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Evaluating the performance of continuous air monitors —

Part 1:
Air monitors based on accumulation sampling techniques

Évaluation de la performance des dispositifs de surveillance de l'air en continu —

Partie 1: Moniteurs d'air basés sur des techniques d'échantillonnage par accumulation

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Foreword

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

A list of all the parts in the ISO/TR 22930 series can be found on the ISO website.

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

Introduction

Sampling and monitoring of airborne activity concentration in workplaces are critically important for maintaining worker safety at facilities where dispersible radioactive substances are used.

The first indication of a radioactive substance dispersion event comes, in general, from a continuous air monitor (CAM) and its associated alarm levels. In general, the response of a CAM is delayed in time compared to the actual situation of release.

The knowledge of a few factors is needed to interpret the response of a CAM and to select the appropriate CAM type and its operating parameters.

The role of the radiation protection officer is to select the appropriate CAM, to determine when effective release of radioactive substances occurs, to interpret measurement results and to take corrective action appropriate to the severity of the release.

The objective of ISO/TR 22930 series is to assist radiation protection officer in evaluating the performance of a CAM.

ISO/TR 22930 series describes the factors and operating parameters and how they influence the response of a CAM.

This document deals with monitoring systems based on accumulation sampling techniques.

Evaluating the performance of continuous air monitors —

Part 1:
Air monitors based on accumulation sampling techniques

1 Scope

The use of a continuous air monitor (CAM) is mainly motivated by the need to be alerted quickly and in the most accurate way possible with an acceptable false alarm rate when a significant activity concentration value is exceeded, in order to take appropriate measures to reduce exposure of those involved.

The performance of this CAM does not only depend on the metrological aspect characterized by the decision threshold, the limit of detection and the measurement uncertainties but also on its dynamic capacity characterized by its response time as well as on the minimum detectable activity concentration corresponding to an acceptable false alarm rate.

The ideal performance is to have a minimum detectable activity concentration as low as possible associated with a very short response time, but unfortunately these two criteria are in opposition. It is therefore important that the CAM and the choice of the adjustment parameters and the alarm levels be in line with the radiation protection objectives.

The knowledge of a few factors is needed to interpret the response of a CAM and to select the appropriate CAM type and its operating parameters.

Among those factors, it is important to know the half-lives of the radionuclides involved, in order to select the appropriate detection system and its associated model of evaluation.

CAM using filter media accumulation sampling techniques are usually of two types:

a) fixed filter;

b) moving filter.

This document first describes the theory of operation of each CAM type i.e.:

— the different models of evaluation considering short or long radionuclides half-lives values,

— the dynamic behaviour and the determination of the response time.

In most case, CAM is used when radionuclides with important radiotoxicities are involved (small value of ALI). Those radionuclides have usually long half-life values.

Then the determination of the characteristic limits (decision threshold, detection limit, limits of the coverage interval) of a CAM is described by the use of long half-life models of evaluation.

Finally, a possible way to determine the minimum detectable activity concentration and the alarms setup is pointed out.

The annexes of this document show actual examples of CAM data which illustrate how to quantify the CAM performance by determining the response time, the characteristics limits, the minimum detectable activity concentration and the alarms setup.

2 Normative references

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

ISO 16639, *Surveillance of the activity concentrations of airborne radioactive substances in the workplace of nuclear facilities*

IEC 60761-1, *Equipment for continuous monitoring of radioactivity in gaseous effluents — Part 1: General requirements*

ISO 11929-1, *Determination of the characteristic limits (decision threshold, detection limit and limits of the coverage interval) for measurements of ionizing radiation — Fundamentals and application — Part 1: Elementary applications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11929-1, ISO 16639, IEC 60761-1 and the following apply.

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

- ISO Online browsing platform: available at http://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

3.1
annual limit on intake
ALI
derived limit for the amount of radioactive substance (in Bq) taken into the body of an adult worker by inhalation or ingestion in a year

[SOURCE: ISO 16639:2017, 3.7]

3.2
continuous air monitor
CAM
instrument that continuously monitors the airborne activity concentration on a near real-time basis

[SOURCE: ISO 16639:2017, 3.10]

3.3
decision threshold
value of the estimator of the measurand, which when exceeded by the result of an actual measurement using a given measurement procedure of a measurand quantifying a physical effect, it is decided that the physical effect is present

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

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

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

3.4
derived air concentration
DAC

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

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

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

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

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

[SOURCE: ISO 16639:2017, 3.12]

3.5
detection alarm level
S0

value of time-integrated activity concentration activity concentration corresponding to an acceptable false alarm rate

Note 1 to entry: When S0 increases false alarm rate decreases.

Note 2 to entry: Others values of alarm level higher than S0 can also be set up for operational reasons.

3.6
detection limit

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

Note 1 to entry: With the decision threshold according to 3.3, the detection limit is the smallest true value of the measurand for which the probability of wrongly deciding that the true value of the measurand is zero is equal to a specified value, β, when, in fact, the true value of the measurand is not zero. The probability of being detectable is consequently $(1-\beta)$.

Note 2 to entry: The terms detection limit and decision threshold are used in an ambiguous way in different standards (e.g. standards related to chemical analysis or quality assurance). If these terms are referred to one has to state according to which standard they are used.

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

3.7
limits of the coverage interval

values which define a coverage interval

Note 1 to entry: The limits are calculated in the ISO 11929 series to contain the true value of the measurand with a specified probability $(1-\gamma)$

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

Note 3 to entry: The coverage interval is defined in ISO 11929-1:2019, 3.4, as the interval containing the set of true quantity values of a measurand with a stated probability, based on the information available.

[SOURCE: ISO 11929-1:2019, 3.16 modified – Note 3 to entry has been added]

3.8
measurand
quantity intended to be measured

[SOURCE: ISO 11929-1:2019, 3.3]

3.9
minimum detectable activity concentration
time-integrated activity concentration or activity concentration measurements and their associated coverage intervals for a given probability ($1-\gamma$) corresponding to the detection alarm level S0

3.10
model of evaluation
set of mathematical relationships between all measured and other quantities involved in the evaluation of measurements

[SOURCE: ISO 11929-1:2019, 3.11]

3.11
potential missed exposure
PME
time-integrated activity concentration or maximum activity concentration, as applicable, that can acceptably be missed

Note 1 to entry: The value of PME is defined according to ALARA/ALARP principles, and below legal limits.

Note 2 to entry: In order to be alerted when a measurement is likely to exceed the value of PME, an alarm level S1 is set up. The PME is then the upper limit of the coverage interval for a given probability ($1-\gamma$) of time-integrated activity concentration or activity concentration measurements corresponding to S1.

[SOURCE: ISO 16639:2017, 3.18]

3.12
response time
time required after a step variation in the measured quantity for the output signal variation to reach a given percentage for the first time, usually 90 %, of its final value

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

Note 1 to entry: The intrinsic response time is related to the measurement principle and its associated model of evaluation of an ideal detector (without taking account of the counting time of the detector).

3.13
transit time
duration corresponding to the complete scrolling of the moving filter in front of the detector, in case of moving filter, and considering that the entire deposition area is viewed by the detector

Note 1 to entry: If v is the moving filter speed and L the detector aperture or length of the deposition area considering a constant width w_D then the time transit $t_T = \frac{L}{v}$.

4 Symbols

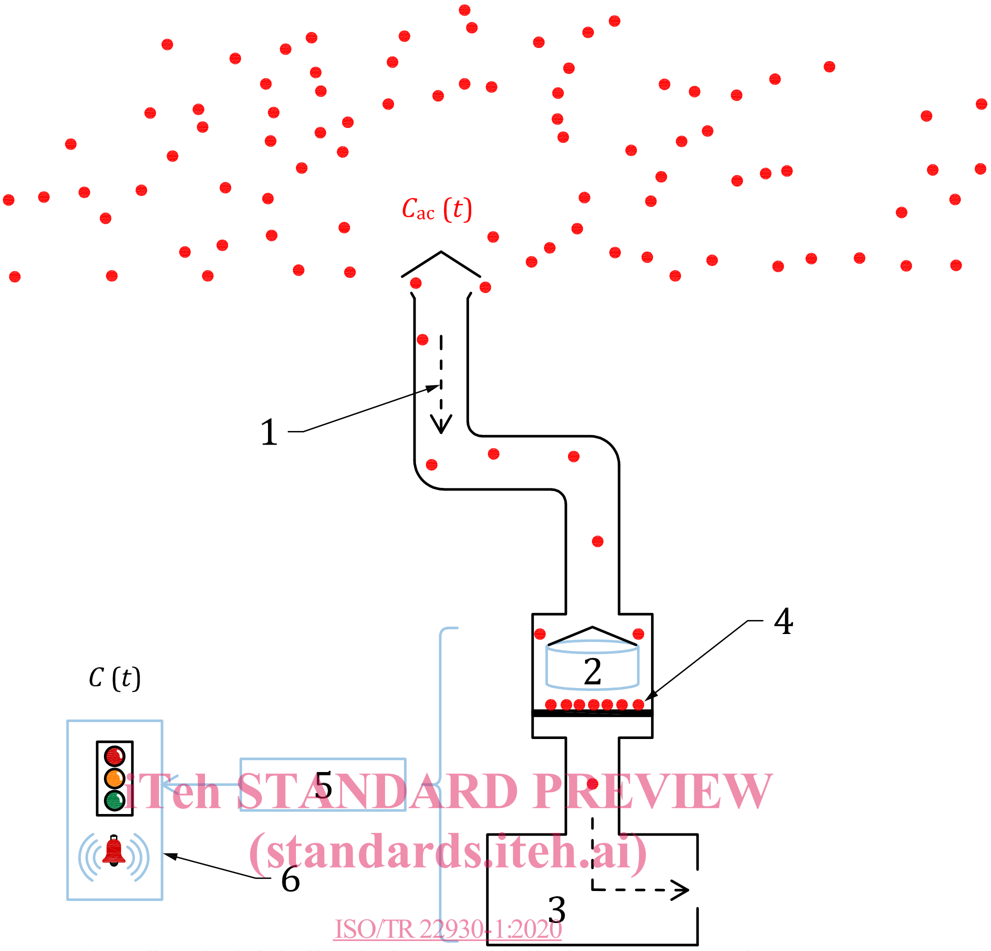
$a(t)$	Activity deposited on the media filter at a time t, in Bq
b_{LR}	Slope of the linear regression line obtained from a set of n successive points $(i,\ y_i)$, y_i being the i^{th} measurement of the counting pulse ($i = 1, \ldots, n$), in s^{-2}
C_{LR}	Correlation coefficient of the line resulting from the linear regression, dimensionless

C_{ST}	Coefficient of Student, dimensionless
c	Activity concentration, in Bq·m^{-3}
c^{*}	Decision threshold of the activity concentration, in Bq·m^{-3}
$c^{\#}$	Detection limit of the activity concentration, in Bq·m^{-3}
$c^{\triangleleft}$	Lower limit of the coverage interval of the activity concentration for a given probability (1−γ), in Bq·m^{-3}
$c^{\triangleright}$	Upper limit of the coverage interval of the activity concentration for a given probability (1−γ), in Bq·m^{-3}
$c(t)$	Activity concentration measured at a time t, in Bq·m^{-3}
$c(t_j)$, c_j	Activity concentration measured at a time t_j, in Bq·m^{-3}
$c_{ac}(t)$	Actual activity concentration measured at a time t, in Bq·m^{-3}
c_{det}	Detectable activity concentration, in Bq·m^{-3}
c_g	Activity concentration of a gross measurement, in Bq·m^{-3}
c_{mi}	Minimum detectable activity concentration, in Bq·m^{-3}
$c_{min}^{\triangleleft}$	Lower limit of the coverage interval of the minimum detectable activity concentration for a given probability (1−γ), in Bq·m^{-3}
$c_{min}^{\triangleright}$	Upper limit of the coverage interval the minimum detectable activity concentration for a given probability (1−γ), in Bq·m^{-3}
$c_{0,i}$	Activity concentration of the i^{th} measurement of a series of gross measurements (with $i = 1, \ldots, n$) which represent a background situation, in Bq·m^{-3}
$\overline{c_0}$	Mean value of $c_{0,i}$ in Bq·m^{-3}
D	Diameter the circular window deposition area viewed by the detector, in m
K	Detection alarm setup parameter corresponding to the chosen acceptable false alarm rate level, dimensionless
k	Quantile of a standard normal distribution, if $k_{1-\alpha} = k_{1-\beta}$, dimensionless
$k_{1-\alpha}$	Quantile of a standard normal distribution for a probability (1−α), dimensionless
$k_{1-\beta}$	Quantile of a standard normal distribution for a probability (1−β), dimensionless
$k_{1-\frac{\gamma}{2}}$	Quantile of a standard normal distribution for a probability $\left(1-\frac{\gamma}{2}\right)$, dimensionless
L	Length of the rectangular window deposition area viewed by the detector, considering a constant width w_D, in m
N	Number of atoms on the media filter, dimensionless
$n_g(t, t_c)$	Gross count during the counting time t_c of the media filter at a time t, dimensionless
p_{ST}	Student test acceptance parameter of the linear regression with a risk less than one out of ten thousand to be aberrant, dimensionless

q	Flow rate, in $\mathrm{m}^3 \cdot \mathrm{s}^{-1}$
$r_\mathrm{g}(t)$	Instantaneous gross count rate of the media filter at a time t, in s^{-1}
$r_\mathrm{g}(t, t_\mathrm{c})$	Gross count rate during the counting time t_c of the media filter at a time t, in s^{-1}
$r_\mathrm{g}(t, t_\mathrm{c}), r_j$	Gross count rate during the counting time t_c of the media filter at a time t_j, in s^{-1}
r_0	Background count rate, in s^{-1}
s_0	Standard deviation of the activity concentration at a series of i measurements which represent a background situation
t, t_j	Time, in year (YYYY)-month (MM)-day (DD) T hour (hh):minute (mm): second (ss)
t_C	Counting time, in s
t_F	Duration of airborne release, in s
t_I	Time interval, in s
t_R	Response time, in s
t_RI	Intrinsic response time, in s
t_T	Transit time, in s
t_0	Counting time for background measurement in s
$t_{1/2}$	Half-life, in s
v	Moving filter speed, in $\mathrm{m} \cdot \mathrm{s}^{-1}$
w	Calibration factor, in $\mathrm{Bq} \cdot \mathrm{m}^{-3} \cdot \mathrm{s}$
w_D	Width of the rectangular deposition area viewed by the detector, in m
y_1	Counting pulse measurement at the initiation of a linear regression process
δ	Correction factor related to sampling (sampling point representativity, aerosol deposition in the transport line, …), dimensionless
ε_D	Detector efficiency, in $\mathrm{Bq}^{-1} \cdot \mathrm{s}^{-1}$
λ	Decay constant, in s^{-1}

5 Measuring principle

A representative sample of ambient air to be monitored containing an actual activity $c_\mathrm{ac}(t)$ at a time t is continuously captured through a transport line which deposits the radioactive substance on a media filter. In parallel, a detector continuously measures the activity deposited on the media filter which can be fixed or moving. Then a processing algorithm calculates the activity concentration $c(t)$ and the appropriate alarms on the basis of the evolution of the deposited activity and the volume of air sampled. The processing algorithm can also, if necessary, take into account parameters which may perturb the measurement result (see Figure 1).



Key

1	transport line
2	detector
3	sampling pump
4	media filter
5	processing algorithm
6	alarm processing unit

Figure 1 — Model of the sampling and alarming

6 Fixed-media filter monitor

6.1 Preliminary note

In Clause 6, fixed-media filter means any type of fixed trapping method of radioactive contaminant (e.g. “filter” used for aerosols monitoring, “charcoal cartridge” used for iodine, etc.).

6.2 Study of the dynamic behaviour

6.2.1 General

This subclause describes the evolution over time of the activity concentration $c(t)$ during the sudden appearance of an actual activity concentration $c_{ac}(t)$. The dynamic behaviour is quantified by the response time t_R. The response time t_R is due to the intrinsic response time t_{RI} related to the measurement principle and its associated model of evaluation, the time delay provided by the counting time t_C of the radioactivity measurement on the media filter, if needed the time interval t_1 for calculating the activity concentration $c(t)$, and also the duration of the processing algorithm. This latter duration is not taken into account in this document but it should be kept in mind.

It is considered in the following that the actual activity concentration measured at a time t changes over time in steps to the duration of airborne release t_F :

$$c_{ac}(t) = c_{ac} \qquad \text{when } 0 \le t < t_F \tag{1}$$

$$c_{ac}(t) = 0 \qquad \text{when } t \ge t_F \tag{2}$$

The differential equations describing the number of atoms N of the radionuclide deposited on the media filter can be expressed as a function of the activity concentration c_{ac} at the sampling point according to the following Formulae:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = \frac{q\,\delta\,c_{ac}}{\lambda} - \lambda N(t) \qquad \text{when } 0 \le t < t_F \tag{3}$$

NOTE 1 The monitor flow rate q is taken to be constant over the interval of interest.

and

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -\lambda N(t) \qquad \text{when } t \ge t_F \tag{4}$$

Moreover, the evolution of the activity on the filter is given by Formula (5)

$$a(t) = \lambda N(t) = \frac{r_g(t) - r_0}{\varepsilon_D\,\delta} \tag{5}$$

NOTE 2 The detector efficiency ε_D is supposed to be constant that is to say that at any time the activity is distributed uniformly on the media filter surface or volume.

Considering that $N(0) = 0$ at the beginning of the sampling, the solutions of the differential Equations (3) and (4) are:

$$r_g(t) - r_0 = \varepsilon_D\,\delta\,\lambda\,N(t) = \frac{\varepsilon_D\,q\,\delta\,c_{ac}}{\lambda}\left[-\mathrm{e}^{-\lambda t}\right] \qquad \text{when } 0 \le t < t_F \tag{6}$$

$$r_g(t) - r_0 = \varepsilon_D\,\delta\,\lambda\,N(t) = \frac{\varepsilon_D\,q\,\delta\,c_{ac}}{\lambda}\left[1 - \mathrm{e}^{-\lambda t_F}\right]\mathrm{e}^{-\lambda(t - t_F)} \qquad \text{when } t \ge t_F \tag{7}$$

6.2.2 Short half-life model of evaluation of the activity concentration

From the Formulae (5), (6) and (7), the model of evaluation of the activity concentration can be expressed as

$$c(t) = \frac{\lambda}{\varepsilon_D\,q\,\delta}\left[r_g(t) - r_0\right] \tag{8}$$

with

$$c(t) = c_{ac}\left[1 - \mathrm{e}^{-\lambda t}\right] \qquad \text{when } 0 \le t < t_F \tag{9}$$

$$c(t)=c_{\mathrm{ac}}\left[1-\mathrm{e}^{-\lambda t_{\mathrm{F}}}\right]\mathrm{e}^{-\lambda(t-t_{\mathrm{F}})} \qquad \text{when } t\geq t_{\mathrm{F}} \tag{10}$$

The evolution of the ratio of the activity concentration and the actual one according to Formula (9) by considering an infinite duration release ($t_{\mathrm{F}} \rightarrow \infty$) is given in Table 1, with:

$$\frac{c(t)}{c_{\mathrm{ac}}(t)}=\frac{r_{\mathrm{g}}(t)-r_0}{r_{\mathrm{g}}(t\rightarrow\infty)-r_0}$$

Table 1 — Evolution of the ratio of the measured concentration and the actual one according to Formula (9)

Ratio %	**Time** s	
0	$\frac{0{,}69}{\lambda}$	(~1 half-life)
50	$\frac{2{,}3}{\lambda}$	(~3 half-lives)
95	$\frac{3}{\lambda}$	(~4 half-lives)
99	$\frac{4{,}61}{\lambda}$	(~7 half-lives)
99,5	$\frac{6{,}91}{\lambda}$	(~10 half-lives)

Table 1 shows that, according to Formula (9), the intrinsic response time is t_{RI} approximately 3 times the half-life value of the considered radionuclide.

The model of evaluation of the activity concentration given by the Formulae (9) and (10) is therefore only suitable for radionuclides with short half-life of few minutes of magnitude order, otherwise the intrinsic response times and the associated counting rates are too large to be practically exploitable. The evolutions over time of the activity concentration as defined in the Formulae (9) and (10) assume that the gross count rate $r_{\mathrm{g}}(t)$ is instantaneous which means:

$$r_{\mathrm{g}}(t)=\lim_{t_{\mathrm{C}}\rightarrow 0}\left[\frac{n_{\mathrm{g}}(t,t_{\mathrm{C}})}{t_{\mathrm{C}}}\right]$$

This implies that $r_{\mathrm{g}}(t)$ does not depend on the counting time t_{C}. In reality, any measurement is associated with a counting time t_{C} and then the following Formulae are obtained:

$$r_{\mathrm{g}}(t,t_{\mathrm{C}})-r_0=\frac{1}{t_{\mathrm{C}}}\int_0^t\left[r_{\mathrm{g}}(t)-r_0\right]\mathrm{d}t \qquad \text{when } 0\leq t<t_c \tag{11}$$

$$r_{\mathrm{g}}(t,t_{\mathrm{C}})-r_0=\frac{1}{t_{\mathrm{C}}}\int_0^t\left[r_{\mathrm{g}}(t)-r_0\right]\mathrm{d}t \qquad \text{when } t\geq t_c \tag{12}$$

Taking account of the counting time t_{C}, the model of evaluation of the activity concentration given in the Formulae (9) and (10) for short half-life radionuclide becomes:

$$c(t)=\frac{\lambda}{\varepsilon_{\mathrm{D}}\,\delta\,q}\left[r_{\mathrm{g}}(t,t_{\mathrm{C}})-r_0\right] \tag{13}$$

The development of Formulae (11) to (12) applied to (13) makes it possible to quantify the dynamic behaviour of the evaluation model in all release conditions knowing λ (or $t_{1/2}$) and t_{C} and so to determine