) design of the sampling system:

   - source terms,
   - selection of extraction locations,
   - selection of sampling and monitoring devices,
   - selection of collection procedures;

3) operating procedures:

   - sample extraction procedures,
   - sample collection procedures,
   - system operation procedures,
   - calibration procedures,
   - data analysis,
   - maintenance and check procedures,
   - 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.

Annex A
(informative)

Techniques for measurement of flow rate through a stack or duct

A.1 Introduction

The volumetric flow rate, q, through a stack or duct is defined as given in Equation (A.1):

$$q = \int_A V \cdot \mathrm{d}A \tag{A.1}$$

where

V is the velocity at any location across a stack or duct, expressed in metres per second;

A is the cross-sectional area of the duct, expressed in square metres.

A method for determining q involves measuring the velocity at a finite number of points in a duct, where each point is chosen as the centroid of an area element. The relationship defining q is as given in Equation (A.2):

$$q = \sum_{i=1}^{N} V_i \, \Delta A_i \tag{A.2}$$

where

V_i is the velocity at the centroid of the ith element of area, expressed in metres per second;

ΔA_i is the area of the ith element, expressed in square metres.

The cross-section of the stack or duct is divided into N elements. In usual practice, all of the N elements have equal areas. The approach embodied in ISO 10780 serves as the reference method for this International Standard. The requirements for the absence of cyclonic flow given in ISO 10780:1994, Annex C, are also included in the reference method.

The flow rate, q, is associated with the air density, ρ, that exists in the stack or duct. The density is calculated from the ideal gas equation for dry air as given in Equation (A.3):

$$\rho = \frac{p}{RT} \tag{A.3}$$

where

p is the absolute pressure in the stack or duct, expressed in kilopascals;

T is the absolute temperature, expressed in kelvin;

R is the individual gas constant for air, equal to 287 J/(kg·K).

The volumetric flow rate at standard conditions, q_{std}, is the parameter that is being calculated for reporting and analysis purposes, and it is related to the actual volumetric flow rate, q, as given in Equation (A.4):

$$\rho q = \rho_{\mathrm{std}} q_{\mathrm{std}} \tag{A.4}$$

where ρ_{std} is the density of air based on standard temperature and pressure (101,325 kPa and 298 K), expressed in kilograms per cubic metre.

The flow rate at standard conditions from Equation (A.4) can then be expressed as given in Equation (A.5):

$$q_{\mathrm{std}} = q \frac{T_{\mathrm{std}}}{T} \frac{P}{P_{\mathrm{std}}} \tag{A.5}$$

In practice, q is determined from velocity measurements at traverse points as specified in ISO 10780, with the value calculated from Equation (A.2). The temperature and pressure in the stack or duct are measured in accordance with the requirements of ISO 10780.

A.2 Special considerations for use of ISO 10780 in sampling stacks and ducts of the nuclear industry

The reference method for determining air flow rate through a stack or duct, as modified by ISO 10780, is developed for flow rate determinations in non-nuclear stacks and ducts. It is necessary to take into consideration several differences between sampling from non-nuclear stacks and ducts and their nuclear counterparts.

A.2.1 Pitot tubes

An S-type Pitot tube was recommended in ISO 10780 for the purpose of reducing the risk of dust plugging the ports of the Pitot tube when measurements are made in dusty environments. However, as dust loading during velocity mapping in a stack or duct in the nuclear industry is not usually a concern, Prandtl-type Pitot static tubes (Type L in ISO 10780) should be considered as the reference apparatus for sampling under the requirements of this International Standard. However, when dust loading is of concern, an S-type Pitot tube may be considered.

A.2.2 Mean molar mass of the stack gas

In the industrial applications for which ISO 10780 was designed, the gas being tested often contains products of combustion or an elevated water-vapour content resulting from drying operations. In contrast, the gas in most stacks and ducts of the nuclear industry is ventilation air. In the latter case, it is unnecessary to determine the mean molar mass, M, for most stacks and ducts. However, if it is anticipated that there can be more than 10 % water vapour in the stack or duct, or if there are other gases that can change the mean molar mass by more than 4 % from the value for dry air (28,96 kg/kmol), it is necessary to make a determination of the mean molar mass of the gas. In this case, the resulting value is used to calculate the gas constant, R, as given in Equation (A.6):

$$R = \frac{R_{\mathrm{u}}}{M} \tag{A.6}$$

where

R_{u} is the universal gas constant, equal to 8,314 J/(mol·K);

M is the molar mass of the gas, expressed in grams per mole.

A.2.3 Thermal anemometers

If the mean molar mass and water content of the stack gas are in accordance with the values stated, the gas can be treated as air; if the dust loading in the stack or duct is such that any deposits on a thermal anemometer probe do not change the calibration of a thermal anemometer by more than 3 % during the course of the velocity measurements and, if there is no condensation of water vapour or other vapour on the sensor during flow measurements, a thermal anemometer can be used in this International Standard in lieu of a Pitot tube.

When a thermal anemometer is used for velocity mapping in a stack or duct, the flow rate based on standard conditions, q_{std}, is determined as given in Equation (A.7):

$$q_{\mathrm{std}} = \sum_{i=1}^{N} V_{\mathrm{std},I}\ \Delta A_i \tag{A.7}$$

where $V_{\mathrm{std},I}$ is the equivalent velocity at standard conditions measured with a properly calibrated thermal anemometer at the centroid of the ith element of area, expressed in metres per second.

A.3 Conversion of data from single point or single line measurements to total flow rate

If continuous single-point velocity measurements from a Pitot tube or a thermal anemometer or line-integral measurements from an acoustic flow meter are used to infer the total flow rate through a stack as a function of time, the resulting data should include a correction factor accounting for the shape of the velocity profile. The correction factor is determined by comparing the flow rate determinations from use of the single-point technique with those of the reference method defined in ISO 10780.

A.3.1 Pitot tube

The velocity-averaging correction factor for a Pitot tube, C_{pt}, is defined as given in Equation (A.8):

$$C_{\mathrm{pt}} = q/VA \tag{A.8}$$

where

V is the velocity measured by a Pitot tube at the single point where monitoring is being carried out, expressed in metres per second;

A is the cross-sectional area of the duct, expressed in square metres;

q is the flow rate through the stack or duct as determined from use of the reference method and as calculated from Equation (A.2), expressed in cubic metres per second.

Usually, the single point is located near the centre of the duct. Multiple points can be used, in which case the value of V is the average of the values from the multiple points.

The velocity, V, is continuously monitored during the period that the reference method testing is performed to establish the velocity-averaging correction factor, C_{pt}. If the value of V changes by more than 5 % during the course of testing, the data should be rejected and the test repeated. If the stack is subject to long-term flow rate variations that exceed 25 %, additional tests should be carried out at the highest flow rate (if it exceeds the base condition by more than 25 %) and the lowest operational flow rate (if it deviates from the base condition by more than 25 %) to establish values of the velocity-averaging correction factor at those conditions. A single value of the flow correction factor may be used if the range of flow-correction-factor values is within 7 % of the base condition. If the values of the correction factor at the extreme flow conditions are greater than 7 % of the base condition, then it is necessary that a relationship be established between the velocity correction factor and flow rate.

At least two replicate tests should be employed to establish a value of the correction factor. During routine use, the flow rate, q, is determined from readings of the single-point Pitot tube as given in Equation (A.9):

$$q = C_{\mathrm{pt}} V A \tag{A.9}$$

A.3.2 Thermal anemometer

A thermal anemometer located at a single point in a flow field provides a reading that is related to the total flow rate at standard conditions, q_{std}, through the relationship given in Equation (A.10):

$$q_{\mathrm{std}} = C_{\mathrm{ta}} V_{\mathrm{std}} A \tag{A.10}$$

The numerical value of the velocity-averaging correction factor, C_{ta}, is determined by comparing the readings from a thermal anemometer operated at a single point with simultaneous data from a reference method flow rate test. It is necessary to correct the data from the reference method test to standard conditions through use of Equation (A.5). The requirements for carrying out the tests are the same as those for the Pitot tube correction factor as given in A.3.1.

Continuous measurements of the effluent flow rate at standard conditions can be obtained by using a rake of parallel thermal anemometers, with the individual anemometer elements placed on an ISO 10780:1994 EPA method 1 grid. Provided that the electronic signals are processed properly, the output reading of such a system is the flow rate according to Equation (A.10).

A.3.3 Acoustic flow meter

The reading provided by an acoustic flow meter is a distance-weighted average velocity across a line between a sending transducer and a receiving transducer. As such, the velocity reading is not directly related to flow rate, even along the line, because it is necessary to base the flow rate on an area-weighted average velocity. To obtain the flow rate, q, through a stack or duct from acoustic flow meter readings also requires development of a velocity-averaging correction factor, C_{af}, as given in Equation (A.11):

$$q = C_{\mathrm{af}} V A \tag{A.11}$$

where

V is the line-average velocity obtained from the acoustic flow meter, expressed in metres per second;

A is the cross-sectional area of the duct, expressed in square metres.

The approach and requirements for determining C_{af} are the same as those for the single-point Pitot tube method.

Annex B
(informative)

Modelling of particle losses in transport systems

Aerosol particles can be deposited on internal surfaces of transport systems as a result of mechanisms that cause particles to move transversely to air flow streamlines. Included are such phenomena as gravitational settling, inertial impaction, turbulent inertial deposition and Brownian diffusion. For most transport systems, the Brownian diffusion mechanism is of significance only for aerosol particles with sizes smaller than approximately 0,3 µm, whereas the other mechanisms are of importance for particles larger than this size. Turbulent deposition is of consequence for flows with Reynolds numbers $> 2\,200$, where the Reynolds number (Re) is as given in Equation (B.1):

$$Re = \frac{\rho U_{\mathrm{m}} d_{\mathrm{t}}}{\mu} \tag{B.1}$$

where

ρ is gas density, expressed in kilograms per cubic metre;

U_{m} is mean (spatial) velocity at a cross-section of the transport system, expressed in metres per second;

d_{t} is tube diameter, expressed in metres;

μ is air dynamic viscosity, expressed in pascal-seconds.

For a tube of circular cross-section, the Reynolds number can also be expressed as given in Equation (B.2):

$$Re = \frac{4 \rho q}{\pi d_{\mathrm{t}} \mu} \tag{B.2}$$

where q is the volumetric flow rate through the tube, expressed in cubic metres per second, and is equal to the product of the mean velocity and the cross-sectional area.

The combination of flow rate and tube diameter of most aerosol-particle sampling systems is such that the flow is turbulent.

Empirical or semi-empirical models for predicting the effects of the various depositional mechanisms exist for most components of a sampling system. For nozzles, the losses are controlled by inertial forces including those associated with flow turbulence, the Saffman force and, occasionally, by gravitational settling. For vertical tubes, it is assumed that the depositional losses are controlled by turbulent, inertial deposition and Brownian diffusion. For horizontal tubes, the losses are caused by gravitational settling, turbulent inertial deposition and Brownian diffusion. For bends, the losses are due to the effects of inertial impaction. The predictive models typically assume that the velocity and concentration profiles are uniform at the entrance section of the component of interest. It is expected that this assumption is not fulfilled in many sampling system components because the flow disturbance created by an upstream component can affect the depositional characteristics in the succeeding component; however, in experimental studies with a composite transport system (nozzle, horizontal tube, inclined tube, vertical tube and bends), McFarland *et al*. (1991) and Wong *et al*. (1996) showed that the use of a model based on a sequential combination of components with assumed undisturbed inlet conditions compared well with experimental data.

B.1 Aerosol particle penetration through transport system components

The penetration, P_j, of aerosol particles through the jth component of a transport system is defined as given in Equation (B.3):

$$P_j = \frac{c_{\mathrm{e},j}}{c_{\mathrm{i},j}} \tag{B.3}$$

where

$c_{\mathrm{e},j}$ is the aerosol particle concentration at the exit plane of a component;

$c_{\mathrm{i},j}$ is the aerosol particle concentration at the inlet plane of a component.

If there are n components in a sampling system, it is assumed the overall penetration, P, can be calculated as though each component were independent, as given in Equation (B.4):

$$P = \prod_{j=1}^{n} P_j \tag{B.4}$$

Estimates of particle losses in sampling systems should be calculated or determined experimentally. Hand calculations may be performed; for example, using the methods in this annex, in McFarland *et al*. (2001) or in Brockman (1993). Machine computations may be performed with one of several available computer codes. As an example(1), the computer code Deposition 2001a(2) calculates the losses of aerosol particles in transport systems (McFarland *et al*., 2001). It includes models for losses in certain types of nozzles, straight tubes, bends, splitters and fittings that serve as transitions in tube diameter, either to enlarge or reduce the diameter. Losses associated with contractions in fittings are discussed in Muyshondt *et al*. (1996). Similar capabilities are available in Astec/Sophaeros(3) (Kissane *et al*., 1994; Granga *et al*., 1994) and PAPAV (Vogl, 1992, 1994 and 1995).

B.1.1 Wall losses in nozzles

As of the date of publication of this International Standard, there was no general model for predicting wall losses in nozzles. Fan *et al*. (1992) made an experimental correlation of wall losses as a function of design and operational conditions for isokinetic nozzles of a Willeke-Okazaki configuration (1987), where those nozzles are similar in design to those in the previous edition of this International Standard, ISO 2889:1975 (which has been withdrawn) except that there is no bend. The model of Fan *et al*. (1992) is based on experiments with particle sizes of only 10 µm and 20 µm, so it cannot be used as a general predictive tool for all nozzle applications; nevertheless, it does provide the basis for estimating internal wall losses in the straight region of the ISO 2889:1975 nozzles upstream of the bends.

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1) This information is given for the convenience of users of this International Standard and does not constitute an endorsement by ISO of these products.

2) Contact address for Deposition code:
Aerosol Technology Laboratory
Department of Mechanical Engineering
Texas A&M University
College Station, TX 77843
USA
http://www1.mengr.tamu.edu/ATL/depo.html

3) Contact address for Astec/Sophaeros code:
IRSN/DPAM
B.P.3
13115 Saint-Paul-lez-Durance CEDEX
France

The code, Deposition 2001a, includes the Fan *et al*. (1992) and Vincent *et al*. (1986) models for use with unshrouded isokinetic nozzles. The Fan *et al*. (1992) model can overestimate the losses in the more modern designs of isokinetic nozzles, such as is illustrated in Figure B.1 (Chandra, 1992). A shrouded nozzle (McFarland *et al*., 1989) is basically a nozzle fitted with a flow decelerator; see Figure B.3. It has lower wall losses than an unshrouded nozzle and it is less susceptible to off-design sampling conditions (e.g. off-angle flow direction, flow turbulence, changes in sampling flow rate or changes in the free-stream velocity) than an unshrouded nozzle (Chandra and McFarland, 1995). If the Deposition model is applied to a system fitted with a shrouded nozzle, the code calculates aerosol particle transmission based on the model of Gong *et al*. (1995).

B.1.2 Straight tubes

The penetration of particles through a straight tube is calculated as given in Equation (B.5):

$$P = \exp\left(-\frac{\pi d_{\text{t}} v_{\text{e}} L}{q}\right) \tag{B.5}$$

where

v_{e} is the effective depositional velocity, expressed in metres per second;

L is the length of the straight section of tubing, expressed in metres.

The effective depositional velocity is the vector sum of the gravitational settling terminal velocity, which is always directed downward, and the turbulent inertial deposition and Brownian diffusion velocities, which are directed radially outward in a tube. A basic assumption when using this model is that aerosol particles are well mixed across any cross-section of the tube.

The effective deposition velocity for an inclined tube, Figure B.2, was modelled by Anand *et al*. (1992) as given in Equation (B.6):

$$v_{\text{e}} = \frac{1}{2\pi}\int_0^{2\pi}\left(v_{\text{d}} - v_{\text{ge}} \sin\alpha\right)\text{d}\alpha \tag{B.6}$$

where

α is the angular coordinate of a tube cross-section, expressed in radians; see Figure B.2;

v_{d} is the depositional velocity due to the combined effects of thermal (Brownian) diffusion and turbulent inertial deposition, expressed in metres per second;

v_{ge} is the cross-stream component of gravitational settling velocity, expressed in metres per second.

For a tube that is inclined at an angle of ϕ, expressed in radians, relative to the vertical direction, v_{ge} is as given in Equation (B.7):

$$v_{\text{ge}} = v_{\text{g}} \sin\phi \tag{B.7}$$

where v_{g} is the sedimentation velocity, expressed in metres per second.

Equation (B.6) is subject to a constraint as given in Equation (B.8):

$$\left(v_{\text{d}} - v_{\text{ge}} \sin\alpha\right) > 0 \tag{B.8}$$

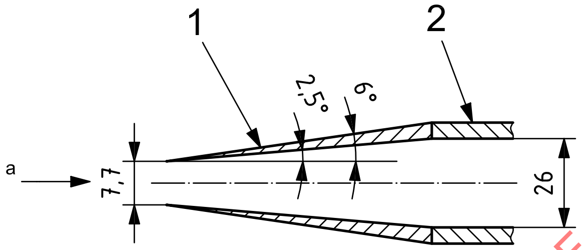
If the constraint is not satisfied, then Equation (B.9) holds:

$$v_e = 0 \tag{B.9}$$

The constraint is necessary because otherwise the prediction would be equivalent to aerosol particles being transported from the environment through the top (relative to the earth's surface) of a tube.

If the effects of both gravitational settling velocity in the cross-stream direction and the turbulent inertial deposition velocity are of consequence, there is a tube diameter that optimizes aerosol particle penetration, because for a fixed flow rate, tube sizes smaller than the optimal value have increased turbulent depositional losses and tube sizes larger than the optimum have enhanced gravitational depositional losses.

Dimensions in millimetres unless otherwise indicated



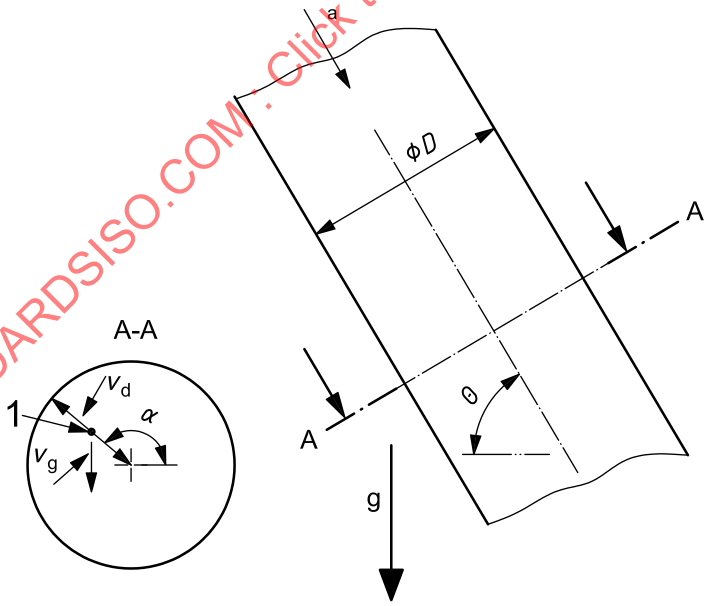
Key

1 nozzle

2 transport line

[a] Flow.

Figure B.1 — Unshrouded nozzle of Chandra (1992), with wall losses of aerosol particles with a D_a of 10 µm equal to about half of those of a nozzle with a constant internal diameter

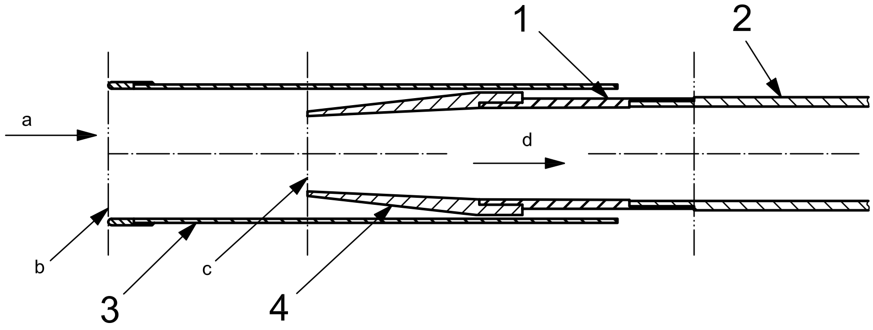


Key

1 particle

[a] Flow.

Figure B.2 — Geometric model to illustrate parameters used to model particle deposition in a straight tube



Key

1	nozzle
2	transport line
3	shroud
4	inner nozzle
a	Stack gas flow.
b	Shroud entrance plane.
c	Nozzle entrance plane.
d	Sample flow to collector or monitor.

Figure B.3 — Shrouded nozzle

A particle-deposition velocity in tubes can be correlated with a particle-relaxation time. Several semi-analytical models that lead to this correlation have been proposed; however, as of the date of publication of this International Standard, none can predict deposition of particles in the inertial size regime ($D_a > 1$ μm) from basic principles. Onda (1977) reviewed the various models and compared them with experimental data and concluded the model of Beal (1970) provided the best fit. The version of Deposition as of the date of publication of this International Standard uses this model. However, pure curve fitting of experimental data can also be used to provide estimates of the depositional velocities. The latter approach is used by Agarwal (1975), but his model does not take into account deposition due to the Brownian diffusion mechanism.

Particle deposition in fully developed laminar flow can be modelled with the theory of Thomas (1958) for gravitational settling and Gormley and Kennedy (1949) for Brownian diffusion. However, true laminar flow does not often occur in straight tubes because straight tubing sections are usually preceded by disturbances such as bends. Typical sample transport tubes have Reynolds numbers that are greater than 1 000, which can cause upstream flow disturbances to effect flow mixing downstream of the disturbance and, thus, renders a well mixed deposition model such as Equation (B.5) more relevant than a laminar model with no bulk fluid mixing. For this reason, a well mixed sub-model, such as that utilized in Deposition 2001a, can be employed for straight tubes when the Reynolds number is greater than 1 000. However, for bends, a distinction is made between laminar and turbulent flows.

B.1.3 Bends

Particle losses in bends are principally due to the effects of particle inertia where the air flow follows a curved path and the particles tend to go straight. Neglecting Brownian diffusion, turbulent inertial deposition and gravitational effects, analyses show that for two-dimensional channels, the penetration is a function of the Stokes number, St, as given in Equation (B.10):

$$St = \frac{C \rho_w D_a^2 U_m}{9 \mu d_t} \tag{B.10}$$

where

C is Cunningham's slip correction (Fuchs, 1964);

ρ_w is the density of water;

D_a is the aerodynamic particle diameter.

The analysis for particle deposition in bends of circular cross-section is complicated by the fact that the flow is three dimensional. A secondary flow is established as the air passes through the bend, where the secondary flow consists of a set of counter-rotating vortices in which air goes from the inside of the bend to the outside of the bend along the tube cross-sectional radius; Equations (B.11) and (B.12) hold:

$$De = \frac{Re}{\sqrt{R_o}} \tag{B.11}$$

$$R_o = \frac{R_c}{d_t} \tag{B.12}$$

where R_c is the radius of the tube bend.

Pui *et al.* (1987) noted that for turbulent flow, when the curvature of the bend, R_o, is between 2,5 and 15, the radius of curvature has little effect on particle trajectories and the deposition depends, at most, on St and Re. Experimental data for 90° bends with turbulent flow Reynolds numbers of 6 000 and 10 000 show that the penetration can be correlated only with the Stokes number as given in Equation (B.13):

$$P = 10^{-0,963 St} \tag{B.13}$$

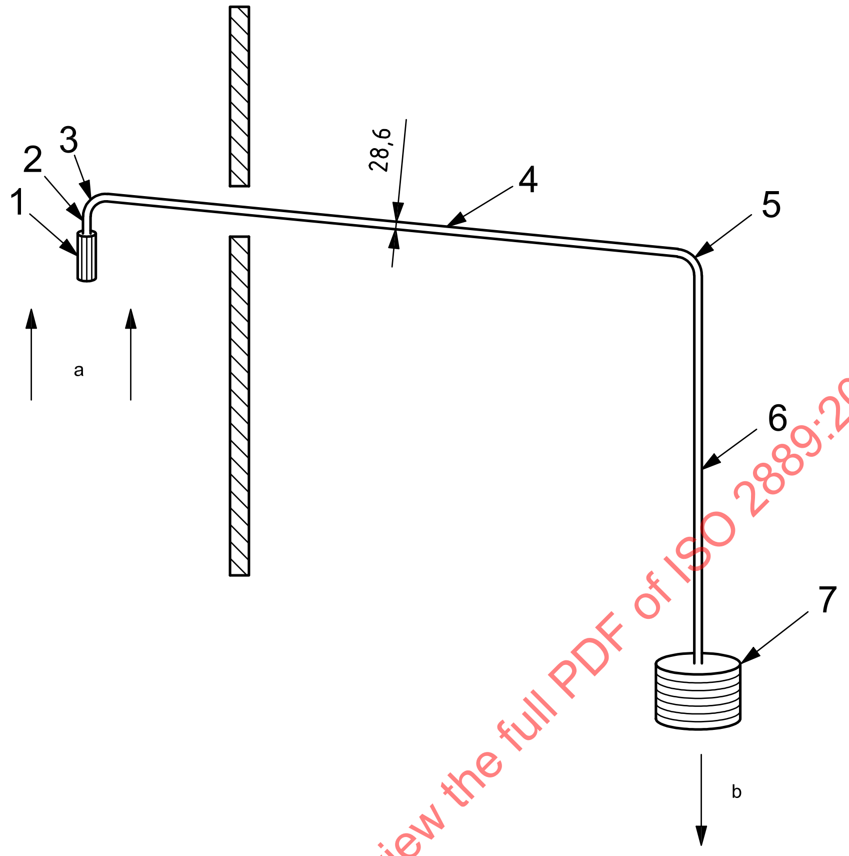
It should be assumed that the uncertainty in this model increases for Reynolds numbers outside of the test range. For laminar flow, Tsai and Pui (1990) numerically modelled particle deposition in 90° bends and their results include the effects of secondary flow. They carried out calculations over a range of curvature ratios and Dean numbers and provided empirical correlations of the results, which show that the efficiency depends on the Stokes number, the curvature ratio and the Dean number.

In the software Deposition 2001a, the model of Cheng and Wang (1981) is used for Reynolds numbers less than 1 100 and the model of McFarland *et al.* (1991) is used for Reynolds numbers equal to or greater than 1 100.

B.2 Calculation of sample losses in a transport system

As an illustration of the calculation of particle losses in a transport system, assume the geometrical configuration shown in Figure B.4 for a system that is designed to sample aerosol particles with a D_a of 10 µm at a flow rate of 56,6 l/min from a free stream that has a velocity of 10 m/s. Assume that the nozzle is a shrouded nozzle in which the velocity inside of a 52,5 mm diameter shroud is 3 m/s and the internal nozzle samples isokinetically from the 3 m/s stream (18,2 mm diameter inner probe). Also, assume that the sampling tube has a 28,6 mm inside diameter (31,8 mm outside diameter with a 1,6 mm thick wall). The input and output values for the Deposition 2001 code are shown in Table B.1. The overall penetration through the system is 74,3 %, with the losses predominantly from the 2 m long horizontal tube and the bends.

Dimensions in millimetres



Key

1 to 6 see Table B.1

7 collector or monitor

NOTE Free-stream velocity, equal to 10 m/s, is reduced to 3 m/s in the shroud.

[a] Flow in stack or duct.

[b] Flow to vacuum source.

Figure B.4 — Layout of example aerosol particle transport system

Table B.1 — Example of using a computer code (Deposition 2001a) to predict aerosol particle penetration through a six-component transport system

Element		Penetration through the element[a] %
Number	**Description**	
1	Shrouded probe: a) shroud diameter, 52,8 mm b) shroud velocity reduction ratio, 10:3 c) probe angle with free stream, 0°	91,6 (through nozzle)
2	Tube, 0,2 m long, 90° from horizontal	100,0
3	Bend, 90°	98,7
4	Tube, 2 m long, 0° from horizontal	83,4
5	Bend, 90°	98,7
6	Tube, 2 m long, 90° from horizontal	99,9
		Overall penetration: 74,3

[a] Conditions:

— flow rate:	56,6 l/min
— tube diameter:	28,6 mm
— particle density:	1 g/cm^3
— particle size:	monodisperse, D_a equal to 10 µm
— free-stream velocity:	10 m/s

Annex C
(informative)

Special considerations for the extraction, transport and sampling of radioiodine

C.1 General considerations

Obtaining samples of airborne radioiodine is complicated because it is present in air effluents in several forms, specifically as particulate matter, as elemental iodine (I_2), as hypoiodous acid (HOI) and in organic form, principally as methyliodide (CH_3I). The existence of the HOI form is not universally accepted, but it is the postulated identity of an otherwise indeterminate form with a deposition velocity lower than that of elemental iodine that can penetrate a cadmium iodide bed but is collected by an iodophenol bed in a species sampler.

These chemical forms of radioiodine, particularly the elemental form, may be expected to deposit initially in ducts and in sampling lines and then subsequently be resuspended and emitted as the same or another form (Cline, 1991). The organic form is the least likely to be deposited and only a small fraction of it is collected by some of the solid adsorbents that are used to limit radioiodine emissions (Kovach, 1980). However, it cannot be ruled out that, during off-normal events, the major form of radioiodine is elemental. Therefore, evaluations of sample transmission under off-normal conditions should assume that form. Glissmeyer and Sehmel (1991) summarize the most recent studies at that time on radioiodine sampling and transport and many of the following considerations are based on that summary.

C.2 Extraction and transport

The considerations for the extraction of gases and vapour set forth in 7.4 are applicable to radioiodine. In view of the likelihood that at least some of the radioiodine in an air effluent is attached to particulates, all of the considerations applicable to them as set forth in the main body of this International Standard and its annexes also apply to the extraction and transport of radioiodine.

Laboratory studies have shown that, in the extraction and transport of radioiodine, materials that contact the radionuclide can interact with it (e.g. copper, PVC, Buna-N). These materials should be avoided. Studies by Kabat (1983) indicate that the preferred materials are PTFE, polyethylene, aluminium, carbon steel and stainless steel.

Condensation of the iodine and water vapour in transport lines should be avoided by heat tracing the lines to at least 323 K (50 °C) and by avoiding abrupt temperature transitions.

Equation (C.1) (Glissmeyer and Sehmel, 1991) relates the penetration at equilibrium, P, the dimensionless ratio of the outlet concentration, c_e, to the inlet concentration, c_i, of radioiodine in transport lines, to the so-called deposition velocity and parameters of the sampling system:

$$P = e^{-4 \frac{v_d L}{U_m d_t}} \tag{C.1}$$

From Equation (C.1), it is evident that the penetration of radioiodine vapour is optimized by minimizing the length of the transport line, L, and using the largest diameter, d_t, and the highest flow velocity, U_m, subject to external constraints (e.g. particle transport, space availability, or collector capacity).

Equation (C.1) does not take into account radioactive decay or resuspension. A model by Unrein *et al*. (1985) gives an equilibrium relationship that includes these effects, as given in Equation (C.2):

$$P = \frac{1}{1 + v_\mathrm{d}\left(\frac{\pi\, d_\mathrm{t}\, L}{q}\right)\left(\frac{\lambda}{\lambda + r}\right)} \tag{C.2}$$

Equation (C.2) suggests that the greater the resuspension rate, the larger the penetration. This is also illustrated in Figure C.1, where penetration is shown as a function of time and resuspension rate. However, Glissmeyer and Sehmel (1991) indicate that resuspension rate of deposited radioiodine, for each radioiodine species, decreases as a function of time. Resuspension rates are also dependent on the amount of iodine initially deposited, some of which seems to remain firmly deposited. The latter has not been directly observed by laboratory studies but can be estimated on the basis of an activity balance following prolonged observation. Finally, Glissmeyer and Sehmel (1991) state there is no satisfactory experimental verification of predicted penetration factors under either equilibrium or transient conditions. However, the following generalizations can be made from the limited available data, principally that of Unrein *et al.* (1985).

In a summary of sampling systems for reactors, Glissmeyer and Sehmel (1991) indicate that a typical sampling system consists of a 15 mm diameter stainless steel transport line that is about 52 m in length with a flow rate of about 57 l/min. Simulated sample transport lines with a range of similar designs were tested by Unrein *et al*. (1985), who measured short-term (on the order of 2 h) penetration factors of 0,62 for injected ^{131}I (as I_2) through 19 mm diameter by 48 m long tubes. Glissmeyer and Sehmel (1991) predicted the equilibrium penetration factor to be about 0,75, with an approximate time of two weeks to reach equilibrium.

With the caveat that the penetration factor was not measured in the Unrein *et al*. (1985) tests until 2 h after beginning the iodine injection (lower penetration factors might have been found for measurements earlier in the test sequence), these short-term results provide a conservative estimate of penetration factors following a step increase in radioiodine concentrations in conventional transport lines. The equilibrium value provides a conservative estimate for longer-term sampling of normal concentrations.

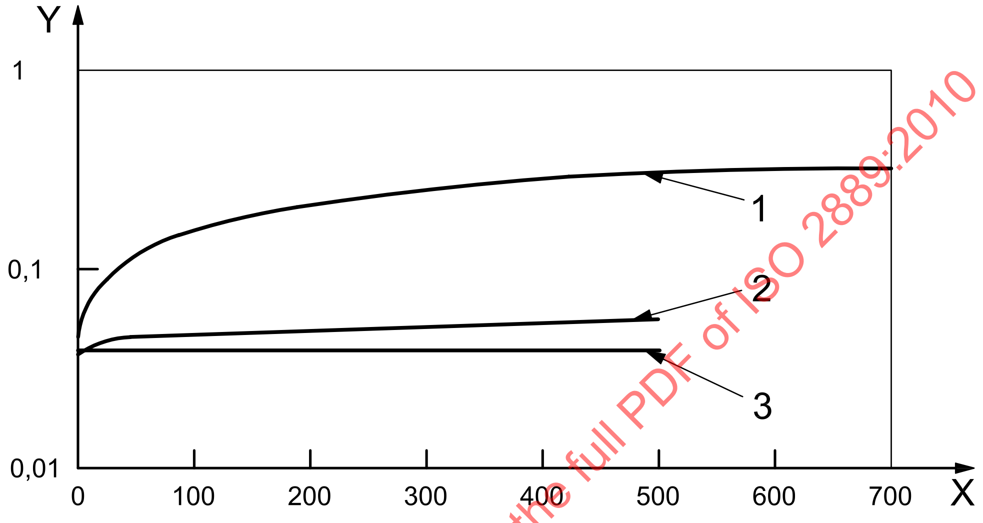
Much smaller penetration factors are found for a few tests of systems with long transport lines of 6 mm (1/4 in.) diameter tubing when operated at flow rates of less than 1,7 l/min. Some accident-air sampling systems used this design to reduce the potential dose at the sample collector by using a low sample flow rate and a small-diameter transport line. Tests simulating such systems (Unrein *et al*. 1985) show very poor penetration of the radioiodine to the collector. Consequently, many of these systems were redesigned to collect a low-flow-rate subsample from a high-flow, large-diameter transport line to take advantage of its favourable sample penetration from the stack. An example of the effect of flow rate on the penetration of I_2 in a small-diameter transport line is shown in Figure C.2.

The foregoing applies primarily to the transport of elemental radioiodine and, to a lesser extent, to the hypoiodous iodide form. It may be expected that radioiodine in organic forms, with their much lower deposition velocities, be transported with higher efficiencies, thus making the above estimates additionally conservative. As summarized in Glissmeyer and Sehmel (1991), the fraction of organic radioiodine during normal operations appears to be quite variable from facility to facility, and there are no data based on which an estimation of the fraction can be anticipated for the facility effluent during upset or accident conditions. Initially, the predominant form of radioiodine during upset or accident conditions is elemental or particulate.

An example of a code modelling iodine losses in transport systems is Astec/Sophaeros[3)]. It includes models for losses to physical phenomena (condensation, sorption), chemical reactions as well as iodine-particle losses. Models and qualification examples are described in Alpy *et al*. (2003).

C.3 Collection media for radioiodine

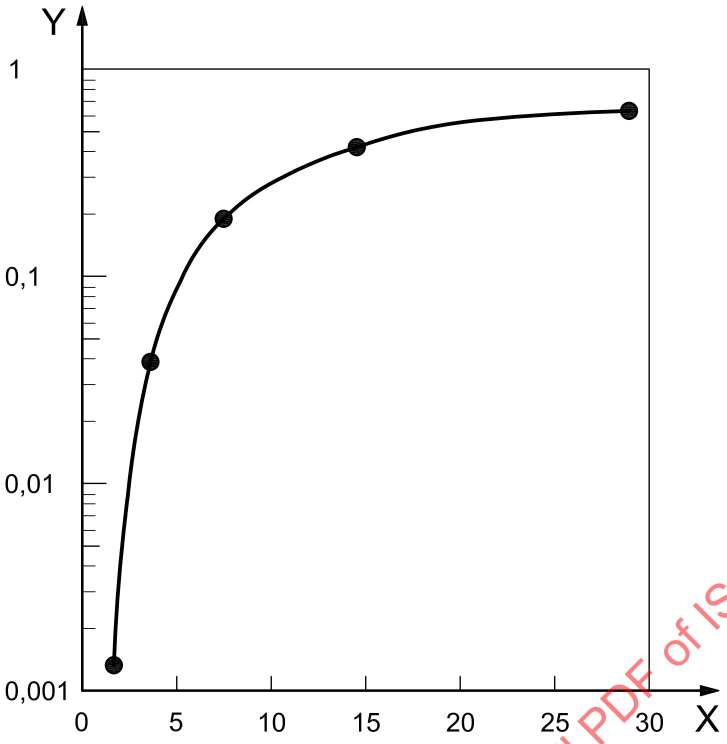
While carbon is an efficient collector of I_2, it is much less efficient for the organic iodines having a low deposition velocity. Kovach (1992) has indicated that the removal mechanism of elemental iodine on carbon adsorbents is primarily by physical absorption, the removal of hydrogen iodide (HI) by physical absorption, chemical reaction and isotopic exchange, and that the removal of organic iodides such as CH_3I is by isotopic exchange. To improve the latter process, carbon filter media treated with potassium iodide (KI) or triethylenediamine (TEDA) should be utilized. Packages with different types of adsorbents in series are available for the collection of radioiodine with separation by chemical form.



Key

X	time, expressed in hours
Y	ratio of outlet to inlet concentration
1	curve for a resuspension rate of $1{,}5 \times 10^{-6}$
2	curve for a resuspension rate of $1{,}5 \times 10^{-7}$
3	curve for a resuspension rate of $1{,}5 \times 10^{-8}$

Figure C.1 — Predicted penetration of radioiodine as a function of time for various resuspension rates



Key

X flow rate, expressed in litres per minute

Y ratio of outlet to inlet concentration

NOTE Tube size: 6,4 mm inside diameter by 43 m long.

Figure C.2 — Predicted initial radioiodine penetration through a stainless steel transport line

Annex D
(informative)

Optimizing the selection of filters for sampling airborne radioactive particles

Filters are porous structures with controlled external dimensions, such as thickness and cross-sectional area normal to the flow. Filtration is the most widely used technique for collection of aerosol particles because of its low cost and simplicity. Filters capture particles by a combination of physical processes, which include direct interception, inertial deposition, Brownian diffusion, electrical attraction and gravitational sedimentation. As shown in Figure D.1 (Lee and Ramamurthi, 1993), filters typically have a minimum collection efficiency for particles that are approximately 0,1 µm to 0,5 µm in diameter. Above this size, filtration efficiency increases due to inertial impaction and below this size, efficiency increases due to Brownian diffusion.

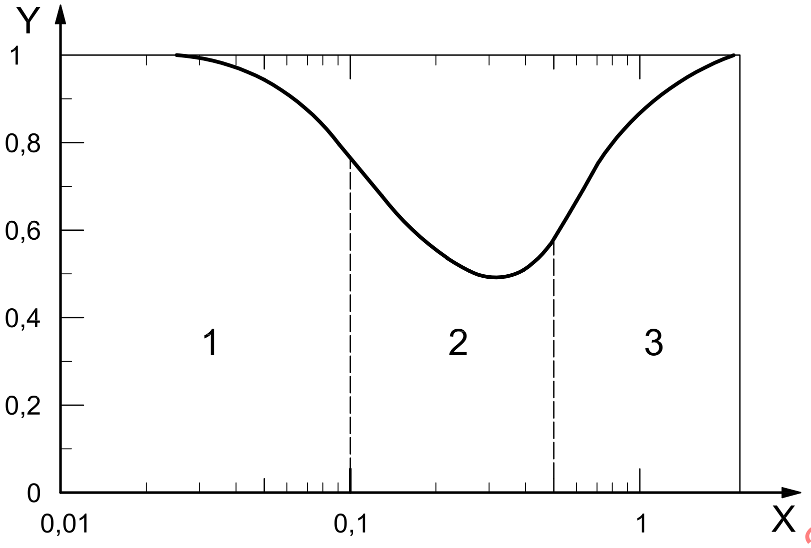
A common misconception is that filters act as sieves, and that there is a direct relationship between the pore size of a filter and the minimum particle size that can be collected. In reality, because collection occurs by a complex combination of mechanisms, filters with nominal pore sizes larger than 1 µm can be very efficient collectors of sub-micrometer particles. As demonstrated by Lindeken *et al*. (1964), membrane filters show no serious degradation of collection efficiency until the pore diameters exceed 5 µm. Filters with a 5 µm pore size are often preferred because they result in lower pressure drops than smaller pore-size filters yet retain high efficiency values

Many filter media are available for use in the collection of aerosol particles (see, for example, Liu *et al*., 1983, and Lippman, 1989). Materials include cellulose, glass, quartz and plastic fibres. Sintered structures of metals or mineral particles are used for high-temperature filtration. Users are cautioned to be selective in their choice of filter media.

If a sample is being separated from the filter for a particular analytical method, the user should select a filter medium that can be easily dissolved by a method that does not attack the particles of interest. In other cases, it is imperative that the sample be collected on the surface of the filter rather than imbedded in the filter. Higby (1984) has demonstrated that absorption of alpha radiation emitted from airborne particles collected on glass-fibre filters does not constitute a major source of error in estimating concentrations of airborne alpha-emitting radionuclides, but excellent resolution in alpha spectroscopy requires the use of membrane-type filters that are front-surface collectors.

Decisions on changing the filter media should include considerations such as the potential loss of continuity between historical and future sampling results, potential impacts on vacuum-system performance, requirements for analyser retesting, requirements for revision and approval of documentation, retraining requirements for workers, and potential impacts on secondary uses of the filter samples, such as periodic chemical analyses for process control. However, some filter media date back many decades and their continued use is not justified simply because of historical precedents.

Table D.1 summarizes the type of information that is useful for selecting an appropriate filter for sampling airborne radioactive particles. This table includes a variety of coarse-fibre, glass-fibre and membrane-type filters, but does not constitute an endorsement of any particular manufacturer or filter type. Conversely, the absence of any particular filter from the example table does not constitute a rejection of that medium. For general sampling applications, information is provided on durability, flow resistance and efficiency. Information on collection of radon decay products and their resolution for alpha spectroscopy is included for alpha continuous air monitor (CAM) applications. The alpha spectroscopy resolution is based on detection of the 6,0 MeV alpha emission of polonium-218 (a naturally-occurring decay product of ambient radon-222, which causes interference in instruments used to detect plutonium or uranium isotopes).



Key

X particle diameter, expressed in micrometres

Y efficiency

1 diffusion regime

2 diffusion and interception regime

3 inertial impaction and interception regime

Figure D.1 — Schematic of filter efficiency versus particle size illustrating the different filtration regimes

Filter efficiencies range from > 99,999 % at all particle sizes and flow rates for the Millipore type AA, 0,8 µm pore size membrane filter to < 50 % for the Whatman 41 cotton cellulose filter at low flow rates and small particle sizes. Typical flow rates range from as low as 4 l/min/cm^2 at 35 kPa pressure drop for the Millipore Type AA membrane filter to as high as 59 l/min/cm^2 for the Millipore Fluoropore, 5 µm pore-size polytetrafluoroethylene (PTFE) membrane filter. Resolution for alpha spectroscopy of the polonium-218 alpha emission at 6,0 MeV ranges from as low as 350 keV (full width at half maximum) for the Fluoropore 3 µm PTFE membrane filter to greater than 1 500 keV for the Whatman 41 cotton-cellulose fibre filter. The poor resolution associated with the Whatman 41 filter makes that filter unsuitable for use in continuous air monitors that are employed to detect plutonium or uranium in the presence of ambient radon decay products. In addition, although the Whatman 41 is easily dissolved for chemical analyses, it has a collection efficiency that decreases dramatically at low flow rates. The Fluoropore filters have a very low pressure drop, good collection efficiency and excellent resolution for alpha spectroscopy, but are not readily dissolved for radiochemistry. Selection of the larger pore 5 µm Fluoropore filter over the 3 µm pore option provides a substantial improvement in flow rate, with only a modest decrease in sampling efficiency and resolution for alpha spectroscopy. Table D.2 provides other information useful for the selection of sample filters.

As new filter types become available, comparisons such as these can be made by the user to ensure that appropriate filter types are selected for sampling radioactive aerosol particles.

Table D.1 — Characteristics of filters evaluated for use in sampling radioactive particles

(adapted from Hoover and Newton, 1992)

Filter type	**Filter composition and durability**	**Typical flow rate**[a] l/min/cm^2	**FWHM**[b] **of the Po-218 PEAK** keV	**Relative radon progeny counts in the Pu ROI**[c]	**Relative radon progeny collection efficiency**[d]	**Filter efficiency range**[e] %
Millipore type SMWP (5,0 µm pore size), Millipore Corp., Bedford, MA	Mixed esters of cellulose acetate and cellulose nitrate (fragile; electrostatic; both sides identical)	16	670	1	1	98,1 to > 99,99
Millipore type AW19 (5,0 µm pore size), Millipore Corp.	Homogeneous, microporous polymers of cellulose esters formed around a cellulose web (rugged; both sides identical)	16	470	0,57	0,99 ± 0,01	99,93 to > 99,99
Durapore (5,0 µm pore size), Millipore Corp.	Polyvinyldiene fluoride (rugged; both sides identical)	14	790	1,55	0,67 ± 0,1	—
Fluoropore (3,0 µm pore size), Millipore Corp.	Polytetrafluoroethylene bonded to polypropylene high-density fibers (rugged; front is membrane; back is fibres; sides barely distinguishable by naked eye)	23	350	0,47	1,04 ± 0,02	98,2 to > 99,98
Fluoropore (5,0 µm pore size), Millipore Corp.	Polytetrafluoroethylene	—	—	—	—	—
Versapor 3000 (3,0 µm pore size, Gelman Sciences, Ann Arbor, MI	Acrylic copolymer on a nylon fibre support (rugged; both sides identical)	25	590	0,94	0,75 ± 0,02	99,7 to > 99,99
Gelman type A/E (~1,0 µm pore size) Gelman Sciences	Borosilicate glass fibre without binder (breakable during handling; both sides identical)	25	⩾ 1 000	1,31	0,92 ± 0,01	99,6 to > 99,99
Whatman EPM 2000, Whatman LabSales, Hillsboro, OR	Borosilicate glass microfibre without binder (breakable during handling; both sides identical)	20	⩾ 1 000	1,48	1,00 ± 0,03	—
Whatman 41, Whatman LabSales	Cotton-cellulose filter paper (rugged; currently used primarily for liquid filtration; both sides identical)	25	⩾ 1 500	1,65	0,42 ± 0,01	43 to > 99,5
Nuclepore (0,6 µm pore size), VWR Scientific, Pleasanton, CA	Polycarbonate membrane (rugged; thin; very electrostatic; currently used primarily for liquid filtration; collection side recommended by manufacturer is the shiny side)	4	500	0,89	0,85 ± 0,02	53 to > 99,5
Millipore type AA (0,8 µm pore size), Millipore Corp.	Mixed esters of cellulose (fragile; electrostatic; collection side is darker)	7	520	0,91	1,05 ± 0,01	99,999 to > 99,999

[a] Flow rate determined under vacuum at 35 kPa.

[b] FWHM is the typical full width at half maximum of the polonium-218 peak obtained with a 2,5 cm diameter filter and a 2,5 cm diameter solid state detector with a 0,5 cm separation distance during sampling of room air at the Inhalation Toxicology Research Institute in Albuquerque, NM.

[c] Radon progeny background counts in the Pu ROI for the filter of interest, divided by similar counts obtained simultaneously on a Millipore SMWP filter.

[d] Total radon progeny background counts on the filter of interest, divided by similar counts obtained simultaneously on a Millipore SMWP filter. Mean and standard uncertainty for five replicate tests.

[e] The range of filter efficiency values given generally corresponds to a particle diameter range of 0,035 µm to 1 µm, a pressure drop of 1 cm to 30 cm Hg, and a face velocity range of 1 cm/s to 100 cm/s. Values are from Liu *et al.* (1983), Liu (1992), Hoover *et al.* (1997a) and Hoover *et al.* (1997b).

Table D.2 — Other characteristics of filters

Filter type	Product	Specification	Binding agent	Pore size/ Fibre diameter	Thickness	Area weight	Collection efficiency	Flow resistance	Temperature	Burst pressure		Ash residue
								$v_a = 0{,}34$ m/s	max.	Wet	Dry	
				µm	µm	g·m^{-2}	%	Pa·s·m^{-1}	°C	kPa	kPa	%
Fibre filter	GF 6	Borosilicate fibre	Inorganic	—	350	80	99,97	15 000	500	> 6	> 18	> 90
Fibre filter	GF 8	Borosilicate fibre	Inorganic	—	350	75	99	7 000	500	> 4	> 10	> 90
Fibre filter	GF 9	Borosilicate fibre	Inorganic	—	350	70	99,97	7 000	500	> 5	> 10	> 90
Fibre filter	GF 10	Borosilicate fibre	Organic	—	350	70	99,97	6 500	180	> 10	> 30	> 85
Fibre filter	MN 85/90	Borosilicate fibre	Organic (acrylic resin)	0,4 to 1,8	400	90	99,99	6 500	250	—	—	—
Fibre filter	GF/A	Borosilicate fibre	None	—	260	—	—	—	500	2	—	—
Membrane	AE 99	Cellulose nitrate	—	8	—	44	99,95	10 650	125	—	—	—
Membrane	W 41	Cellulose	—	5	220	85	70	5 800	—	1,5	69	0,007
Membrane	SMWP	Cellulose acetate and cellulose nitrate	—	5	—	—	> 98	—	—	—	—	—
Membrane	AW 19	Cellulose ester	—	5	—	—	99,9	—	—	—	—	—
Membrane	TE 38	PTFE-laminate supported by polyester-tissue	—	5	270	—	—	8 200	145	—	—	—
Capillary pore filter	—	Polycarbonate	—	0,6	10	—	53 to 99,5	—	—	—	—	—

Annex E
(informative)

Evaluating the errors and the uncertainty for the sampling of effluent gases

E.1 Introduction

Error in the determination of a quantity, such as the amount of radioactive substance emitted from a stack during a certain period, can be defined as the difference between its actual value (in some sense) and the measured value. Yet the real situations in which both the actual value and the measured value are known are typically those found when calibrating or qualifying a measurement procedure or instrument against standards, baseline data or against one of the basic conservation laws of engineering. In most situations, it is the limits of uncertainty that can bound the possible errors that are quantifiable (Moffat, 1988). Generally, the uncertainty consists of random uncertainties (type A uncertainty) and systematic uncertainties such as, for example, model assumptions (type B uncertainty, or bias). An estimate of the limits of uncertainty is needed for a measurement that properly and completely combines both sources of error (ANSI/ASME PTC 19.1; ISO/IEC Guide 98-3, formerly known as the GUM).

The case of a simple stack-effluent measurement system, such as a filter air sampler (FAS) connected by a transport line to a nozzle, is used to illustrate a typical effluent measurement process. To estimate the amount of radioactive substance emitted from a stack, a sample of the effluent is extracted, transported to a collection medium and then collected. It is further necessary to quantify the collected material, then relate the quantified amount to the effluent. For the estimation of the effluent concentration, it is necessary to know or estimate the effluent flow rate, the area of the sampling plane, the sample flow rate, the nozzle transmission, the mixing ratio of constituents in the duct, the sample transport penetration, the sample collection efficiency and the analysis efficiency.

The sampling and analysis processes contribute both bias and random uncertainties to the overall uncertainty in the estimated activity. In the case of the extraction-plane parameters and instrument calibrations, both bias and type A uncertainties are combined into one uncertainty carried into the operation phase. For example, during the calibration of the measurement devices, a known and constant input is presented and output or measured response is observed. Bias is evidenced by offset of the mean value from the expected standard response, and type A uncertainty by variation in the output. In other elements, such as the nozzle inlet or transport line, calibration is not possible, but performance in tests with standard aerosol particles under known, controlled conditions can be conducted to establish bounds on expected performance. Similarly, uncertainty estimates can be put on parameters such as the area of the sample-extraction plane, the degree of mixing of contaminants at the plane, and the mean axial velocity of effluent through that plane. Calibration removes part of the bias but not the uncertainty.

The bias that remains embedded in the predetermined parameter or calibrated device elements is not fully known in a particular application. Bounds can be placed on the embedded uncertainties. The random components of uncertainty arise during the calibration measurement processes. These are estimated by the standard deviation of the variable measurement component, such as the sample flow rate or the activity in the sample. Such standard deviation estimates are derived from the data alone without external reference.

E.2 Contaminant transport uncertainty estimation

Regulatory limits on radionuclide emissions are generally stated in terms of limits on the resultant dose per year to members of the public. Thus, it is necessary that a facility sampling and measurement system generate an accurate and reliable estimate of quantities emitted in a given sampling interval that can then be input into a model of an environmental transport and a dose estimation. The average radionuclide activity emission rate over the period of integration, E, expressed in becquerel per second, being transported out of a stack can be represented as given in Equation (E.1):

$$E = c_\mathrm{A} U_\mathrm{M} A \tag{E.1}$$

where

A is the area of the sample extraction plane in the stack, expressed in square metres;

c_A is the effluent radionuclide activity concentration, expressed in becquerel per cubic metre;

U_M is the mean axial effluent velocity in the stack, expressed in metres per second.

The first factor of Equation (E.1), c_A, the effluent activity concentration, is determined by activity measurement, measured sample volume and constant parameters of the system, as given in Equation (E.2):

$$c_\mathrm{A} = \frac{r_\mathrm{n}}{Q P M_\mathrm{P} \varepsilon_\mathrm{f} \varepsilon_\mathrm{d}} \tag{E.2}$$

where

r_n is the net count rate (gross minus background) from the sample, expressed in reciprocal seconds;

Q is the volume of effluent that produced the sample at stream temperature, pressure, and gas composition, expressed in cubic metres;

P is the overall penetration of sample from the free stream to the sample-collection medium (combining transmission through the nozzle, τ_p, and through the transport line, τ_L): the ratio of concentration at the output of the sample transport line to the effluent free-stream concentration;

M_P is the proportion 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, expressed as a fraction;

ε_f is the collection efficiency of the collection medium, expressed as a fraction;

ε_d is the detection efficiency, expressed as the reciprocal of becquerel-seconds [1/(Bq·s)].

The second factor of Equation (E.1), U_M, is the average effluent flow velocity, typically determined by pre-operational measurements from traverses across the duct. Other methods and devices can be used such that near-real-time data for U_M are developed.

In ISO 10780, the mean axial velocity of the effluent is computed from the results of multiple velocity determinations, one at each subsection of the traverse pattern over the sampling plane. Once again, this determination is made during site qualification and subsequent verification, not during operational phases. The relation between U_M at a particular location and the actual parameters measured with a Pitot tube is as given in Equation (E.3):

$$U_\mathrm{M} = U \cos\theta = C_\mathrm{P} \cos\theta \sqrt{\Delta p / \rho_\mathrm{g}} \tag{E.3}$$

where

C_P is the Pitot calibration factor;

Δp is the differential pressure, expressed in pascals;

ρ_g is the gas density, expressed in kilograms per cubic metre, determined from measured static pressure, molar mass of the gas and temperature, using the equation of state;

$U\cos\theta$ is the measured velocity corrected for flow angularity at angle θ.

The last factor of Equation (E.1), the flow cross-sectional area, A, is also predetermined from blueprints or from measurements across the stack or duct. That area is divided into subsections of equal area for purposes of measuring an average axial velocity.

The stack emission rate, E_{average}, expressed in becquerel per second, is calculated by combining Equations (E.1), (E.2) and (E.3) as given in Equation (E.4):

$$E_{\text{average}} = \frac{r_n C_P \cos\theta \sqrt{\Delta p / \rho_g}\, A}{Q P M_p \varepsilon_f \varepsilon_d} \tag{E.4}$$

Equation (E.4) is the mathematical model of the emissions measurement.

E.3 Quantifying uncertainty

E.3.1 Stack emission measurement uncertainty analysis methods

An emission release rate is a function of a large number of measured parameters as contained in Equation (E.4). A basic analysis of uncertainty can be carried out under the assumption of a near-normal distribution of type A uncertainties, which is valid for most, but not necessarily all, of the variable parameters involved.

E.3.2 Overall uncertainty associated with the measurement process

An uncertainty analysis of the measurement processes that take place either in the pre-operational or operational phases has been developed. Each of the terms in the convective emission model has been examined and expanded as appropriate. This is a recommended approach rather than attempting to write a single complex uncertainty equation. The total emission rate from the stack is calculated from measurements on a continuous sample extracted from a qualified sampling location, and other measurements of parameters of the emission equation. The overall uncertainty in that number can be estimated by summing over each of the terms of an uncertainty equation (Moffat, 1988).

E.3.3 Uncertainty associated with bias

The several components of fixed uncertainty in an emission measurement can be combined in one term. An overall bias limit, B_L, defined as the maximum probable value of the total bias in the measurement estimated at the 95 % confidence level, is the root-sum-square combination of all bias components. These can be classified as calibration bias, B_{CAL}; parameter estimate bias, B_{PAR}; and design and test bias for components such as nozzles and transport lines, B_{TST}.

The calibration bias term, B_{CAL}, represents the overall calibration uncertainty, combining elements of both bias and random uncertainty, that accrue during calibration of instruments or devices. This is typically the residual bias remaining after gross bias is zeroed out (up to an acceptance limit) during calibration; in some cases it is identified by manufacturers as the accuracy limit of the calibrated scale or readout device.

The parameter bias term, B_{PAR}, represents the overall uncertainty (again combining type A and type B uncertainties) that is derived from field and laboratory determinations of sample-extraction parameters, such as the degree of particulate mixing, M_P, or mean profile velocity, U_m, that ultimately are applied as a single value to estimations of stack emissions. Other bias contributions related to sampling location effects are treated separately below.

The design and test bias term, B_{TST}, results from residual uncertainties in the process of design and qualification of sampling nozzles and devices that are engineered from first principles and empirical factors, and then manufactured and tested to confirm that certain performance characteristics, such as nozzle-inlet penetration efficiency, have been met. Such a critical performance characteristic is specified by an acceptable range for a given set of operating conditions, and there is an acceptance limit on deviation between the design performance and the result of confirmation tests with tracer materials.

The overall bias limit, then, can be expressed as given in Equation (E.5):

$$B_{\mathrm{L}} = \left(\sum_i B_{\mathrm{CAL},i}^2 + \sum_i B_{\mathrm{PAR},i}^2 + \sum_i B_{\mathrm{TST},i}^2 \right)^{1/2} \qquad \text{(E.5)}$$

where the summations are over the i contributions from devices or parameters, each contributing uncertainty to the measurement outcome.

The bias limit estimated at the 95 % confidence limit serves the same purposes for the bias as does the two-standard-deviation random uncertainty estimate. It is combined with the 95 % confidence limit estimate of the type A uncertainty component in calculating the overall uncertainty of measurement. A full uncertainty analysis entails a careful consideration of the many sources of uncertainty and proper combining of each component to generate an overall uncertainty estimate.

The Table I.1 guidance levels for acceptable accuracy and precision of measurement require evaluation of factors that can contribute uncertainty to components of the system. Without detailed analysis, it can be difficult to demonstrate that estimates are reasonably complete and defensible. The discussion in the remainder of this annex is meant to provide a framework for an evaluation of uncertainty in an effluent measurement based on an analytic expression relating radionuclide emission to variable parameters in the measurement, and on residual bias and implicit uncertainty inherent in the methodology of continuous emission monitoring from a single point.

It is worthwhile to reflect here on what interpretation should be given to the “true value” of the measured effluent-radioactive-substance emission rate by the single-point representative sampling method. If we use the classification and nomenclature developed by Moffat (1988), the fact that flow and mixing parameters are averaged over the profile implies that the intended “true” emission rate is the “conceptual value” at the sampling location, i.e. that the area-averaged emission rate of radioactive substance from the stack based on the axial locations of the nozzle(s), assuming that the installed instrumentation does not disturb either the concentration or the flow distributions and that the pre-operational measurements of critical parameters, i.e. U_{M}, P, Q and M_{p}, properly reflect sampling under operational conditions. The conceptual value shall be distinguished from the “available value”, which is the emission rate estimated only at the axial location of the nozzle(s), without assumptions about disturbance, mixing or how representative the parameter estimates are. Because it is the well mixed, mean effluent radioactive substance emission rates that are of interest, the effects of the non-uniform distribution of velocity and contaminant mal-distribution shall be added to the list of sources of uncertainties, and uncertainties in the correction factors that account for the non-uniform distribution shall be considered. The estimation of the true emission rate (the conceptual value) depends on parameters measured at other times, under possibly different conditions, and with test aerosol particles and gases rather than the actual radioactive contaminants; so it is evident that the uncertainty in the result of a single-point sample depends on considerations other than explicit operational or pre-operational measurement uncertainties.

E.3.4 Uncertainty associated with conceptual bias

As noted in E.1, a useful distinction can be made between the uncertainty of the measurement processes and the uncertainty associated with the overall methodology. The measurement uncertainty is attributable to explicit performance aspects of the sampling and analytic hardware. Sampling methodology bias derives from issues related to sample extraction location and related implicit factors that affect how well the sample represents the true emissions from the stack during the period of the sample. These are what Moffat (1988) terms “pattern factors”, defined as factors that describe variation in velocity and mixing in the profile and an estimate of how the value of the emission rate at the nozzle location compares with the mean value. In some situations, the conceptual bias can be the largest by far. Two of the more significant sorts of conceptual bias derive from assumptions about temporal variation and about the completeness and accuracy of model assumptions.

E.3.4.1 Uncertainty associated with temporal variations

Changes over time in stream conditions following site qualification are assumed not to significantly influence the measurement outcome. Yet, increases or decreases in volumetric sample flow, effluent discharge rate or modifications in the stack use can cause distortions in sample extraction or contaminant mixing. The degree to which a single-point sample is representative can then change. This is why it is particularly important that those factors that are counted on to produce a well-mixed condition at a qualified sample-extraction location be robust with respect to reasonably anticipated changes in stack conditions. Mechanical mixing elements or deflected, colliding flows produce mixing conditions at the selected sample extraction plane that are resistant to change under modifications in facility use or under upset conditions, and so their use is compatible with small values of estimated uncertainty, δ_{TE}. A judgement is required about assigning the significance of temporal variations and, hence, the magnitude of this uncertainty term.

E.3.4.2 Model bias, δ_{ME}

There are a number of simplifying model assumptions implicit in the representation of continuous emission monitoring by extractive sampling from a single point. Among these are that the contaminant-transport processes in the sample nozzle and line are well represented by semi-empirical models (see Annex B), that the measured uniformity of the velocity profile and degree of mixing at the stage of site qualification continue to apply during operations (a pattern assumption), and that the activity-measuring process is well represented by the single-parameter sample collection and radiation-detection efficiencies. To varying degrees, model-based assumptions might not be fully correct for a particular application. Again, a judgment is required to assign an estimate to this uncertainty term. Both the temporal variation uncertainties and model bias can be combined with other fixed uncertainties arising from various measurements in generating an overall bias limit estimate.

The user is advised to become very familiar with the assumptions and limitations of the models used to optimize sample-transport-line design to ensure that special provisions properly take into account the deposition of highly reactive species, particle bounce or resuspension from previously deposited materials. The same applies to models of other aspects of the sampling and measuring process. The use of computational modelling aids should be viewed as a part of a larger process of design and evaluation that should include data from laboratory studies, findings in the peer-reviewed literature and field testing.

E.3.5 Describing the combined uncertainties in emission measurement

The last step of an uncertainty analysis is bringing together the 2σ random uncertainties and the overall bias limit [Equation (E.1)] into a combined estimate of overall uncertainty stated in terms of the emission estimate, $E_{\mathrm{total(0,95)}}$, the estimated uncertainty limit of the effluent measurement at the 95 % limit (ANSI/ASME PTC 19.1; ISO/IEC Guide 98-3, formerly known as the GUM), as given in Equation (E.6):

$$E_{\mathrm{total(0,95)}} = 2\left(B_{\mathrm{L}}^{2} + \sum_{i} s_{i}^{2}\right)^{1/2} \tag{E.6}$$

where

B_{L} is the expected upper limit of the total true bias (the difference between the average of the total population and the true value, which is the type B uncertainty);

s_i is the sample standard deviation based on N measurements of the ith term (precision index) for variable terms in the emission rate equation.

E.4 Evaluation of uncertainties

According to Brooks (1979), estimates of the magnitude of most of the uncertainty terms can be described at least to the level of what is attainable at the 95 % confidence level (corresponding to a 2σ interval for random variables). Many of the uncertainties considered above are relatively small and controllable by good practice. Others require more careful consideration.

E.4.1 Uncertainty in sample volume, stack area, and transmission efficiency

Uncertainty in sample volume, Q, and stack area, A, are generally small and well understood. Sample volume measurement is readily accomplished and corrected for altitude and temperature. As described in J.2.2, the accuracy of the measurement of the sample flow (and hence sample volume) with a flow meter should be periodically checked with a secondary standard flow meter, and differences maintained to less than 10 % of standard [see Equation (J.2) for further details]. Expanded uncertainty with a factor of 2 σ in the order of 5 % should be achievable.

The cross-sectional area of the effluent flow at the sample-extraction location should be accurately ascertained from engineering drawings of the effluent stack. Bias associated with this determination should be much less than 2 %.

Sample-transport-line penetration in the case of particulate effluent is harder to estimate because the characteristics of the aerosol particles being sampled cannot be fully described in advance. Although the particle-size characteristics of many types of radioactive aerosols have been studied (see Annex G for a discussion of such studies), many possibilities for HEPA filter failure and associated unique aerosol-particle-size distributions exist. Nonetheless, an estimate of the magnitude of uncertainty in this parameter can be made. The estimate may be based on in-place tests with particles of either conservative or realistic size characteristics. The estimate may also be obtained with the aid of suitable particle-penetration models (see Annex B) and appropriately varied parameters. It is expected that a proposed transport line for a sampling system is designed for optimal performance using a conservative assumption; for example, 10 µm monodisperse aerosol particles. A conservative design establishes the lower limit of penetration because polydisperse aerosol particles with an equal or smaller geometric mean have greater transmission efficiency. So, in the case of the system analysed in Table B.1, the range of possible transmission efficiencies for particles having a D_a smaller than 10 µm exceeds 74,3 %. In cases where additional data about the relevant size distribution (e.g. activity size distribution) are available, the test or design aerosol particle size may be selected accordingly.

For example, assume that there is a polydisperse log-normal distribution of particle sizes with an average activity median aerodynamic diameter (AMAD) of 1,8 µm and $\sigma_g = 2,2$, like that found in a research and development facility glovebox line by Ettinger *et al*. (1973). Further assume that the model predicted transmission efficiency for the fictional sampling system is 94,2 %. For uncertainty analysis purposes, suppose the aerosol particles actually encountered in an accident effluent is more like the fabrication facility average size distribution reported by Ettinger *et. al*. (1973) (AMAD of 4,0 µm, $\sigma_g = 1,7$). Then, the predicted transmission efficiency can be 85,9 %, a relative difference of 8,8 % compared with the 94,2 % estimate. The average predicted deviation using a range of size distribution parameters from four other plutonium handling facilities included in their study was 7 %. A 15 % estimated 95 % confidence level uncertainty relative to predicted performance and assuming a realistic aerosol particle size distribution appears to be attainable.

These estimates are summarized in Table E.1.

E.4.2 Uncertainty in velocity measurement parameters

Uncertainties in the determination of velocity at each equal-area location in a profile are summarized from Brooks (1979) in Table E.2, assuming that an S-type Pitot tube nozzle is used. Here, as for the parameters in Table E.1, attention to the details of the design and operation of the hardware in use is required.

Table E.1 — Uncertainty in sample volume, stack area and transmission line efficiency

Parameter		Uncertainty %
Sample volume	$2\sigma_{\mathrm{Q}}/Q \times 100\ \%$	$\leqslant 5$
Stack area	$2\delta_{\mathrm{A}}/A \times 100\ \%$	$\leqslant 2$
Transmission line efficiency	$2\delta_{\tau\mathrm{p}}/\tau_{\mathrm{p}} \times 100\ \%$	$\leqslant 15$

Table E.2 — Velocity measurement parameter bias

Parameter		Uncertainty %
Pitot calibration	$2\delta_{\mathrm{Cp}}/C_{\mathrm{p}} \times 100\ \%$	$\leqslant 1$
Flow angularity	$2\tan(\theta)\delta_{\theta} \times 100\ \%$	$\leqslant 8$
Differential pressure	$2\delta_{\Delta\mathrm{p}}/\Delta p \times 100\ \%$	$\leqslant 14$

E.4.3 Uncertainty in measurement parameters

Measurement of activity in a sample can be either an on-line process in a continuous monitor or an off-line process in a laboratory. In all systems, detector efficiency and sample capture efficiency parameters can usually be well defined. Detector efficiency is typically determined by comparison against a transfer standard traceable to the governing national institute of standards and measurements. Uncertainty can be held to a minimum (1 % to 2 %).

Type A uncertainty in the counting process and associated with background-interference variability are the largest contributors to this uncertainty. However, bounds can be put on this uncertainty by careful planning.

In most circumstances, a relative 95 % confidence level uncertainty of 5 % to 10 % appears to be attainable by adjustment of sample and background count times. But in practice this might not always be possible due to the unrealistically long count intervals that can result.

E.4.4 Methodological bias

Turning now to the implicit methodological or conceptual uncertainties, there is a large component of engineering judgment required to assign values to these, but bounds can be placed on the estimated uncertainty.

The uncertainty associated with the sample-withdrawal location, for example, can be estimated by the measured coefficient of variations in the mixing of tracer gas and tracer particles that are required as part of qualifying a sample-extraction location for continuous-emission single-point sampling and monitoring. Based on limited studies, it appears that a 95 % confidence limit bias of δ_{RE} equal to 10 % is attainable, and in any event it should be much less than 20 %.

Uncertainty associated with changes in effluent emission conditions over time are difficult to predict. If mixing elements installed in a stack are employed to ensure complete mixing, then an estimate of the 95 % confidence limit on uncertainty due to time varying effects on the order of δ_{TE} equal to 2 % to 4 % appears to be reasonable.

Similarly, model assumption uncertainty, at the 95 % confidence level, on the order of δ_{ME} equal to 2 % to 4 % is feasible as long as proper qualifications of the sampling nozzle, sample transport line, and sample withdrawal location are demonstrated.

E.5 Summary of uncertainty analysis

Estimated uncertainties in Tables E.1 and E.2 (or equivalent from an independent analysis) and the other parameter uncertainty estimates can be substituted into appropriate equations to obtain a total explicit measurement-process uncertainty estimate. The estimated activity measurement uncertainty (5,5 %), sample volume measurement uncertainty (5 %) and sampling plane area uncertainty (1 %) contribute least to the total. The uncertainties in the sample-transport-line efficiency (15 %) and emission mean-axial-velocity (10,7 %) terms contribute the most. The resultant combined uncertainty is on the order of 19 %.

Combined with the conceptual uncertainty estimates, the overall uncertainty of the effluent activity measurement, $E_{\text{total(0,95)}}$, expressed as a percentage, is as given in Equation (E.7):

$$\begin{aligned} E_{\text{total(0,95)}} &= \pm\sqrt{(0{,}19)^2 + (0{,}07)^2 + (0{,}02)^2 + (0{,}02)^2} \times 100 \\ &= \pm 20 \end{aligned} \tag{E.7}$$

This estimate should be understood as an indication of what can be attainable based on the assumptions concerning the measurement procedures carried through the analysis. Differences in the way that mean axial velocity is determined, improvements in reducing uncertainties in volumetric flow measurement and better potential transport-line-loss estimation can be possible in some cases, as can reductions in the uncertainty in certain profile “pattern” parameters, such as any of the statistics describing mixing at the sampling plane.

E.6 Correlated uncertainties

The analysis in this annex to this point has been based on the assumption that the uncertainties are separable. The uncertainties are not separable in all cases. The transport efficiency, ε_{Ts}, and the collection efficiency, ε_{f}, are dependent upon the flow rate. In some cases, the detection efficiency is dependent on the flow rate.

Based on the uncertainty analysis of the emission rate given in Equation (E.4), it may be concluded that the intrinsic uncertainty of the flow-rate can be ignored, but not its extrinsic or correlated uncertainty.

The transport penetration is dependent upon the flow rate. If the transport penetration is high (> 90 %) for all particle sizes, flow rate changes of 10 % or less can have little effect on the transport efficiency. When the transport penetration is lower, small changes in the flow rate can greatly effect the transport efficiency for some particles sizes. These changes should be empirically determined or calculated using a code, such as Deposition. A similar relationship for particle collection can be developed, for which the same correlated uncertainty arguments apply.

The detection efficiency can be affected by the flow rate if detection is dependent upon geometry and the geometry is collection-dependent. A simple example is alpha-particle detection on a filter. If the collection of large, high-activity particles takes place primarily near the edge of the filter and, therefore, the edge of the detector, then the detection efficiency for these particles is diminished. The flow-rate-correlated uncertainty should be determined.

Flow-rate-correlated uncertainties in these cases are further dependent on the particle-size distribution, i.e. the effect of a few large particles can be quite small, while for a significant number of large particles, this effect can dominate.

Annex F
(informative)

Mixing demonstration and sampling system performance verification

F.1 Mixing demonstration methods

At least two methods have been used to demonstrate the state of mixing of the potential contaminants with the effluent air stream. They are described in F.1.1 and F.1.2.

F.1.1 Method 1

Method 1 was developed specifically to assess conformance with 6.2.

F.1.1.1 Tracers

To test for contaminant mixing, the tracer should be introduced as far upstream as possible of the sampling probe, yet downstream of feeder ducts, fans and air-pollution-abatement equipment. If it is necessary that a stack be tested for both particles and gases, the same injection location should be used for both tracers. The gaseous tracer should be introduced at five or more locations across the cross-section of the air stream. For a rectangular duct, the injection should be at the centre and near each corner (at or within a distance of 25 % of a hydraulic diameter from a corner). For a round duct, the introduction should be at the centre and near the wall (within 20 % of the diameter from the wall). The aerosol particle tracer may be introduced at only one location, located at the centre of a stack or duct.

The degree of mixing for particles should be tested with particles having a diameter, D_a, between 8 µm and 12 µm, or larger if there can be a significant fraction of the aerosol particle mass or activity associated with sizes larger than a D_a of 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, in any foreseeable circumstances, only gaseous contaminants can be present, it is not necessary to test for particle tracer uniformity.

Testing to establish the degree of mixing requires sufficient gas or particles to provide an adequate signal at the extraction point. The method of detection and its detection limit are the important considerations in the amount of material introduced. Sufficient material should be introduced to allow detection after dilution in the effluent stream. Examples of methodologies for obtaining data on velocity, tracer gas and aerosol particle profiles are given by Glissmeyer and Davis (1998), Rodgers *et al.* (1996), and McFarland (1998).

Tracer uniformity measurements should be conducted at the location of the sampling probe using the measurement grid developed in F.1.1.3.

F.1.1.2 Measurement conditions

The tests should be conducted while the stack flow rate is approximately the same as the expected normal flow rate. If the stack flow rate is expected to vary more than 25 % from the mean, then the tests should be conducted at the flow rate extremes.

It is essential to establish with confidence that the location chosen for sample extraction is based on demonstrated complete mixing using the above methods and that the criteria will continue to meet mixing-performance requirements under changed conditions relative to those at the time of testing. Historical records of effluent flows may be used to provide evidence of extremes (high or low) of flows that can be encountered in a stack. Calculations of expected flows under accident conditions or very different operating modes may be based on documented engineering judgment. Mixing under flow rates that are considerably different from normal may be substantiated by tests with models or field testing of the stack or duct. Under most conditions, changes in the effluent flow rate does not significantly affect the mixing. In general, if the flow rate increases, acceptable mixing is not jeopardized; however, if the flow rate were reduced to the point where the Reynolds' number becomes much less than 10 000, there can be a major degradation in the mixing effectiveness. This event is generally possible only with a stack or duct having a very small cross-section, such as a tank vent. If this is possible, the flow system should be modified to preclude the onset of near-laminar conditions.

F.1.1.3 Measurement points

The combination of flow angle, velocity and tracer concentration profile measurement points at the candidate sampling location should be selected in accordance with the velocity measurements of ISO 10780. It can be necessary to add or adjust measurement to achieve a suitable grid. Also, it can be necessary to adjust points because of the proximity of a sampling point to a wall.

F.1.1.4 Transference of qualification test results

It is not always necessary to perform the full qualification test series on all stacks if a geometrically similar design has already been shown to meet the qualification criteria given in 6.2 and provided that the following apply.

a) A geometrically similar stack or duct (one with proportional critical dimensions) has been tested and the sampling location has been found to comply with the requirements of 6.2. Critical dimensions are those associated with components of the effluent flow system that can influence the degree of contaminant mixing and the velocity profile. The prior testing may be conducted either on a stack or duct in the field, or it may be conducted on a scale model.

b) The product of mean velocity [see Equation (A.2)] and hydraulic diameter of the candidate stack or duct is within a factor of six of that of the tested stack or duct, and the hydraulic diameter of the candidate stack or duct is at least 250 mm at the sampling location. The Reynolds numbers based on hydraulic diameter of both the candidate stack or duct and the tested stack or duct are greater than 10 000 [see Equations (B.1) and (B.2) for examples of expressions that can be used for calculation of Reynolds numbers)].

c) The measured velocity profile in the actual stack or duct should meet the requirements of 6.2.

d) The difference between the velocity COVs of the two systems is not more than 5 %.

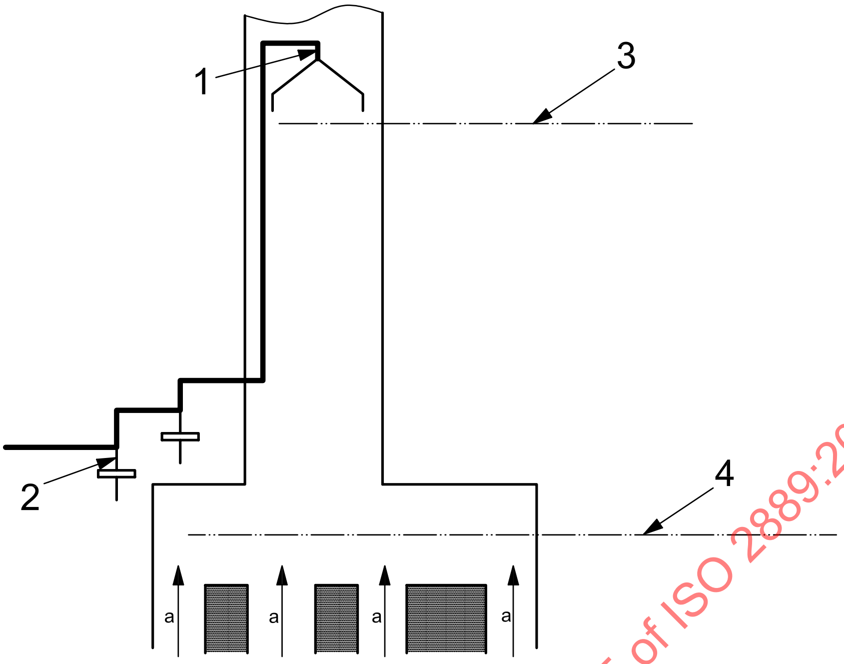
e) The sampling location in the candidate stack or duct is placed at a location geometrically similar to that in the tested stack.

If these transference requirements are fulfilled, the sampling location in the second stack or duct is considered to be acceptable.

F.1.2 Method 2

Figure F.1 shows how a number of ventilation channels come together in a chamber on top of which stands the stack. Sample extraction for effluent monitoring is done about four diameters up the stack. The test was originally developed to measure particle losses in probes and pipes, but it can also be used for investigating the effects of incomplete mixing of the contaminants in the effluent air.

Figure F.1 shows a two-stage sampler installation. The first stage brings air down to the measurement room at a rate of 60 l/s. There, several samplers withdraw air at 0,5 l/s. The probe in the stack has four to six nozzles.



Key

1	sample extraction location
2	samplers
3	tracer gas detectors
4	injection level for tracer gas and particles
[a]	Air flows from reactor building, turbine building.

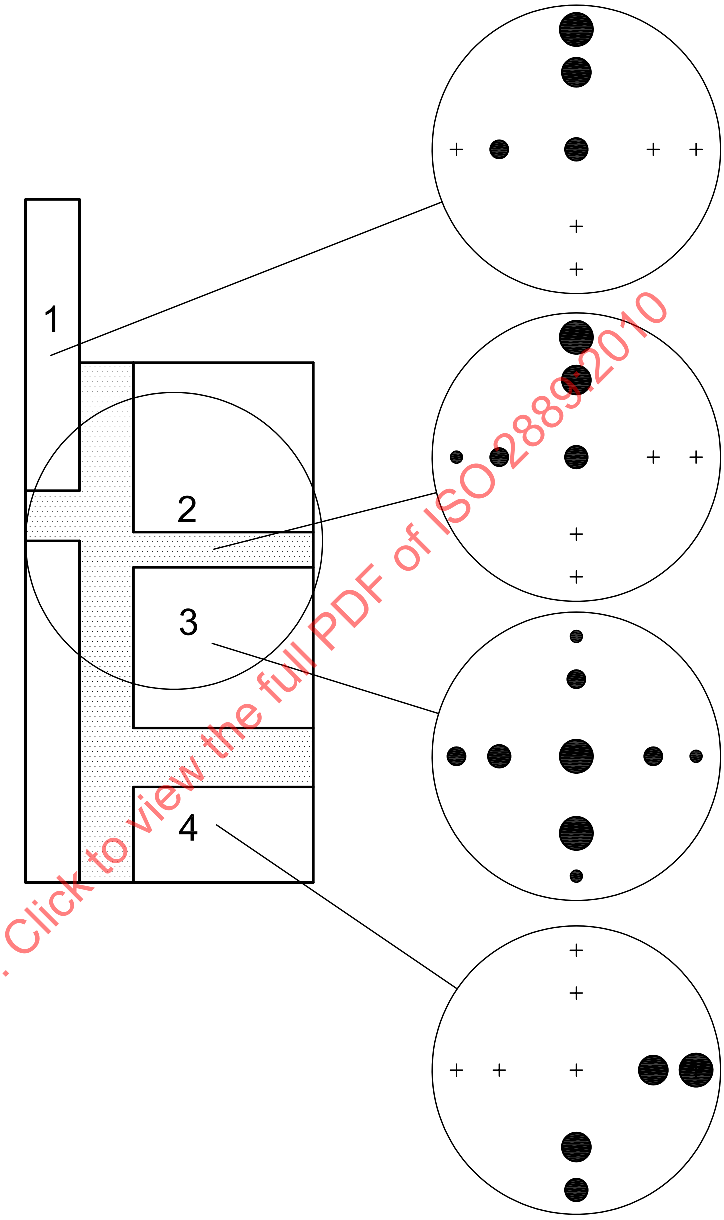
Figure F.1 — Illustration of the use of method 2 to determine mixing

The test is comprised of the injection of known amounts of monodisperse particles in the stack air stream at a suitable point upstream of the sampling installation. To find a suitable injection point, the gas flow is mapped by means of a tracer gas, ethanol, released as a spray at various points in the stack base. The resulting concentration distributions at the stack-sampler level are observed by means of an array of gas detectors. An injection point that produces symmetrical distribution over the stack area, and low concentrations at the stack walls, is selected for the particle tests (Figure F.2, key item 3). In this way the losses of tracer particles become small and limited to the flow near the stack wall where the stack probe doesn't sample.

Monodisperse particles nominally with a D_a of 2 µm, 4 µm, 8 µm, and 16 µm tagged with dysprosium are dispersed at the selected injection point. The particle concentrations at the sampler inlets are calculated from the observed gas distribution. The amount calculated as aspirated into the sampler piping is compared with the quantity collected by the ordinary filters of the sampling train to obtain the sampling-line transmission efficiency.

The sample-extraction location is situated about half-way up the stack. This is enough for producing an even velocity field, but it is not enough for mixing. Figure F.2 shows the stack base as seen from above. (The cross-section at the stack base is irregular because several ducts discharge into the base of the stack.) Key items 1 to 4 represent the different injection points for the tracer gas. The tracer gas that is injected into the different ventilation channels is not well mixed into the main air stream as it passes the sample-extraction location. The spots in the four circles to the right represent observed concentrations at the sampling level. As is evident from Figure F.2, the air streams from different ventilation systems are not well mixed. The corrective measures outlined in Clause 6 are advised for this example, and single-point sampling is not appropriate unless the mixing is corrected.

With the data from the tests using the tracer gas and a knowledge of the positions of the individual sampling nozzles of the probe, the response to different concentration patterns can be estimated. It seems that four to six nozzles can be quite satisfactory with geometry as described above. Further details about this test method are reported in Ström (1996).



Key

1 to 4 gas injection points in the stack base

Figure F.2 — Stack base as seen from above with diagram of sample results

NOTE The corresponding tracer distributions over the circular stack section at the sampling level are shown to the right. The area of the spot is proportional to the observed concentration. The "+" symbols indicate where no tracer was detected.

F.1.3 Alternative approaches

Other approaches may be used to qualify a location for sampling provided that the accuracy of the methodology is equal to, or exceeds, that based on the criteria given in this annex. For example, in an application dealing with sampling of radioactive gases, it can be possible to inject a tracer gas into the stack at a known mass flow rate. If the mass flow rate of tracer emitted from the stack based on use of a single-point sampler at a candidate location were to show a value within ± 20 % of the mass flow rate of injected tracer, the sampling location may be considered acceptable. In such a situation, it can be necessary to demonstrate the quality of samples acquired at different flow rates (e.g. average, high and low) of the stack gas.

F.2 When to conduct sampling system performance verification

There are instances when a performance verification of a sampling system is advisable. These include the following:

- when the air stream being sampled is not well mixed before a new system becomes operational;
- when an existing system has just come under additional regulatory requirements;
- when the potential to emit contaminants through an existing system has changed significantly;
- when an existing system has had significant changes, for example: changing the stream flow beyond the original design limits; adding a new effluent stream in a manner that destroys the well mixed state at the nozzle location; or changing system operating parameters outside of the design range;
- when the supporting documentation for a newly installed system is deficient.

F.2.1 Approaches to verification

The methods for verifying sample-transmission performance through nozzles and transport systems fall into four categories:

- in-place testing;
- laboratory simulations;
- modelling based on deposition and resuspension rates determined in the laboratory;
- a combination of the above.

Table 1 summarizes the requirements for qualifying sample extraction locations, nozzles and transport lines for particles, gases and vapour. In 7.2.1, it is recommended that nozzle performance for particles be tested using liquid aerosol particles. In 7.3.1, it is recommended that transport-line performance be assessed either through aerosol particle testing or through calculations with a verified model. In 6.4, a general method is provided for use in qualifying the sampling location for particles, gases and vapour using in-place testing. Nozzle and transport-line performance methods for gases and vapour are not specified in this International Standard.

Meeting the performance requirements usually involves a combination of methods. In-place testing can give the most unambiguous result, but it can also be difficult to implement in all situations. The discussion in F.2.2 gives examples of methods in each category.

F.2.2 In-place testing

F.2.2.1 Particle sampling examples

Glissmeyer and Davis (1998) and Rodgers *et al*. (1996) provide examples of employing the methods outlined in Clauses 7 and 8. Sulfur hexafluoride gas and oleic-acid aerosol particles are used as the tracers to qualify the sample extraction location. Oleic-acid aerosol particles are also used to verify the performance of nozzles and transport lines for particles. Examples of other verification methods attempted include the following:

- Leuba and Schwabacher (1961), using 3 µm to 30 µm aluminium and iron powder aerosol particles;
- Schappel (1961), using uranium aerosol particles;
- Ström and Hesböl (1977), using fluorescent-dye-tagged dioctylphthalate 20 µm aerosol particles;
- Curtis and Guest (1986), using sub-micrometre aerosol particles of sodium fluoroscein dye;

- SAIC (1991), tests performed on several stacks using polystyrene latex microspheres using optical particle counters on samples from the nozzle inlets and the exits of the transport lines;
- Newton *et al.* (1983), tests conducted on sampling systems at the Waste Isolation Pilot Plant using salt aerosol particles;
- Glissmeyer (1992), systems tested using powdered tracer aerosol particles with geometric mean diameters of 1,3 µm and 8,5 µm. Temporary sample collectors were arrayed across the stack to characterize the mixing and to determine the average emission rate for comparison against the existing system;
- Vogl (1994), systems tested using powdered test aerosol particles with geometric mean diameters of 1 µm (TiO_2), 3 µm ($SrTiO_3$), 8,5 µm (Mo_2C), 200 µm (brass) and 800 µm (WC). The test aerosol particles had been injected into the stack as well as into some nozzles. With these tests, the concentration distribution of test aerosol particles over the sampling plane as well as the penetration of these test aerosol particles from the stack and from the nozzle entrance was determined.
- Kenoyer (1993), using cascade impactors and optical particle counters to test several systems without employing tracer aerosol particles.

These last examples might not necessarily meet the current guidelines of this International Standard, but provide insight into other approaches.

F.2.2.2 Radioiodine sampling examples

Ström and Hesböl (1977) tested sampler performance for radioiodine by injecting both depositing and non-depositing forms of iodine into the ventilation stream. Samples were collected both in the stack at the elevation of the sampler nozzles and at the regular sample-collection point. The non-depositing form was ^{131}I-tagged methyl iodide and $^{131}I_2$ was used as the depositing form.

Curtis and Guest (1986) used stable methyl iodide and elemental iodine injected into the stack flow upstream of the fan. Collected iodine samples were analysed using neutron activation.

Leuba and Schwabacher (1961) used ^{131}I injected into a stack, which was sampled at several locations in the cross-section using charcoal traps. These data, together with velocity data and tracer aerosol particle tests, were used to determine the contaminant profiles for the stack.

F.2.3 Laboratory simulation

F.2.3.1 General

Laboratory simulations are more rapid and convenient than in-place tests. It is unlikely that complete systems can be simulated and the effects of surface contaminants in older systems can significantly affect real performance.

F.2.3.2 Particle examples

SAIC (1991) conducted a test of a full-scale sampling system of simple design. The tests were conducted using polystyrene latex microspheres and laser particle counters sampling from the nozzle inlet and from the end of the transport line. McFarland *et al.* (1991) conducted tests of a simulated sampling system using oleic acid aerosol particles tagged with sodium fluoroscein. Glissmeyer and Ligotke (1995) conducted wind-tunnel tests comparing the performance of probes using shrouded nozzles to those using tapered inlet isokinetic nozzles.

F.2.3.3 Radioiodine examples

Unrein *et al.* (1985) and Edson *et al.* (1987) conducted radioiodine line-loss tests to simulate air samplers used at several nuclear generating stations. The tests cover the range of air sampler characteristics commonly observed at reactor sites. The sample transport tubes were either 304 or 316 stainless steel as clean as received from the distributor. The results from these and other tests are summarized by Glissmeyer and Sehmel (1991).

F.2.4 Modelling

F.2.4.1 General

Modelling is often used to address the performance of transport lines. Modelling does not completely address all performance aspects of a sampling system, notably the adequacy of contaminant mixing at the sampling plane. This weakness may be overcome in the future as illustrated by Gielow and McNamee (1993), who used a three-dimensional fluid mechanics model to identify potential flow-measurement locations in the off-gas ductwork of a power station. They also compared the model results with velocity-traverse data.

F.2.4.2 Particle examples

Fan *et al*. (1992) provides an example of the use of the Deposition code and compares the results against tests of a simulated air sampling system. Examples of the use of earlier models include the following:

- Rodgers (1987);
- Alvarez *et al*. (1985);
- Schwendiman *et al*. (1975).

Annex B describes most of the elements that it is necessary to take into account in a particle-loss model. An example calculation using the Deposition code is also given.

F.2.4.3 Radioiodine examples

SAIC (1991) modelled the radioiodine transmission through several sampler-transport lines. Other examples are summarized by Glissmeyer and Sehmel (1991). See also Annex C.

Annex G
(informative)

Transuranic aerosol particulate characteristics — Implications for extractive sampling in nuclear facility effluents

G.1 Introduction

The engineering of stack monitoring and sampling systems for nuclear facilities requires close attention to the design and placement of the sample-extraction nozzle and transport line to ensure the most representative sample possible (McFarland and Rodgers, 1993). With respect to the physical characteristics of the effluent that it is necessary to sample under normal conditions and particularly under emergency conditions, little has been said other than that the most significant accident in a facility in terms of both an event and its consequences is likely to be fire (Corley and Corbit, 1983). Fire can cause radioactive sources to release airborne radioactive aerosols, and smoke can plug filtration systems causing the filter to lose its integrity by rupture of the medium or seals. Therefore, while there are no definite answers concerning the aerosol particle characteristics that a sampling nozzle and transport line should be capable of handling, a number of investigations have been made of the expected filtration performance of HEPA filters under standard operating conditions. Also, a number of investigations have been made of the characteristics of aerosol particles present in gloveboxes or generated when containment structures, flammable liquids or mixed radioactive materials are spilled and burned. Because these aerosol particles can be expected to be present in a fire, they provide a first approximation of the character of aerosol particles that it can be necessary to sample in effluent stacks. The discussion in this annex is meant to place some reasonable bounds on the size of particles that can typically be present in the event containment is lost and to provide some perspective on the type of design and testing considerations that it is necessary to apply to sampling nozzles and transport lines.

G.2 HEPA filtration effects

Nuclear-facility stack emissions are typically controlled by multiple stages of HEPA filters. The HEPA filter is designed to remove particulates from a gas stream with an efficiency of at least 99,97 %. Selective penetration of HEPA filters by sub-micrometre particles (0,1 µm to 0,4 µm) and negligible penetration by other sizes of particles is predicted by filtration theory (Scripsick, 1994). Therefore, it is sometimes concluded that it is not necessary to design sampling systems for HEPA filtered stacks that take into account inertial effects in the sampling-nozzle inlet and transport line. However, this conclusion is invalid.

In studies at the Rocky Flats Plant of particulate emissions in stack effluents, Nininger and Osborne (1992) sampled particles downstream of HEPA filters. A laser particle counter was employed to obtain number/size distribution data over the size range from the sub-micrometre range to over 10 µm (optical diameter). While only a small fractional percentage of particle counts correspond to diameters greater than 5 µm, when these data are converted to a volume distribution (hence reflecting the actual distribution of particle mass, and possibly activity, in the samples), the volume percentages corresponding to particles with diameters greater than 5 µm are quite significant (greater than 30 %). Nininger and Osborne (1992) also observed the presence of white fibres in the vent discharge and speculated that fibres and other large particles might have been shed by the HEPA filters.

A different explanation for the presence of the larger particles downstream of HEPA filters comes from studies by Scripsick (1994) of leak phenomena in HEPA filter systems (pinhole leaks, frame seal leaks, etc.). Particle penetration through filter perimeter seals and the filter pack was determined separately and in combination. Penetration is observed only when the challenge aerosol particles are introduced into the system, ruling out the possibility that the observed particles were shed from the filter pack. He found that whereas filtration theory predicts a penetration fraction of 10^{-16} for 0,7 µm particles, the observed penetration was approximately 10^{-5}. Scripsick concluded that system leakage phenomena and the size distribution of the challenge aerosol particles can override filtration theory considerations in predicting the size distribution of particles penetrating the HEPA filter systems.

This is consistent with studies of multiple HEPA banks by Ettinger *et al*. (1973), whose data are summarized in Table G.1. In this case, the presence of a small but significant fraction of supra-micrometre-sized particles after the second and third stages is indicated because the geometric standard deviations remain large. But the respective activity concentrations are very small due to the reduced challenge and narrowing spectrum of particle size at each successive stage. At the same time, failure of earlier stages can be expected to result in both higher release concentrations and larger quantities of particles in the inertial size range (with a D_a equal to 1 µm and larger). Therefore, the design of extractive sampling systems in HEPA-filtered stacks should reflect a consideration of the presence of large particles, even under the presumption of normal operating conditions and HEPA filtration.

Table G.1 — HEPA efficiency and particle penetration of Pu aerosol particles

HEPA stage	Particle size AMAD[a] of challenge µm	Mean measured efficiency %	Remaining activity[b] Bq/m^3
1	0,7 to 2,1, $\sigma_g = 2$ to 3	99,998 76	10^7 to 10^8
2	0,45 to 0,82, $\sigma_g = 1,5$ to 2	99,998 17	10^2 to 10^4
3	0,37 to 0,70, $\sigma_g = 1,3$ to 1,8	99,864 92	1 to 5

[a] AMAD is the activity median aerodynamic diameter.

[b] Challenge aerosol particle concentration is equal to 10^{12} Bq/m^3 to 10^{14} Bq/m^3.

G.3 Transuranic aerosol particulate characteristics under accident conditions

HEPA filter failure under a variety of accident conditions adds another dimension to the concern for being prepared to sample particulate radioactive substances in the larger size ranges. But now it is necessary to ask, what, if a substantial HEPA failure occurs, is the upper particle-size limit that one can expect that it is necessary to sample efficiently in order to properly represent the majority of the activity in the effluent? In other words, can the size distribution of effluent aerosol particles at the sampling plane suddenly shift to one characterized by the occurrence of a significant particle-size mode in a region above D_a equal to 10 µm to 15 µm? It is understandably difficult to characterize aerosol particles that can be expected as a result of HEPA failure. As is the case with normal, intact HEPA filter banks, the characteristics of the aerosol particles penetrating a failed HEPA are determined by the characteristics of the challenge aerosol particles. The literature, derived from studies of aerosol particles associated with accidental spills and fires in nuclear facilities and of *in situ* dust and debris in uranium/plutonium gloveboxes and ducts, provides the best indications of what to expect. The following synopses of a few cases are indicative of what is known and expected.

a) In a study of plutonium particle sizes in air samples taken in operational areas at the Rocky Flats Plant many years ago when maintenance operations on gloveboxes resulted in loss of containment (Kirchner 1986), it was found that operations such as machining, oxide crushing and fluorination of plutonium produced airborne particles with mass median aerodynamic diameters (MMAD) of 2 µm to 4,5 µm (assumed density of 11,45 g/cm^3). Conditions related to glove failure in a glovebox for burning plutonium metal leading to worker exposure produced larger airborne particles having a MMAD of 13,8 µm. Kirchner noted that these data agree very closely with the activity median aerodynamic diameters (AMAD) of particles measured at the AERE radiochemical laboratories in Harwell, England by Sherwood and Stevens (1965).

b) Ettinger, Elder and Gonzales (1973) placed sampling nozzles in process lines or gloveboxes under “worst normal” conditions (i.e. when aerosol-particle generation as a result of routine operations was highest) in a study of challenge aerosol particle characteristics and the response of multiple HEPA filters. Facility operations included research and development activities, fabrication, and chemical recovery. Activity concentrations in challenge aerosol particles were in the range of 10^8 Bq/m^3 to 10^{10} Bq/m^3. Fabrication operations produced fairly large aerosol particles (predominant AMAD, D_a, equal to 3 µm to 5 µm), while recovery operations consistently produced particles in the sub-micron range (0,1 µm to 1,0 µm).

Research and development operations generated particles predominantly in the intermediate range (1 µm to 4 µm). The largest reported size bracket in the log-normally distributed impactor data from all sites was a 10,9 µm bracket (normalized frequency of 4 % by activity), from a research and development facility.

c) Apart from accidents, processing facilities' age and contaminated structural materials can become suspended downstream of HEPA filter systems. The contamination can occur gradually or during process and filter upsets. Mahoney *et al.* (1994) summarizes the historical measurements of particle-size distributions in a plutonium finishing and reclamation complex downstream of HEPA filter systems. The AMAD of plutonium-bearing particles ranged from 1,3 µm to 20 µm. Ventilation ducts damaged by exposure to acidic fumes can generate significant concentrations of slightly contaminated rust particles.

d) When accidental events are considered, the potential contribution of fire-generated aerosol particles should be included. In Pacific Northwest Laboratory studies of burning radioactively contaminated materials (Halverson *et al.*, 1987) uranium was used as a surrogate for plutonium. Combustion aerosol particles containing uranium from contaminated plastics produced fairly large particles with an MMAD equal to 1 µm to 5 µm. Compounds in glovebox gloves (polychloroprene) produced the largest particles (MMAD of 19,9 µm). Burning cellulose produced particles with an MMAD from less than 1 µm to as large as 10,5 µm. Conversion of these numbers to aerodynamic diameter is uncertain as the density and shape factors are unknown.

e) Accident conditions can involve leaks or spills of liquid and powder forms of radioactive substances that generate airborne materials. In studies with uranium and other surrogates, Ballinger *et al.* (1988) measured particles with a wide range of MMADs between 3 µm and 20 µm. Liquid spills appear to produce the largest particles from splash droplets that start large but get smaller as the liquid evaporates. The particle size distributions resulting from powder spills have more variability due to agglomeration effects in the bulk state.

f) Agglomeration in accident-generated aerosol particles has been shown to produce larger particles in a polydisperse aerosol of smaller particles. However, it appears that this process does not yield extraordinarily large particle-size modes. Using data from the Oak Ridge National Laboratory nuclear safety pilot-plant experiments with burning sodium in a containment structure, Jordan (1986) predicted (and confirmed with observation) a relatively stable evolution of the mean aerodynamic diameter. Diameters remained below a D_a of 5 µm for 5 days following release and confinement.

g) In some facilities, there is the potential for involvement of plutonium metal in fire scenarios. Studies have been made of the release of aerosol particles under reducing and oxidizing environments. Edison *et al.* (1988), for example, found that the activity-median diameters of plutonium aerosol particles generated from plutonium metal pellets and foils were variable, but ranged from a D_a of 4 µm to approximately 10 µm.

G.4 Implications for nozzle design

The available data indicate that the most common mode of particle size for plutonium and uranium aerosol particles under a wide variety of conditions of generation is a D_a of between 1 µm and 5 µm with measurable percentages of particles up to 10 µm, or even 20 µm. The appearance of particles in the inertial size range (with a D_a above 1 µm) can be anticipated, even under routine operating conditions and certainly under a wide range of accident conditions. Inlets of sampling nozzles for particulate emissions should, then, be tested for transmission performance in the range of 3 µm to 15 µm. The shrouded nozzle inlet, for example, is designed so that the transmission of inertial-sized particles through the inlet is between 83 % and 103 % under the flow conditions of intended use. Predicted performance of a design is confirmed with measurements in a wind tunnel using test aerosol particles with a D_a of 10 µm. The design is iterated until there is good agreement between predicted and measured performance, at which point the shrouded nozzle is qualified for use. Unless it is known that a facility stack effluent can contain a sizeable mode of very large-sized particles due to the nature of the materials being handled, it is not necessary to require performance testing in size ranges beyond 15 µm.

G.5 Implications for other nuclear facilities

Although the discussion in this annex has relied largely on data from plutonium facility experience, the concern for proper sampling and monitoring of the large-particle components of effluents downstream of HEPA filtration in other types of nuclear facilities is equally important. In their review of a wide range of literature on particle-size distributions of radioactive aerosol particles measured in workplaces throughout the nuclear industry and government laboratories, Dorrian and Bailey (1995) found that in a total of 52 papers reporting 160 measurements of particle AMAD, the measurements of AMAD in the nuclear power industry and fuel handling facilities follow distributions similar to those in workplaces as a whole, with median values of about 4 µm. The exception seems to be for uranium mills, where the median is about 7 µm. Ström (1989) reviewed the characteristics of accident-generated aerosol particles in Swedish power reactors. A large body of literature exists on aerosol particles, vapour, and gases generated in postulated power-reactor accidents. Little is available concerning less consequential off-normal events. The implication is clearly that the challenge aerosol particles presented to HEPA filtration in practically any nuclear facility contain a significant component of particles with a D_a larger than 2 µm to 3 µm and, thus, can be present downstream of the filtration banks where sample extraction takes place.

Annex H
(informative)

Tritium sampling and detection

H.1 Tritium chemistry

Tritium, an isotope of hydrogen, generally behaves in a manner similar to hydrogen. Typically, it is found in two primary forms in the exhaust stream:

a) in the elemental form as a gas;

b) in the oxide form as water vapour.

It is of particular interest that tritium in the oxide form has a boiling point slightly above 100 °C. For some regulatory analysis this allows the oxide form to be considered a liquid instead of a gas, which in turn allows the use of a liquid physical form factor instead of that for a gas.

Also, tritium is sometimes found in the exhaust stream as a component of methane or other volatile organics, or as a component of particulate matter. One such example is LiOH, where the hydrogen is replaced with a tritium atom, LiOT. This compound is a solid material at temperatures up to 400 °C.

H.2 Sampling considerations

The first step in selecting an appropriate sampling system is to determine the chemical form of tritium in the exhaust stream. If it is present in multiple forms, multiple sampling techniques may be employed. When the oxide form is present, it is necessary to consider carefully the temperature and moisture content of the exhaust stream. If the exhaust stream contains water in droplet form, then the tritium can also be in this form and sampling as though particles were present is recommended. Sampling for a vapour only is appropriate when the oxide is not be expected to condense.

H.2.1 Sampler nozzle

The sampler nozzle should be located in the appropriate place depending on the chemical form of tritium. The location and nozzle configuration should conform to practices outlined elsewhere in this International Standard.

H.2.2 Heat tracing

The use of heat tracing on sample lines designed for tritium sampling should be evaluated very carefully. Several of the tritium sample-collection methods rely on either absorption of water vapour into a medium or condensation in a condenser apparatus. If the temperature of the sample is maintained too high, the tritium can desorb from the medium; not all of the vapour condenses and, therefore, some of the absorbing solution in the bubblers can be lost. All of these conditions lead to biased results.

On the other hand, if the physical state of the tritium in the exhaust is gaseous or vapour and the exhaust stream contains high humidity, then heat tracing can be necessary to avoid condensation of sample in the sample lines and sample chamber. Condensation can cause the sample collector to plug and, in the case of an ionization chamber, the reading can be disrupted because of shorting of the central electrode to ground or of the high-voltage electrode.

H.2.3 Medium location

Except for tritium existing in a particulate form, the tritium sample medium is generally located downstream of a particulate filter. This keeps particles from plugging the sample medium.

H.3 Sample media

There are several generally acceptable methods and/or media available for sampling tritium when it is not in the particulate form. When it is in the particulate form, then sampling methods for particulate matter discussed elsewhere in this International Standard should be used.

Although there are many factors that affect the sensitivity of a method, sensitivities on the order of 40 000 Bq/m^3 are possible with sampling followed by laboratory analysis. Typical factors, but certainly not all possible factors, that can affect sensitivity are sample flow rate, temperature of sampling, pressure of sampling, analytical method and sample medium.

Often, information on the concentrations of both the oxide and the elemental gas forms of tritium is desired. The uptake of tritium in the oxide form is very efficient, on the order of 99 % (NCRP 62, 1979); however, only 0,004 % of the elemental tritium entering the body is converted to the oxide form and adsorbed. Therefore, releases of tritium in the elemental form have a much lower dose than that from the same quantity of tritium oxide. Combinations of the following methods can be used to determine total tritium and oxide levels, with the difference being the elemental tritium in the stream being sampled. Direct measurement is also possible by first removing the tritium oxide, then converting the elemental tritium to an oxide form, followed by additional sampling.

H.3.1 Silica gel

This method of sampling tritium oxide is the simplest to perform. This is a continuous sample collected over a period of days to weeks. It involves placing a canister of silica gel in the sample stream and absorbing the tritium as water vapour on the silica gel. For sampling tritium oxide, a coloured silica gel may be used. The anhydrous silica gel is blue; as it adsorbs moisture, the colour changes, either to a different blue or to another colour. The sample, once collected, is sent to a laboratory where it is heated to desorb the tritiated water.

If tritium in the elemental form is present, then a catalyst, such as palladium, can be installed upstream of the sample chamber. The catalyst converts the elemental tritium to the oxide form, which can be absorbed on the silica gel.

H.3.2 Molecular sieves

This method is identical to the silica gel method, except molecular sieves are used in place of silica gel. This method has two advantages over silica gel.

a) The media can be better dried initially, resulting in a lower background.

b) A palladium catalyst, which converts the elemental tritium to the oxide form, can be coated directly on the molecular sieve.

A primary drawback of molecular sieves is the desorption of the tritium. This typically involves heating the medium to 500 °C in an evacuated furnace. Also, molecular sieves have a lower moisture-handling capacity than silica gel, but the medium is a more efficient drier. Therefore, when the moisture content of the sampled exhaust is high, silica gel is probably a better medium. However, when the moisture content is low, molecular sieves can be a better choice.

H.3.3 Bubblers

Although a variety of absorbing materials can be used in bubblers, ethylene glycol or water are most often used. This method provides advantages in the laboratory, in that sample desorption is not required. The primary disadvantage is that the bubblers, which are typically of glass, and the liquid media are difficult to handle when it is necessary to use them in the field or plant environment.

H.3.4 Condensation

In high-moisture exhaust streams, condensation is likely to be the most suitable method, since the other methods are limited by exhaustion of the absorption media; however, this method can be difficult to use. This method is based on the condensation of the tritiated water with a dehumidifier or condenser. The sample is routed through a mechanical cooling system and the condensate is collected in the liquid state. A loss or reduction of cooling capacity of the condenser allow the tritium-containing moisture to escape from the system in the exit gas. To ensure representative sampling, regular equipment maintenance is required.

H.3.5 Catalysts

All of the above methods rely on the tritium being in a vapour form, generally water vapour. When tritium is present as an elemental gas, it is then necessary to convert it, using a catalyst, to the oxide form before it can be sampled. Although any catalyst that can convert elemental hydrogen into the water or oxide form can be used, a palladium catalyst is the most common choice.

When tritium is present as an organic chemical species, it is often necessary to use a combustion catalyst. An example is a platinum on aluminium oxide catalyst in a heated combustion chamber. The tritium in the organic compound is oxidized to HTO and collected using the methods described above.

H.4 On-line detection

H.4.1 Ionization detectors

This is a very simple detector that can detect both elemental and oxide forms of tritium. The sensitivity can be as low as 0,04 MBq/m^3 depending on chamber volume. The major drawback to this detector is that it is sensitive to any gamma field in the general area and to any other ionization occurring in the chamber. A second chamber is sometimes used to compensate for external gamma fields by exposing the second chamber only to the field and not the exhaust stream. An additional chamber with a silica gel or molecular sieve pre-treatment is sometimes used to discriminate between oxide and elemental tritium.

This type of detector can be used when tritium is present as an organic vapour, such as tritiated methane.

H.4.2 Proportional counters

This type of counter detects tritium by using a rise-time discrimination principle. Since the soft beta of tritium has a short drift time, this detector can discriminate between tritium and other radionuclides, such as noble gases or other gamma emitters. The sensitivity of these instruments is around 0,4 kBq/m^3.

Annex I
(informative)

Action levels

An action level is an effluent contaminant concentration threshold at which it is necessary to perform an appropriate action. The type of action performed depends on the circumstances. The action can entail generation of alarms, diversion of effluent through added effluent treatment or intervention in the process creating the contaminant. There are inevitable consequences of whatever response is taken. Some responses are relatively minor, others are much more significant in terms of cost, damage to equipment and, possibly, even human health and safety. Careful consideration, taking into account all such consequences, should be given to the setting of an action level for an effluent sampling or monitoring system. There can be not only false negative outcomes (i.e. a true release of significance that is not investigated), but also false positive outcomes (i.e. worker responses to alarms, risks associated with rapid shutdown, and costs that are incurred needlessly). Both types should be anticipated but, depending on the hazard potential of a particular stack effluent and other factors, false positive outcomes can be of more consequence to facility operations and worker safety than false negative ones, due to work stoppage and evacuation of areas. Facility administrators should be cognizant of all reasonably anticipated outcomes.

Action levels involving events with significant releases and potential risks to members of the public are generally set either by the regulator or through discussions between the regulator and the licensee. Releases above these regulatory alarm levels require reporting to the regulator. In addition, the licensee may set his own, lower alarm levels (also called administrative levels or limits). These may be set to avoid reaching the regulatory action levels or they may be set for other reasons, such as costs involved in the releases. For example, tritium releases from heavy water reactors may be based on the economic cost of losses of heavy water. There is usually an internal reporting procedure when administrative levels or limits are exceeded. Administrative levels are usually set somewhat above normal release levels. Alarms based on increasing release rates may be used in control monitoring to warn the operators that conditions have changed and immediate action may be required to avoid exceeding an action level or administrative level.

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

a) the physical and chemical characteristics of the contaminant,

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

c) the type, intensity and variability of interference with the measurement.

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

It is useful in the context of discussing action levels to draw distinctions among the following:

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

— system availability: tracking sampling-system availability and response so the facility operators are alerted if equipment failure takes a system off-line or seriously degrades performance;

— performance sampling: regulatory compliance sampling that yields data of such quality and type that the facility owner can identify and quantify the most significant radionuclides present in the effluent and support demonstration of regulatory compliance by meeting all requirements for sample-extraction location, instrument calibration and maintenance, sample handling and chain of custody.

When determining action levels, consideration should be given to accuracy, precision and uncertainty. These terms apply to both the process of sampling and the process of measurement. The concern for accuracy is directed at the elimination of bias in the sampling and measurement processes. Regular calibration of sampling and measuring equipment using accepted procedures and traceable standards is used to establish accuracy. Accuracy should be estimated at the 95 % confidence level.

Statistical measures of the dispersion of results about a measurement-population mean are used to calculate precision. Sampling precision can be determined by replicate samples obtained under the same conditions. Measurement precision is obtained from the statistics of repeated measurements on replicate samples and by detailed analysis and propagation of uncertainties in component measurements. Sampling and measuring precision are combined statistically to obtain an estimate of overall precision.

The precision should be estimated at the 95 % confidence level. The concern of precision determinations is the estimation and, where possible, reduction of random uncertainties in the sampling and measuring processes.

The departures of measured values from either the true values (accuracy effects) or from the mean of measured values (precision effects) are measures of uncertainty in the sampling and measurement system results. Contributions to uncertainty in sampling or measurement are best determined independently and combined by statistical propagation of uncertainty. A detailed discussion of sampling and measurement random errors and error determination methods leading to an assessment of overall effluent sampling system uncertainty is found in Annex E.

Table I.1 — Guide to uncertainty of sampling and measurement

Factor or consideration	Record sampling	Control monitoring
Frequency of		
a) sampling	continuous	continuous
b) measurement	weekly	near real-time
Relative uncertainty of sampling system		
a) overall accuracy	± 30 %	± 40 %
precision	± 30 %	± 40 %
b) sampling accuracy	± 20 %	± 20 %
precision	± 20 %	± 20 %
c) measurement accuracy	± 20 %	± 35 %
precision	± 20 %	± 35 %
System availability	> 90 %	> 95 %

Each facility should set data quality objectives for its particular sampling and measurement systems. Guidance for recommended levels of uncertainty as they pertain to accuracy and precision of sample extraction and transport, and of measurement, is given in Table I.1. Most of the recommendations for control monitoring in Table I.1 are not as stringent as the recommendations for record sampling. Near-real-time radiation detection by a CAM, for example, usually cannot yield as accurate a measurement as can be expected of a laboratory counting system because variable bias introduced by the presence of interfering background activity can often be significantly reduced or eliminated in the laboratory. It should be recognized that the accuracy and precision recommendations of Table I.1 are not meant to be absolutes that can be equally appropriate in all cases and conditions. For example, effluents containing highly reactive constituents such as radioiodine can be particularly difficult to extract and transport without significant sampling bias, leading to estimated sampling accuracy uncertainties higher than 20 %. In contrast, measurement accuracy in some systems can be easily held well below 20 %, given the characteristics of the instrumentation and measurement processes and should be so reported.

There can be justifiable reasons for sacrificing some degree of measurement accuracy in control systems to achieve higher instrument reliability, extended range of response, more effective background compensation or other optimization goals. The overall system-uncertainty limit values are derived by summing the respective relative-variance estimates of the sampling accuracy or precision components. For example, the recommended limit of 40 % for the overall uncertainty in system accuracy for continuous monitors is the square-root of the sum of squares of the sampling accuracy component, equal to 20 %, and the measurement accuracy component, equal to 35 %, of uncertainty. Mentioning these components separately calls attention to the fact that if the sampling nozzle and transport line are not properly designed and properly placed, uncertainty is created in sampling accuracy, and no amount of attention to measurement accuracy in the system can prevent the system from generating poor, biased data and faulty alarm responses.

I.1 Action levels for control monitoring

The discussion in the previous part of this annex provides a basis for incorporating accuracy and precision considerations in the setting of appropriate action levels. There are no hard-and-fast rules concerning how to set these levels. It should be kept in mind that there is a trade-off between having high confidence in an alarm being triggered only by a “true” contaminant release, and having sufficient alarm sensitivity to the presence of the contaminant, albeit at lower confidence. It is in this context that it is necessary to assess the true costs of false alarms as part of the decision, along with the desire to detect the contaminant at the lowest concentration and shortest integrating time. In some CAM instruments, net counts are converted to activity-concentration estimates by dividing the counts by detector efficiency, volume sampled and time. All of these factors add uncertainty to the results. However, for the purposes of an alarm, the largest uncertainty is typically contributed by the counting uncertainty, as shown in Annex E. If the costs of false alarms in an effluent monitoring system are large, then a decision can be made to set the alarm threshold at a relatively high level and accept the risk of not detecting a lower-level release in a timely fashion. In some contexts, monitoring the trends of the measurement results can be a useful tool to aid in maintaining control below a chosen action level. The user should determine an action level that can be attained, and design and operate the system so the detection limit for that sampling and measurement process is sufficiently below the action level to avoid false alarms.

Control monitoring, using a CAM with an alarm, does not imply that there can be a more relaxed attitude toward achieving a representative sample. In the case of continuous monitoring for particulate radioactive substance in effluent streams, there might not always be a “sufficient” number of small particles in a release to cause an alarm. Nor should it be assumed that, in a poorly designed sampling system, a few large particles can get through to trigger an alarm. Such assumptions are ill-advised and unacceptable. The danger resulting from a lack of attention to the CAM sampling system design and placement is that the component of the sample that is not well represented (possibly the larger size particles, for example) can be the very component that provides the best chance for early warning and, hence, control, worker protection and impact limitation. The inherent limitations of providing radiation detection in the sampler during the sample collection process are due to the large background component in the detected signal. The choice of a relatively insensitive sampling system can lead to alarm thresholds consistent with an acceptable false-alarm rate. However, the system can then be susceptible to excessive false negative responses.

I.2 Action levels for record sampling

A facility or work area that has the potential for radioactive emissions (categories 1 to 3) should carry out record sampling at an appropriate frequency. Record samples are collected continuously in an integrated sample, and then are analysed by subsequent counting (off-line). The levels of activity that can be detected by these means are typically many orders of magnitude smaller than those detectable by on-line monitors. Additional sensitivity can be achieved by preparing composite samples from several week-long samples into monthly or even quarterly samples. The decision to attempt to achieve a certain detection limit goal requires a balance among costs, time and other factors. It is necessary that the uncertainty in the final estimate of quantities, concentration and rates of emission be derived from uncertainties in each of the factors entering into the respective calculation.

Another layer of analysis can be applied after determining the central estimates and their uncertainties, and logging them over time. Here the question is not whether a particular measurement is above the decision level for that contaminant, but whether a given trend in the data is normal or indicative of an off-normal condition, or whether a given datum is an outlier or is actually an elevated concentration. For this purpose, certain statistical tests and trending procedures (e.g. a control chart) are important. A retrospective action level may be set above the trend line in the data (say, at the 3σ level) to help decide whether a datum should be regarded as belonging to the family of normal values for the parameter being measured (e.g. the mean concentration of radioactive substance emitted during the previous month or quarter), or belonging to a new, unidentified situation that requires investigation and intervention. An investigation can determine whether a bias had been introduced in the analytical procedure for radionuclide determination, or can aid in ascertaining if a small leak exists in the filtration system of the facility stacks being sampled or monitored. The decision on the appropriateness of a given multiplier defining the action level hinges on the estimated costs associated with either being wrong in concluding that an excursion beyond the action level has occurred, and that controls in a facility are breaking down (false positive), or being wrong about thinking that emission controls and analytical procedures are normal, only to discover later that chronic low-level releases have been undetected (false negative). If the achieved detection limit for a sampling system is well below the action level, there is sufficient latitude to eliminate false negatives by trending.

I.3 System sensitivity needed to achieve selected action levels

Once an action level has been determined, another issue that should be addressed is whether the proposed sampling or monitoring system is sufficiently sensitive (at the 95 % confidence level). This is not a question of accuracy, but of whether a chosen system is able to provide the needed net response above background. Assume that a particular effluent sampling or monitoring system or instrument has been operating in a given stack effluent long enough to establish the population of blank responses (meaning zero concentration of radioactive material of concern present, but varying levels of background activity) large enough to reliably establish an estimate of the population mean of the blank, μ_B, and standard deviation, σ_B. While in operation, if there is no contaminant present, but there is an interfering background, the number of net counts, S, equal to gross counts minus background counts, would be expected to have a limiting mean of zero, and a standard deviation of $\sigma_S = \sqrt{2}\,\sigma_B$ (i.e. the variance in the gross and background counts are essentially the same). If the distribution of counts is approximately normal, then the upper 95 % confidence level for the distribution of the net counts observed in the instrument is as given in Equation (I.1):

$$L_c\left(0{,}05\right) = 1{,}645\sigma_S = 2{,}33\sigma_B \tag{I.1}$$

Such a level is often referred to as the decision level or the critical level of the measurement, because when the number of counts exceeds that level, there is only a 5 % chance of making the error of concluding that activity is present when there is truly only a background level present (a false positive). Note that the decision level is not the same as the detection limit or MDA level of the system. The decision level is an *a priori* number describing, in effect, the characteristics of the instrument and its operating conditions (levels of interference, counting time, etc.) and not a measure of the uncertainty in a particular determination. If the decision level for a given proposed sampling or monitoring system is above the desired level, or above that required by regulation, a more sensitive system should be developed.

Another type of error that can occur is that of falsely concluding that no activity is present when, in fact, there is significant activity in the sample. One can define another limit, sometimes called the detection limit or lower limit of detection, L_{LD}, as the mean number of net counts for which the observed net counts are 95 % certain to exceed the decision level of the instrument. This avoids errors of the first kind (false positives) and also limits false negative errors. It can be shown that when the instrument background is well defined and there is a sufficiently large number of counts from the sample, the 95 % detection limit, L_{LD}, is as given by Equation (I.2):

$$L_{LD} = 2L_c\left(0{,}05\right) = 4{,}65\sigma_B \tag{I.2}$$

The detection limit so defined is clearly also an *a priori* limit. The suitability of a proposed monitoring system to achieve a chosen alarm limit can be evaluated using the LLD concept. An alarm threshold set at the LLD, or $4{,}65\sigma_B$, or possibly larger, provides good immunity from false alarms (errors of the first kind). But it should be understood that sample counts near the critical level do not necessarily trigger an alarm (usually the case).

For example, assume that the standard deviation, σ_B, in a series of integrated count rates from a CAM is equal to 1 unit in relative terms with nominal background interference (typically radon daughter activity) present but zero concentration of transuranic elements. Then, if the alarm threshold set point is chosen to be 4 units ($4\sigma_B$), the probability of a false alarm when the target radionuclide concentration is equal to zero is $3{,}2 \times 10^{-5}$. If the set point is increased to 6 units, the probability of false alarm in the presence of zero concentration drops to $9{,}9 \times 10^{-10}$. However, as the multiplier is increased, there is an increased probability that low-level concentrations of contaminants will not trigger an alarm. Repeated counts as activity continues to accumulate on the sample filter should eventually result in an alarm or become apparent in data trending.

I.4 System performance and availability alarms

System performance and availability alarms are a separate consideration from action levels based on effluent releases. The designer of the sampling system should consider the requirement for alarms activated by system-component failure that results in the inability to sample properly. Such system-failure alarms should be differentiated from alarms triggered by effluent-release action levels because a very different response is required. Establishing system-failure alarms should be based on a statistical evaluation and consequence analysis, considering acceptable levels of false positives and false negatives as discussed in I.3.

System failure can take two forms. The first is a complete failure. Complete failure can be a system shutdown caused by an interruption of power or by the loss of a vital component. The complete failure should be indicated by an alarm to ensure that action is taken to restore operation. A complete failure due to the loss of a vital component can require a separate alarm for each mode of failure because the different failure modes can require different responses. The importance of the alarm and the priority of response should be determined and entered into the facility alarm-and-response plan.

The second form is a partial failure that compromises the quality of the output, renders the output unusable and causes the system to fall below safety or regulatory requirements. This type of failure should require a system alarm and a graded response because there can be differences in operation that require interpretation of instrumental data before activating an alarm. Two examples of partial failure are a significantly reduced sample flow rate and a significant leak in the sample-transport system. There are many other possibilities for partial failure and it can be impractical to trigger alarms for them all. Consequently, there are guidelines given for maintenance and inspections in Annex J.

Annex J
(informative)

Quality assurance

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

J.1 Documentation

The quality assurance programme should ensure that the air sampling system and its components are characterized and documented.

J.1.1 Source term

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

J.1.2 Effluent flow characterization

The results of studies to characterize the flow conditions of the effluents should be documented (e.g. spatial and temporal variations in velocity across the stack or duct, determination of cyclonic flow, estimates of particle size distributions, etc.). The documentation should include or list all procedures employed, times and dates of the measurements, individuals involved, equipment used and any pertinent information regarding facility operations.

J.1.3 Design and construction

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

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

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

J.2 Maintenance and inspection

The requirements for maintenance and inspection depend on the nature of the sampling equipment. Routine maintenance may be performed as described in the manufacturer's equipment manuals. Non-routine maintenance should also be performed on the basis of the results of inspections. The guidance provided here can be used as appropriate, such as in cases where there are no manufacturer recommendations.

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

J.2.1 Inspections

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

- position and orientation of sampling nozzles or inlets;
- condition of nozzle or inlet openings;
- dust accumulation in the sampling nozzles, inlets and transport lines;
- corrosion, physical damage or dust loading to the transport lines and equipment;
- filter-holder gaskets;
- leakage in the overall sample-transport system;
- tightness of all fittings and connections;
- condition of flow sensors;
- calibration of flow meters (the value of the flow rate determined by the test should not deviate from the nominal value more than 10 %).

J.2.2 Sampling system flow meter inspections

Mass flow meters should be checked at least annually with a secondary or transfer standard, where a transfer standard is typically a calibrated mass flow meter placed in series with the unit being tested. Unscheduled calibrations can be needed if any maintenance to the sampling system has been conducted that can affect the performance of the flow meter. The flow rate at which the mass flow meter is checked should be at a level that is within ± 25 % of the nominal design sampling rate of the system. If the flow rate, q_{std}, of the flow meter being tested differs by more than 10 % from the value indicated by a secondary standard, the flow meter should be removed from service for maintenance and calibration.

Flow through critical flow venturis should be checked at the start of each sampling period by observing the values of Δp_{m} (differential pressure across the meter) and Δp_{f} (differential pressure across the filter). If the value Δp_{m} is less than that needed for critical flow, the vacuum system should be checked to determine the cause. If the value of Δp_{f} is less than 70 % of that normally observed when the particular filter or collector is used, the critical flow meter should be inspected for blockage, or the sampling system should be checked for other possible problems. The critical flow meter should be removed from service for cleaning and re-calibration if it is the cause of the erroneous reading. If the value of Δp_{f} is greater than 130 % of that normally observed, the filter or collector should be inspected for possible problems.

It might not be necessary to check rotometers in the field with secondary standards unless maintenance has been done or changes have been made to the sampling system that can affect its accuracy. A rotometer should be inspected at the start of each sampling interval to ensure that no foreign matter has been deposited on the inside surfaces in the measurement tube. If foreign matter is visible, the rotometer should be removed from service, cleaned and re-calibrated.

J.2.3 Continuous effluent flow measurement apparatus

On an annual basis, response checks should be made of the flow-rate readings from in-stack equipment through use of a reference Prandtl-type Pitot tube. If a thermal anemometer or Pitot tube is used in the stack or duct, the reference Pitot tube should be placed in the vicinity of the in-stack device at a point where, based on previous measurements (see Annex A), the velocity reading is either the same as that of the in-stack device or a known correction factor can be applied to provide a ratio of the two velocity readings. If the in-stack sensor is a Pitot tube, the velocities calculated from use of the two tubes should be within ± 10 % (after taking into account any correction factors). If the in-stack sensor is a thermal anemometer, the velocity, V, determined from use of the reference Pitot tube should be converted to the equivalent velocity, V_{std}, at standard conditions as given in Equation (J.1):

$$V_{\text{std}} = V \frac{T_{\text{std}}}{T} \frac{p}{p_{\text{std}}} \tag{J.1}$$

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

If the velocity value from either an in-stack Pitot tube or thermal anemometer is outside of the specified range, the cause of the difference should be determined. It can be necessary to recalibrate the device. Also, if a sensor requires maintenance that can affect the calibration, the device should be recalibrated.

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

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

J.3 Calibration

Measurement and test equipment should be calibrated using standards whose calibration is traceable to the governing national institute of standards and measurements or derived from accepted values of natural physical constants. The principal calibration activities on a sampling system involve the verification of sample flow rate, sampling time and effluent flow rate. The suggested calibration frequency is annually for systems operated under normal or controlled environmental conditions. For systems used under extreme conditions, the calibrations should be conducted more frequently, e.g. every six months.

The methods used in calibrating all equipment and systems should be clearly described in procedures. The results of all calibrations should be recorded. This includes flow-meter and timer calibrations. The records should include the names of the individuals involved, times and dates, and the types and serial numbers of the calibration equipment.

J.3.1 Calibration of sampling system flow meters

The goal of the flow-meter calibration is to help ensure that the uncertainty in the measurement of the total volume of air sampled is ± 10 %. Annex E describes a number of considerations for uncertainty analysis. All flow meters should be calibrated at least annually against devices that are either based on first principles (bubble meters or proof meters) or that are traceable to the governing national institute of standards and measurements.

The internal sensing region of a flow meter should be inspected before calibration. If there is any indication of surface deposits, the internal components of the flow meter should be cleaned or replaced.

Mass flow meters should be calibrated at conditions corresponding to 40 %, 70 %, 100 %, 130 % and 170 % of the nominal flow rate in terms of standard conditions. Other values may be used; however, technical justification should be documented to show that the use of the selected points provides calibration data of a quality equivalent, or superior, to the recommended points. If the flow rate through the sampling system can, under normal conditions or anticipated or accident conditions, exceed the limits recommended herein for flow calibration, additional calibration points should be used to encompass the possible operating range.

It can be necessary to calibrate critical venturi flow meters only at a single point that corresponds to operating conditions with a sufficient pressure differential across the meter such that the velocity at the throat of the meter is sonic. The temperature at the entrance of the critical flow meter during calibration should be within ± 5 °C of the average temperature anticipated at that same location during sampling. The absolute pressure at the entrance of the critical flow meter should be within ± 2 % of the average absolute pressure anticipated at that location.

Rotameters should be calibrated at flow-rate conditions that correspond to the average anticipated flow rate during sampling, and at 75 % and 125 % of the anticipated sampling flow rate.

The total uncertainty in the volume of air, E_{QT}, can be calculated as given in Equation (J.2):

$$E_{\mathrm{QT}}^2 = \left(F_{\mathrm{k}}\ E_{\mathrm{s}}\right)^2 + E_{\mathrm{c}}^2 + E_{\mathrm{t}}^2 \qquad \text{(J.2)}$$

where

F_{k} is a fluctuation constant, which is set at 1 for a meter whose readings do not fluctuate;

NOTE 1 If there are fluctuations, the parameter is set as the average number of the scale unit above and below the mean indicated value.

E_{s} is the uncertainty in reading the flow meter scale, which is dimensionless, and which can be estimated by dividing one-half the value of the smallest scale division by the indicated flow rate;

E_{c} is uncertainty associated with determining the calibration factor, i.e. correcting the indicated flow, and which is dimensionless;

NOTE 2 As an approximation, the uncertainty associated with the calibration instrument can be used.

E_{t} is uncertainty (dimensionless) associated with the measurement of the sampling time, and which is dimensionless.

J.3.2 Calibration of effluent flow-measurement devices

An effluent flow-measurement system should be calibrated at least annually against the reference method discussed in Annex A. The goal of the calibration is to measure flow rate relative to the Reference Method that is accurate to within ± 10 %.

J.3.3 Calibration of timing devices

Timing devices should be calibrated at least annually. The uncertainty should not be greater than 1 min per month.

Annex K
(informative)

Carbon-14 sampling and detection

K.1 Carbon-14 chemistry

Carbon-14 is a radioactive isotope of carbon with behaviour similar to that of the stable carbon isotopes. The nuclear reactions that produce ^{14}C in reactors with thermal neutrons are $^{17}O(n,\alpha)^{14}C$ ($\sigma = 0{,}24$ b), $^{14}N(n,p)^{14}C$ ($\sigma = 1{,}82$ b) and $^{13}C(n,\gamma)^{14}C$ ($\sigma = 0{,}000\ 9$ b).

NOTE 1 b = 10^{-28} m^2.

Carbon-14 is of concern because of its very long half life (5 730 y), the mobility of carbon in the environment and its ubiquitous presence in biological systems. Carbon-14 has been identified in airborne effluents from nuclear power plants in the forms of particulate ^{14}C, gaseous $^{14}CO_2$ and non-CO_2 gases. The latter can be ^{14}CO or various organic gases, e.g. $^{14}CH_4$.

K.2 Sampling considerations

When selecting a suitable sampling medium for ^{14}C, it is important to consider the presence of other contaminants (both radioactive and non-radioactive) in the sampling stream in addition to the physical and chemical forms of ^{14}C being collected. For example, if the effluent stream has high humidity, it is necessary to remove the moisture before using a molecular sieve to sample the $^{14}CO_2$ or the moisture will saturate the molecular sieve. Likewise, it is necessary to remove HTO from the sample stream before collecting ^{14}C to avoid interference in the counting of ^{14}C, unless a chemical step is added before counting to remove the substances that interfere with the ^{14}C signal.

K.2.1 Particulate ^{14}C

The same requirements for sampling other particulate radioactive substance apply to particulate ^{14}C. These include considerations of sampling location, nozzle design and line penetration.

K.2.2 Gaseous ^{14}C

The same requirements for sampling other gaseous radioactive substance apply to gaseous ^{14}C.

K.3 Sampling media

K.3.1 Particulate ^{14}C

The filters installed to collect other particulate radioactive substances should also collect particulate ^{14}C. One very important consideration, though, is the filter material. Because it is normally necessary to combust the sample to separate the ^{14}C from other radionuclides, it is advantageous to use a non-combustible filter material, e.g. glass fibre. Furthermore, the filters sometimes collect only minute amounts of particulate carbon, so that it is necessary to add a carbon carrier to carry out the analysis. Lampblack compressed into a pellet has been found suitable as a carrier when glass-fibre filters are combusted in a tube furnace. Lampblack is generally made from fossil carbon, so it contains no ^{14}C, but this should be verified by combusting blank pellets. The radiochemical yield can be determined by the recovery of the carbon from the lampblack carrier.

K.3.2 Gaseous $^{14}CO_2$

Sampling systems for airborne effluents normally sample at a flow rate of 25 l/min to 100 l/min. However, sampling systems that take the gas sample by a chemical reaction generally use flow rates on the order of 1 l/min or less. This can require taking a side-stream off the line to the main monitor or installing a separate sample line.

K.3.2.1 Collection with caustic solutions

Collection of $^{14}CO_2$ with a caustic (NaOH or KOH) solution in a bubbler is often a convenient method. If the ^{14}C concentration is sufficiently high, the caustic solution can be analysed directly by adding a scintillation cocktail to a portion of the solution in a scintillation vial and counting it on a liquid scintillation counter (LSC). If the concentrations of ^{14}C are too low for direct counting, then it is necessary that the ^{14}C be released as CO_2 by adding acid and then concentrated by recollecting it in a smaller volume of absorbent. Suitable absorbents and compatible scintillation cocktails are available commercially.

The main drawback to collecting CO_2 in caustic solutions is in handling the corrosive liquids and the necessity of using glassware in the field. These problems can be overcome by having Plexiglas boxes made to hold the bubblers. The bubblers can be filled in the laboratory and placed in the boxes for transport to the field. The Plexiglas boxes can contain any spills and avoid any exposure to broken glass.

Security of the bubbler system should be considered during design and construction, and the bubbler system may be located inside a locked cabinet. All bubbler systems should be clearly labelled and colour-coded to reduce the possibility of cross-contamination between samples from individual bubbler pots when the analysis of the bubbler pot contents is performed.

The bubbler pots should be constructed using plastic-coated (or glass-fibre-coated) glass. The associated tubing should be stainless steel, unless flexibility is required, in which case heat-resistant silicon tubing may be used.

Airflow through the bubbler system should be maintained at a suitable rate (1,0 l/min ± 0,2 l/min) using either ejectors or pumps situated after the sampling equipment with a control valve between any flow measurement and the pumping unit. The airflow should be measured using a calibrated flow meter with an appropriate range. The main flow meter should be placed after the last bubbler and protected using a drying agent installed in-line directly before it. Installing a second flow meter before the first bubbler should be considered to allow routine checking of the flow rate and the ready identification of any gross leakage. The presence of high humidity influences this decision.

Siphon breaks should be installed to guard against the possibility of suck-back. These should be fitted before each set of three bubblers and be of sufficient volume to hold the liquor from the subsequent pots, in order to prevent loss of sample and protect the furnace from liquor ingress. In certain cases, a collection pot can be needed after the final bubbler pot to collect entrained liquor, and any liquor collected in this pot combined with the final bubbler liquor prior to analysis. This final collection pot should be installed first and its use assessed during commissioning.

Experience suggests that three bubbler pots in series are usually all that is needed, but if there is any suggestion that other chemical forms are present (e.g. CO), then oxidation should be ensured, and the sample gas should be passed through a furnace. In order to establish the ratio of any speciation, the existing CO_2 can be captured with one set of pots before oxidizing, and other C species can be captured with a second set of pots after oxidation. This work is normally undertaken during initial commissioning.

For each sampling period, and for the purposes of calculating ^{14}C discharges, the following should be recorded:

a) volume of liquor in each bubbler pot when sampled;

b) date and time for the start and end of sample taking;

c) total airflow volume through each bubbler pot over the reporting period;

d) total discharge volume from the associated stack over the reporting period;

e) sample result from each bubbler pot.

K.3.2.2 Collection with solid caustic materials

The use of caustic solutions can be avoided by absorbing the CO_2 with solid caustic materials such as Ascarite, Ascarite II ®4) and sodalime. Whereas the original Ascarite was derived from granular asbestos, Ascarite II is sodium-hydroxide-coated silica. It rapidly and quantitatively adsorbs CO_2. Sodalime is a mixture of sodium and calcium hydroxides. If commercial materials are used, they should be checked for CO_2 and ^{14}C backgrounds before use and care should be taken to minimize exposure to the atmosphere during storage. After sampling, the $^{14}CO_2$ can be released by acidifying the material and collecting the CO_2 in another absorbent suitable for determining ^{14}C by LSC. Compatibility of this and other adsorbents with other chemicals in the discharge should be considered in selecting adsorbents.

K.3.2.3 Collection with molecular sieves

Molecular sieve 4A can be used to collect CO_2 from the sample stream. Moisture should be removed from the sample stream before it is passed through the molecular sieve, especially if HTO is present. The use of a molecular sieve avoids the use of corrosive materials, but it is necessary to release the CO_2 by heating the molecular sieve in a furnace and then collecting it in a suitable absorbent for determining ^{14}C by LSC.

K.3.3 Non-CO_2 gaseous ^{14}C

Gaseous, non-CO_2 ^{14}C can be oxidized to $^{14}CO_2$, which can then be collected using one of the methods in K.3.2. One way of doing this is to mix the sample stream with oxygen and pass it through a tube furnace with a copper oxide catalyst on the outlet end of the tube. The exhaust gas is then passed through the CO_2 collection system. This gives a measure of the total gaseous ^{14}C; the non-CO_2 ^{14}C can be determined by subtracting the $^{14}CO_2$.

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