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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−γ) 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−γ) 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, ..., 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, ..., 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

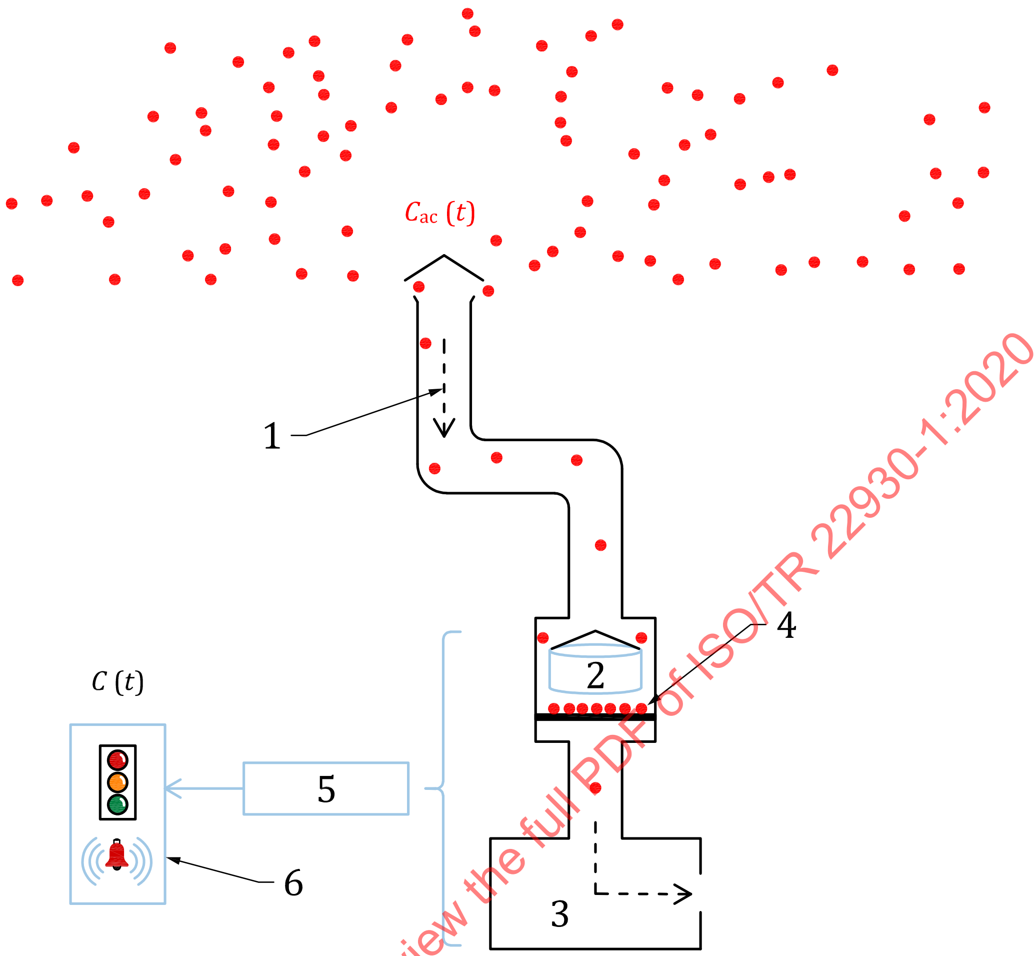
$n_g(t, t_c)$ Gross count during the counting time t_c of the media filter at a time t, dimensionless

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 $m^3 \cdot s^{-1}$
$r_g(t)$	Instantaneous gross count rate of the media filter at a time t, in s^{-1}
$r_g(t, t_c)$	Gross count rate during the counting time t_c of the media filter at a time t, in s^{-1}
$r_g(t, t_c), r_j$	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 $m \cdot s^{-1}$
w	Calibration factor, in $Bq \cdot m^{-3} \cdot s$
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 $Bq^{-1} \cdot s^{-1}$
λ	Decay constant, in s^{-1}

5 Measuring principle

A representative sample of ambient air to be monitored containing an actual activity $c_{ac}(t)$ 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

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

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

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

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

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 $r_g(t)$ is instantaneous which means:

$$r_g(t) = \lim_{t_C \rightarrow 0}\left[\frac{n_g(t, t_C)}{t_C}\right]$$

This implies that $r_g(t)$ 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:

$$r_g(t, t_C) - r_0 = \frac{1}{t_C}\int_0^t \left[r_g(t) - r_0\right] dt \qquad \text{when } 0 \leq t < t_c \tag{11}$$

$$r_g(t, t_C) - r_0 = \frac{1}{t_C}\int_0^t \left[r_g(t) - r_0\right] dt \qquad \text{when } t \geq t_c \tag{12}$$

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:

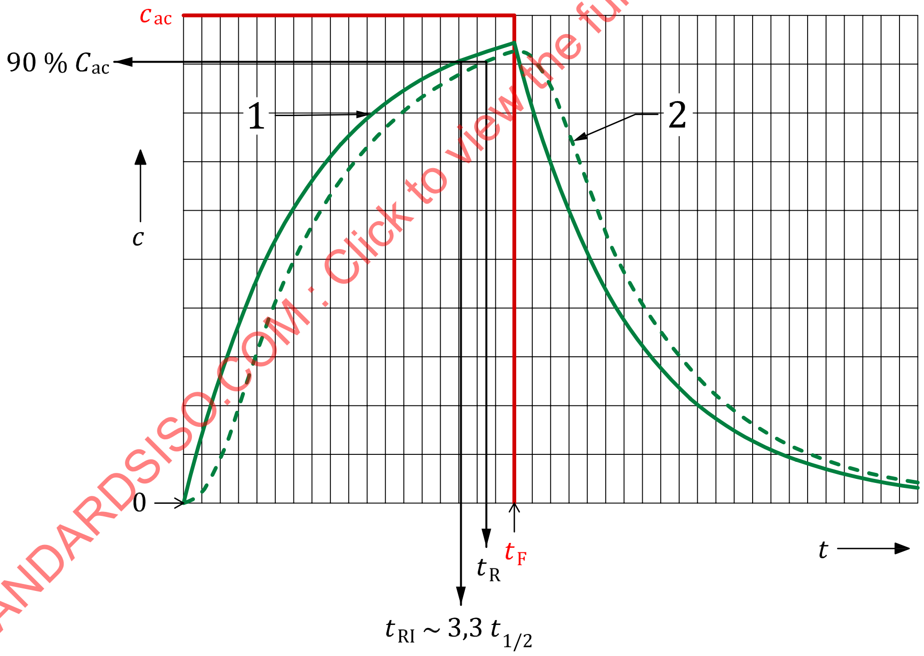
$$c(t) = \frac{\lambda}{\varepsilon_D\, \delta\, q}\left[r_g(t, t_C) - r_0\right] \tag{13}$$

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 the corresponding response time t_R. Table 2 gives the response time t_R for the measurement of the activity concentration as a function of the half-life $t_{1/2}$ of the radionuclide and the counting time t_C.

Table 2 — Response time, t_R, for a fixed media filter and short half-life model of evaluation as a function of half-life, $t_{1/2}$, and counting time, t_C

t_C min	$t_{1/2}$ min								
	0,5	**1**	**2**	**3**	**4**	**5**	**10**	**20**	**30**
0,5	1,9	3,6	6,9	10,2	13,5	16,8	33,4	66,6	99,7
1	2,2	3,9	7,2	10,5	13,8	17,1	33,7	66,8	100,0
5	5,3	6,5	9,5	12,7	16,0	19,2	35,7	38,8	102,0
10	9,7	10,5	13,0	15,9	19,0	22,2	38,5	71,5	104,6
20	18,7	19,4	21,2	23,3	25,9	28,8	44,3	76,9	109,8
30	27,7	28,4	29,9	31,6	33,7	36,2	50,7	82,6	115,3
40	36,7	37,4	38,9	40,3	42,1	44,2	57,5	88,6	121,0
50	45,7	46,4	47,9	49,3	50,8	52,6	64,8	94,8	126,8
60	54,7	55,4	56,9	58,3	59,8	61,3	72,4	101,3	132,9

Figure 2 shows the shift between the activity concentration calculated according to Formula (8), displayed by curve 1, and the activity concentration calculated according to Formula (13), displayed by curve 2, because of the counting time t_C which adds an additional delay to the intrinsic response time, t_R.



Key

t time, in s

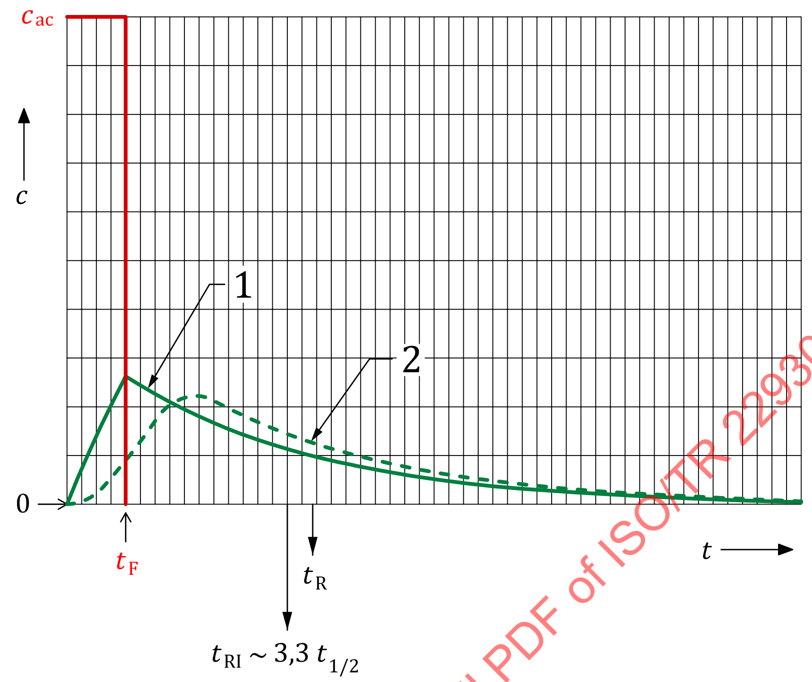
c activity concentration, in Bq·m^{-3}

1 activity concentration calculated according to Formula (8)

2 activity concentration calculated according to Formula (13)

Figure 2 — Short half-life fixed media filter model of evaluation

Figure 3 shows that in some case of puff release ($t_F < t_R$) the value of the actual activity concentration c_{ac} cannot be measured by the CAM because its response time t_R is too long compared to the brief duration of release t_F.



Key

t time, in s

c activity concentration, in Bq·m^{-3}

1 activity concentration calculated according to Formulae (9) and (10)

2 activity concentration calculated according to Formula (13)

Figure 3 — Dynamic behaviour in some case of puff release for short half-life fixed media filter model of evaluation

However in any case of release conditions, it can be demonstrated that the integrated concentration which represents the total internal exposure due to inhalation always remains equal to the actual integrated concentration:

$$\int_0^{t \gg t_F} c(t)\,\mathrm{d}t = \int_0^{t \gg t_F} \frac{\lambda}{\varepsilon_D\,\delta\,q}\left[r_g(t) - r_0\right]\mathrm{d}t = \int_0^{t \gg t_F} \frac{\lambda}{\varepsilon_D\,\delta\,q}\left[r_g(t, t_C) - r_0\right]\mathrm{d}t = c_{ac} \cdot t_F$$

6.2.3 Long half-life radionuclide activity concentration model of evaluation

$$c(t) = \frac{1}{\varepsilon_D\,\delta\,q} \cdot \frac{\mathrm{d}r_g(t)}{\mathrm{d}t} \tag{14}$$

And according to Formulae (6) and (7),

$$c(t) = c_{ac} \cdot \mathrm{e}^{-\lambda t} \qquad \text{when } 0 \le t < t_F \tag{15}$$

$$c(t) = -c_{ac}\left[1 - e^{-\lambda t_F}\right] e^{-(t-t_F)} \qquad \text{when } t \geq t_F \tag{16}$$

It can be seen that the Formulae (15) and (16) tend respectively to Formulae (1) and (2) when $\lambda \to 0$, that is to say when dealing with long half-life radionuclides. In this case, the intrinsic response time is almost instantaneous.

The transposition of Formula (14) shows that in addition to taking account of the counting time t_C, account should also be taken of the time interval t_I between two successive measurements of counting rate. Thus the model of evaluation of the activity concentration given in Formula (14) for long half-life radionuclide becomes:

$$c(t) = \frac{r_g(t, t_C) - r_0}{\varepsilon_D\, \delta\, q\, t_I} \qquad \text{when } t < t_I \tag{17}$$

$$c(t) = \frac{1}{\varepsilon_D\, \delta\, q\, t_I}\left[r_g(t, t_C) - r_g(t - t_I, t_C)\right] \qquad \text{when } t \geq t_I \tag{18}$$

The model of evaluation of the activity concentration given by Formula (18) is only adapted for radionuclides with long half-life because in case of short half-life radionuclide a constant activity concentration leads to a constant activity or count rate on the media filter and the use of Formula (18) shows that the activity concentration equals zero which is wrong.

The development of Formulae (11) to (12) applied to the Formulae (17) and (18) makes it possible to quantify the dynamic behaviour and the response time of the evaluation model in all release conditions knowing t_C and t_I. Table 3 gives the response time t_R as a function of the counting time t_C and the interval time t_I.

Annexes A and C show how to use Table 3 to quantify the response time.

In the evaluation of the response times given in Table 3, the random characteristic of the counting rates is not taken into account. If it is taken it into account, $\frac{dr_g(t)}{dt}$ of Formula (14) can be determined from successive counting measurements by the use of a linear regression method. Then, with specific statistical tests conditions, the minimum detectable activity concentration and its associated response time are determined[5]. The explanation and numerical example of this method are given in Annex D.

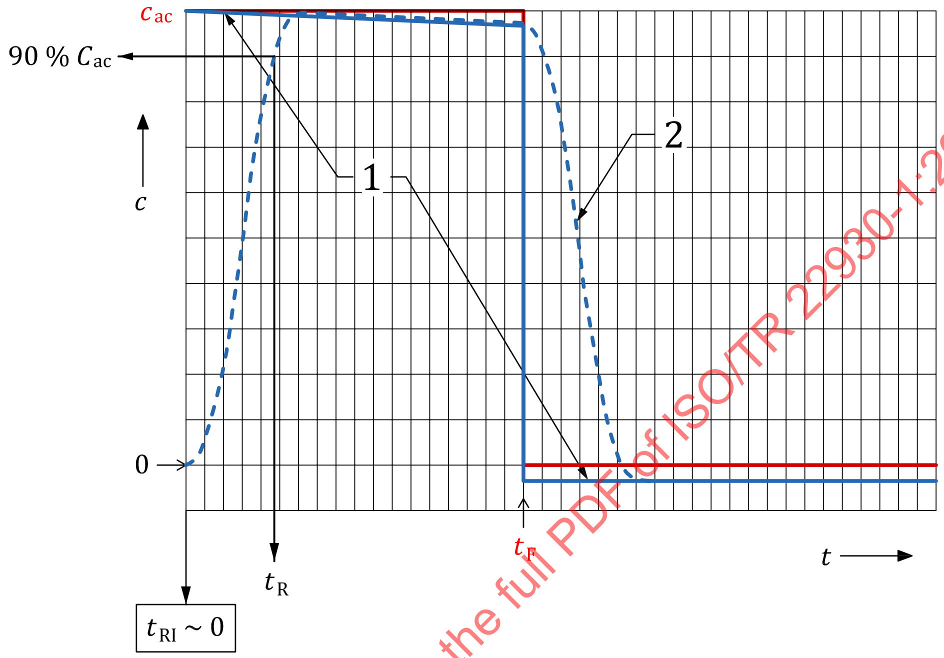
Table 3 — Response time, t_R, for a fixed media filter and long half-life model of evaluation as a function of the counting time, t_C, and the time interval, t_I

t_C min	t_I min								
	1	**5**	**10**	**20**	**30**	**40**	**45**	**50**	**60**
1	1,6	5,0	9,5	18,5	27,5	36,5	41,0	45,5	54,5
5	5,0	7,8	11,8	20,5	29,5	38,5	43,0	47,5	56,5
10	9,5	11,8	15,5	23,7	32,3	41,1	45,5	50,0	59,0
20	18,5	20,5	23,7	31,1	39,0	47,3	51,6	55,8	64,5
30	27,5	29,5	32,3	39,0	46,6	54,5	58,5	62,7	71,0
40	36,5	38,5	41,1	47,3	54,5	62,1	66,0	70,0	78,1
45	41,0	43,0	45,5	51,6	58,5	66,0	69,8	73,8	81,7
50	45,5	47,5	50,0	55,8	62,7	70,0	73,8	77,6	85,5
60	54,5	56,5	59,0	64,5	71,0	78,1	81,7	85,5	93,1

Figure 4 shows that the response time t_R is only due to the counting time t_C and the time interval t_I because when t_C and t_I tend to zero, then t_R also tends to zero which is the value of t_{RI}.

Figure 4 also shows a slight decreasing slope of $c(t)$ when ($t < t_F$) instead of perfectly matching with c_{ac}. This is due to the effect of the radioactive decay on the long half-life model of evaluation. This effect is also manifested by negative values of $c(t)$ when $t >> t_F$.

The effect of the radioactive decay on the long half-life model of evaluation can be neglected when $\frac{t_{1/2}}{t_F} > 50$.



Key

t time, in s

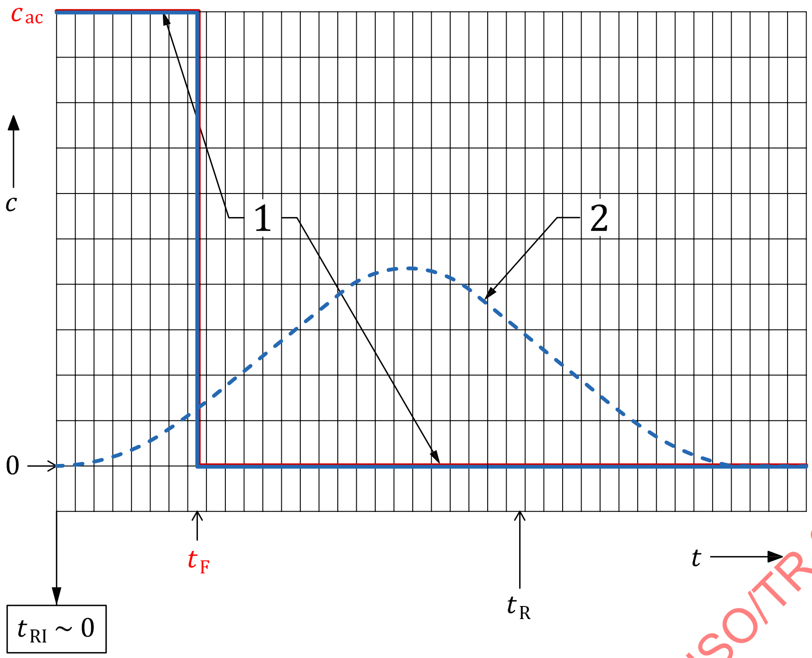
c activity concentration, in Bq·m^{-3}

1 activity concentration calculated according to Formulae (15) and (16)

2 activity concentration calculated according to Formulae (17) and (18)

Figure 4 — Long half-life fixed media filter model of evaluation

Figure 5 shows that in some cases of puff release ($t_F < t_R$) the value of the actual concentration c_{ac} cannot be measured by the CAM because its response time t_R is too long compared to the brief duration of release t_F.



Key

t time, in s

c activity concentration, in Bq·m^{-3}

1 activity concentration calculated according to Formulae (15) and (16)

2 activity concentration calculated according to Formulae (17) and (18)

Figure 5 — Dynamic behaviour in some case of puff release for long half-life fixed media filter model of evaluation

However, in any case of release conditions, it can be demonstrated that the integrated concentration which represents the total internal exposure due to inhalation always remains equal to the actual integrated concentration:

$$\int_0^{t \gg t_F} c(t)\,\mathrm{d}t = \frac{r_g(t \gg t_F, t_C) - r_0}{\varepsilon_D\,\delta\,q} \sim c_{ac} \cdot t_F \qquad \text{when } \lambda . t_F \to 0$$

6.2.4 Intermediate half-life radionuclide activity concentration model of evaluation

In most cases, CAM is used when radionuclides with important radiotoxicities are involved (small value of ALI). Those radionuclides have usually long half-lives. This is why the long half-life model of evaluation is the most currently used.

Nevertheless, in certain accidental situations which may occur in nuclear reactor installations, fission products with relatively short half-lives may be released and may require the use of CAM. This can be the case of ^{88}Rb which has $t_{1/2}$ = 17,8 min for example. In that situation, the following model of evaluation can be used:

$$c(t) = \frac{r_g(t, t_C) \cdot \left(1 + \frac{\lambda t_C}{2}\right) - r_0 \cdot \left(1 - \frac{\lambda t_C}{2}\right)}{\varepsilon_D\,\delta\,q\,t_C} - X_0 \qquad \text{when } t < t_c \qquad (19)$$

$$c(t)=\frac{1}{\varepsilon_D\,\delta\,q\,t_C}\cdot\left[r_g(t,t_C)\cdot\left(1+\frac{\lambda\,t_C}{2}\right)-r_g(t-t_C,t_C)\cdot\left(1-\frac{\lambda\,t_C}{2}\right)\right]-X_0 \qquad \text{when } t\geq t_c \qquad (20)$$

where X_0 is an adjustment factor to make sure that $c(0,t_C)=0$. The value of X_0 is then $X_0=\frac{r_0\lambda}{\varepsilon_D\,\delta\,q}$.

The development of Formulae (11) to (12) applied to Formulae (19) and (20) makes it possible to quantify the dynamic behavior and the response time of the evaluation model in all release conditions knowing t_C and $t_{1/2}$. Table 4 gives the response time t_R as a function of the half-life $t_{1/2}$ of the radionuclide and the counting time t_C.

Note that when $\lambda\to 0$ which means $t_{1/2}\to\infty$ (long half-life radionuclides) and considering that $t_I=t_C$, then Formulae (19) and (20) tend respectively to Formulae (17) and (18). It can be noted that the values of the response time t_R in Table 4 when $t_{1/2}\to\infty$ are the same as in Table 3 when $t_I=t_C$.

Table 4 — Response time, t_R, for a fixed media filter and intermediate half-life model of evaluation as a function of the counting time, t_C, and the half-life, $t_{1/2}$

t_C min	$t_{1/2}$ min									
	0,5	**1**	**2**	**3**	**4**	**5**	**10**	**20**	**30**	**∞**
0,5	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8
1	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6
5	9,3	9,3	8,5	8,0	7,9	7,8	7,8	7,8	7,8	7,8
10	18,4	18,6	18,5	17,7	16,9	16,9	15,6	15,5	15,5	15,5
20	36,4	36,8	37,3	37,4	37,1	36,4	32,7	31,1	31,1	31,1
30	54,4	54,8	55,4	55,9	56,1	56,0	52,3	47,6	46,6	46,6
40	72,4	72,8	73,5	74,1	74,5	74,7	72,7	65,3	62,9	62,1
45	81,4	81,8	82,5	83,1	83,6	83,9	82,8	74,7	71,4	69,8
50	90,4	90,8	91,5	92,2	92,7	93,1	92,6	84,4	80,0	77,6
60	108,4	108,8	109,6	110,3	110,9	111,4	111,9	104,5	97,9	93,1

6.2.5 Comparison of the three fixed filter models of evaluation

For long half-lives radionuclides, that is, when $\frac{t_{1/2}}{t_F}>50$, the intermediate half-life model tends to the long half-life model. In this case, the long half-life model is the most convenient to use.

For short half-lives radionuclides, there may be a competition between the short half-life model and the intermediate half-life model with respect to the response time t_R for a given counting time t_C and half-life $t_{1/2}$.

From Table 2 and Table 4, Table 5 can be build, that indicates the model with the best response time t_R for a given counting time t_C and half-life $t_{1/2}$.

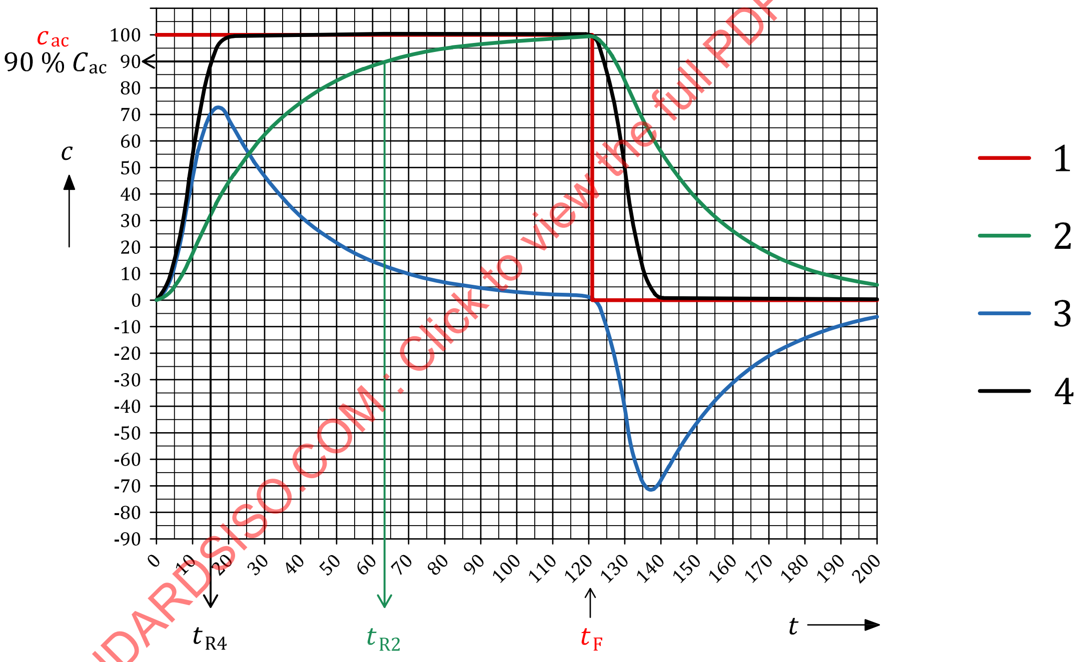
Table 5 — Model of evaluation with the best response time, t_R, for a given counting time, t_C, and half-life, $t_{1/2}$, for short half-lives radionuclides

t_C min	$t_{1/2}$ min								
	0,5	**1**	**2**	**3**	**4**	**5**	**10**	**20**	**30**
1	B	B	B	B	B	B	B	B	B
5	A	A	B	B	B	B	B	B	B
10	A	A	A	B	B	B	B	B	B
20	A	A	A	A	A	A	B	B	B
30	A	A	A	A	A	A	B	B	B
40	A	A	A	A	A	A	A	B	B
50	A	A	A	A	A	A	A	B	B
60	A	A	A	A	A	A	A	B	B

A short half-life model of evaluation: Formula (13)

B intermediate half-life model of evaluation: Formulae (19) and (20)

To illustrate the differences between the three models of evaluation, Figure 6 shows the case ^{88}Rb $\left(t_{1/2} = 17{,}8\ \text{min}\right)$ considering $t_I = t_C = 10\ \text{min}$.



Key

t time, in s

c activity concentration, in Bq·m^{-3}

1 actual activity concentration: Formulae (1) and (2)

2 short half-life model of evaluation: Formula (13)

3 long half-life model of evaluation: Formulae (17) and (18)

4 intermediate half-life radionuclide model of evaluation: Formulae (19) and (20)

Figure 6 — Comparison of the 3 fixed media filter models of evaluation of the activity concentration applied to ^{88}Rb ($t_{1/2}$ = 17,8 min) with $t_I = t_C$ = 10 min

Figure 6 shows that:

— Long half-life model of evaluation is not adapted because the half-life is not long enough to consider a constant slope of the activity deposited on the media filter. As long as the activity concentration c_{ac} is maintained, the activity deposited on the media filter tends towards equilibrium then c decreases towards zero. When c_{ac} ceased the activity deposited on the media filter decreases due to decay process and c becomes first negative and then tends to zero,

— Short half-life model of evaluation seems correct but the response time t_{R2} is about 64 min, while intermediate half-life model of evaluation gives a response time t_{R4} of about 15 min.

It should be noted that short and intermediate half-life models of evaluation are valid for only one given radionuclide since they only apply for a given half-life $t_{1/2}$ (or decay constant λ) value. Therefore, the measurement technique should focus on the radionuclide under consideration with the least possible interference of other radionuclides of different half-lives.

These two models are therefore not applicable for a mixture of radionuclides of different short half-lives values, unlike the long half-life model of evaluation which does not depend on the half-lives values.

7 Moving filter monitor

7.1 Preliminary note

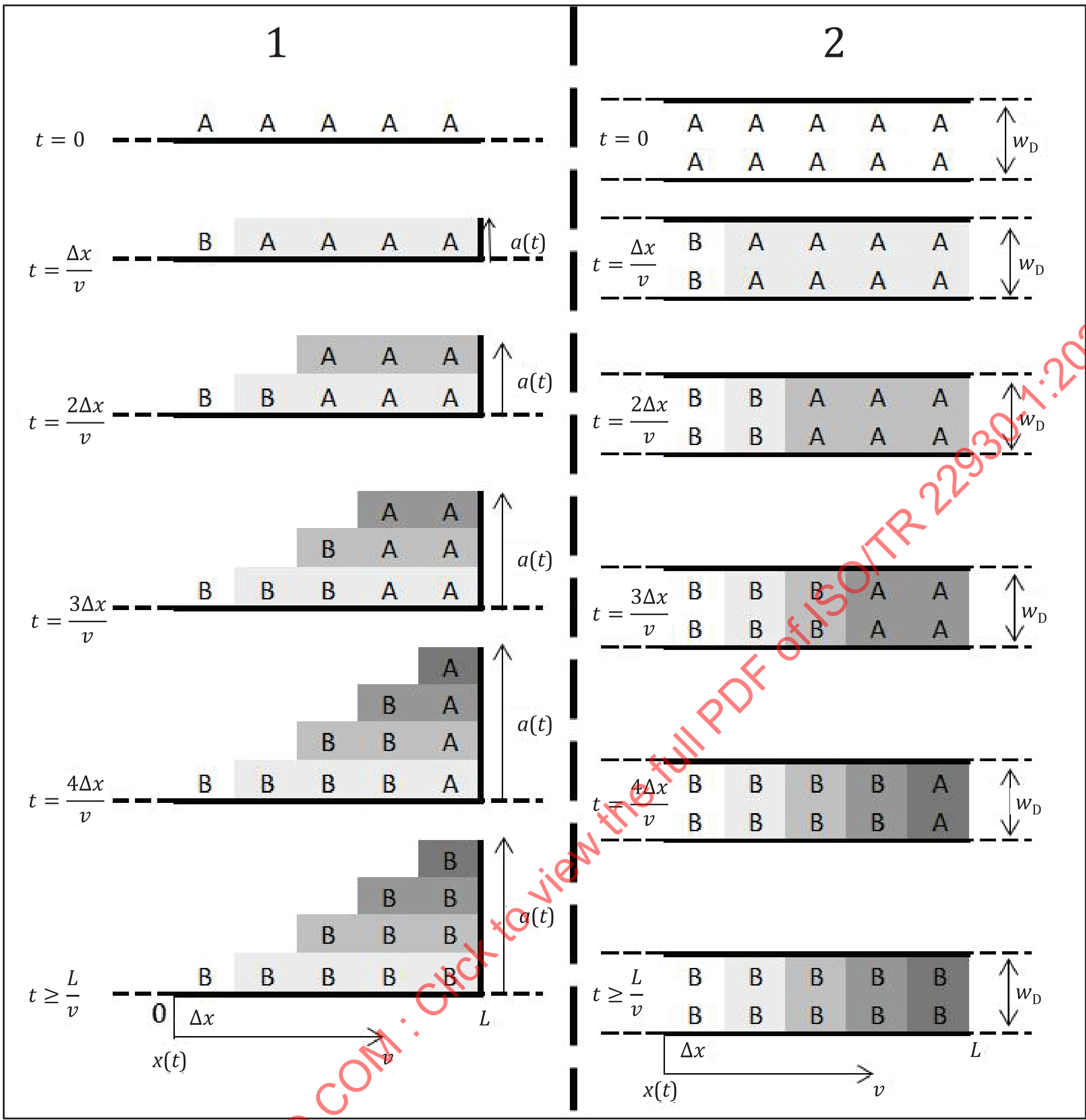
In that situation, a roll filter advances slowly across a deposition window which is usually either rectangular or circular in shape and this deposition area is viewed by the detector.

In Clause 7, only the rectangular window deposition area is described but the differences made are specified, in the case of a circular window deposition area.

7.2 Study of the dynamic behaviour

This subclause describes the evolution over time of the activity concentration $c(t)$ during the sudden appearance of an actual activity concentration c_{ac}. The dynamic behaviour is quantified by the response time. The response time is due to the intrinsic response time 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 filter, the time transit 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 concentration to be measured c_{ac} changes over time in steps of duration t_P as it is described in Formulae (1) and (2).



Key

1 side view

2 top view

$x(t)$ linear position of a portion of a filter at a time t

$a(t)$ deposited activity on each portion of the filter at time t

Figure 7 — Principle of the activity deposition on a moving filter

In Figure 7, the following is considered: the presence of constant activity concentration in the air and the collection medium is moving from left to right at a constant speed, with a deposition area of length L and width w_D. It is also assumed that this entire deposition area is viewed by the detector and that the deposition is uniform across the deposition area.

The deposition area can be divided in two regions A and B described as

— Region A: part of the moving filter present when the released activity event occurs at time $t = 0$. This part increases and then disappears completely at time $t = t_T = \frac{L}{v}$.

— Region B: part of the moving filter emerging in front of the detector that has not yet seen a deposited activity at time $t = 0$ and then progressively increases, andthen stabilize after time $t = t_T = \frac{L}{v}$.

Considering respectively N_A and N_B the number of atoms in region A and B, then the number of atoms N of the radionuclide considered on the moving filter is $N = N_A + N_B$.

The differential equations describing the number of atoms N_A and N_B can be formulated as a function of the concentration c_{ac} at the sampling point according to the following Formulae:

During the release

$$\frac{dN_A(t)}{dt} = \frac{q\,\delta\,c_{ac}}{\lambda}\left[1 - \frac{1}{t_T}\left(t + \frac{1 - e^{-\lambda t}}{\lambda}\right)\right] - \lambda N_A(t) \quad \text{when } 0 \le t < t_F \text{ and } t \le t_T \qquad (21)$$

$$\frac{dN_B(t)}{dt} = \frac{q\,\delta\,c_{ac}}{\lambda\,t_T}\cdot t - \lambda N_B(t) \quad \text{when } 0 \le t < t_F \text{ and } t \le t_T \qquad (22)$$

$$\frac{dN_A(t)}{dt} = \frac{dN_B(t)}{dt} = \quad \text{when } 0 \le t < t_F \text{ and } t > t_T \qquad (23)$$

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

and after the release

$$\frac{dN_A(t)}{dt} = 0 \quad \text{when } t > t_F \text{ and } t \ge t_T \qquad (24)$$

$$\frac{dN_A(t)}{dt} = -\lambda N_A(t) - \frac{N_A(t_F)}{t_T - t_F}\cdot e^{-\lambda(t - t_F)} \quad \text{when } t > t_F \text{ and } t < t_T \qquad (25)$$

$$\frac{dN_B(t)}{dt} = -\lambda N_B(t) + \frac{q\,\delta\,c_{ac}}{t_T}\cdot\left\{e^{\lambda(t - t_T - t_F)} - 1\right\}\cdot e^{-\lambda(t - t_F)} \quad \text{when } t > t_F,\ t \le t_F + t_T \text{ and } t_F \ge t_T \qquad (26)$$

$$\frac{dN_B(t)}{dt} = 0 \quad \text{when } t > t_F + t \qquad (27)$$

Considering that $N(0) = 0$ at the beginning of the sampling and (5) the solutions of the differential Formulae (21) and (23) during the release expressed as $r_g(t) - r_0 = \lambda\varepsilon_D\,\delta\left[N_A(t) + N_B(t)\right]$ are:

$$r_g(t) - r_0 = \frac{q\,\delta\,\varepsilon_D\,c_{ac}}{\lambda}\left[\left(1 - \frac{t}{t_T}\right)\left(1 - e^{-\lambda t}\right) + \frac{\left(e^{-\lambda t} + \lambda t - 1\right)}{\lambda\,t_T}\right] \quad \text{when } t \le t_F + t \text{ and } t \le t_T \qquad (28)$$

$$r_g(t) - r_0 = \frac{q\,\delta\,\varepsilon_D\,c_{ac}}{\lambda^2\,t_T}\left[e^{-\lambda t_T} + \lambda t_T - 1\right] \quad \text{when } t \le t_F \text{ and } t > t_T \qquad (29)$$

7.3 Activity concentration model of evaluation

The model of evaluation of the activity concentration $c(t)$ over time is deduced from Formula (29) which represent the stability of the measurement during release then

$$c(t)=\frac{2}{q\,\delta\,\varepsilon_{\mathrm{D}}\,t_{\mathrm{T}}}\,f(\lambda,t_{\mathrm{T}})\left[r_{\mathrm{g}}(t)-r_0\right] \tag{30}$$

with

$$f(\lambda,t_{\mathrm{T}})=\frac{\lambda^2\,t_{\mathrm{T}}^2}{2\left[\mathrm{e}^{-\lambda\,t_{\mathrm{T}}}+\lambda\,t_{\mathrm{T}}-1\right]} \tag{31}$$

For long half-life radionuclide $f(\lambda,t_{\mathrm{T}})\sim 1$ then the model of evaluation of the activity concentration $c(t)$ over time can be expressed as

$$c(t)=\frac{2}{q\,\delta\,\varepsilon_{\mathrm{D}}\,t_{\mathrm{T}}}\left[r_{\mathrm{g}}(t)-r_0\right] \tag{32}$$

In the case of a circular window deposition area, Formula (32) becomes (33)[3] as follow

$$c(t)=\frac{3\pi}{4\,q\,\delta\,\varepsilon_{\mathrm{D}}\,t_{\mathrm{T}}}\left[r_{\mathrm{g}}(t)-r_0\right] \tag{33}$$

with $t_{\mathrm{T}}=\frac{D}{v}$

The intrinsic response time t_{RI} for model of evaluation of activity concentration according to Formula (30) as a function of the half-life $t_{1/2}$ and time transit t_{T} according to Formula (28) is given in Table 6.

Table 6 — Intrinsic response time t_{RI} for moving filter model of evaluation of the activity concentration according to Formula (30) as a function of the half-life $t_{1/2}$ and time transit t_{T} according to Formula (28)

$t_{1/2}$ min	t_{T} min								
	1	**10**	**20**	**30**	**60**	**120**	**180**	**240**	**300**
1	0,63	2,8	3,1	3,2	3,2	3,3	3,3	3,3	3,3
5	0,68	5,8	9,5	11,7	14,3	15,5	15,9	16,1	16,2
10	0,68	6,3	11,6	15,8	23,4	28,6	30,3	31,0	31,5
20	0,68	6,6	12,6	18,1	31,5	47,0	53,7	57,2	59,2
30	0,68	6,7	13,0	19,0	34,7	57,0	70,2	78,0	82,7
60	0,68	6,8	13,3	19,7	37,9	69,5	94,5	114,1	129,0
120	0,68	6,8	13,5	20,1	39,4	75,8	108,8	138,6	165,3
$\boldsymbol{\gg t_T}$	0,68	6,8	13,7	20,5	41,0	82,0	123,0	163,9	204,9

Table 6 shows that, for a given time transit t_{T}, the intrinsic response time is better when the half-life is low, but according to Formula (30) for a given activity concentration value, the lower the half-life is, the lower the count rate is, because $f(\lambda,t_{\mathrm{T}})$ increases when λ decreases.

Table 6 also shows that for long half-life radionuclides $\left(t_{1/2}\gg t_{\mathrm{T}}\right)$ the intrinsic response time equals $t_{\mathrm{RI}}=0{,}68\,t_{\mathrm{T}}$. In the case of a circular window deposition area, for long half-life radionuclides $\left(t_{1/2}\gg t_{\mathrm{T}}\right)$ the intrinsic response time equals $t_{\mathrm{RI}}=0{,}61\,t_{\mathrm{T}}$ [3].

The evolutions over time of the activity concentration as defined in Formulae (30) and (32) assume that the gross count $r_g(t)$ rate is instantaneous which means:

$$r_g(t) = \lim_{t_C \to 0} \left[\frac{n_g(t, t_C)}{t_C} \right]$$

This implies that $r_g(t)$ does not depend on t_C. In reality, any count rate measurement is associated with a counting time t_C and then (11) and (12) still applies and taking account of the counting time t_C, the model of evaluation of the activity concentration given in Formulae (30) and (32) become:

$$c(t) = \frac{2}{q\,\delta\,\varepsilon_D\,t_T} f(\lambda, t_T) \left[r_g(t, t_C) - r_0 \right] \quad (34)$$

and for long half-life radionuclide $\left(f(\lambda, t_T) \sim 1 \right)$

$$c(t) = \frac{2}{q\,\delta\,\varepsilon_D\,t_T} \left[r_g(t, t_C) - r_0 \right] \quad (35)$$

In the case of a circular window deposition area, Formula (35) becomes (36)[3] as follow

$$c(t) = \frac{3\pi}{4q\,\delta\,\varepsilon_D\,t_T} \left[r_g(t, t_C) - r_0 \right] \quad (36)$$

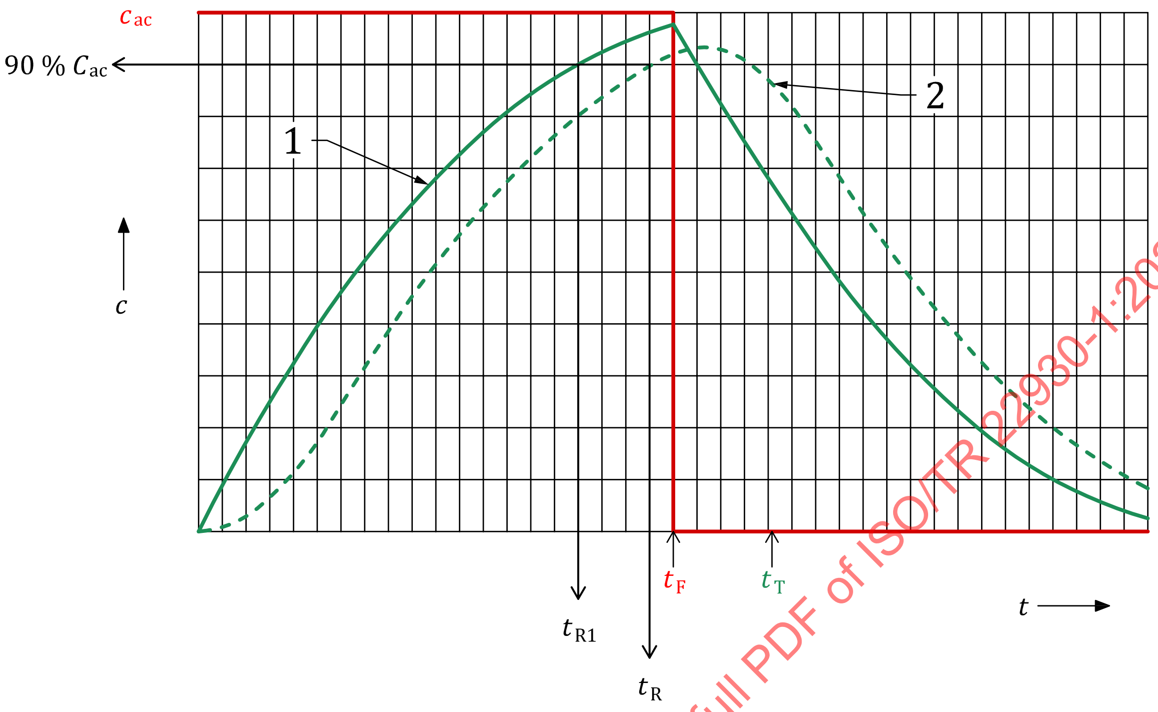
with $t_T = \dfrac{D}{v}$

The development of Formulae (11) to (12) applied to Formulae (34) and (35) makes it possible to quantify the dynamic behaviour and the response time of the evaluation model in all release conditions knowing λ (or $t_{1/2}$) t_T and t_C. Table 7 gives the response time as a function of the time transit t_T and the counting time t_C considering long half-life radionuclides $\left(t_{1/2} \gg t_T \right)$. It was noted previously that the intrinsic response time, t_{RI} of a circular window deposition is of the same order magnitude as that of a rectangular one. Then it can be reasonably considered that the response time given in Table 7 also apply to the case of a circular window deposition area. An example of use of Table 7 is given in Annex B.

Table 7 — Response time of the moving media filter model of evaluation of activity concentration as a function of the time transit t_T and the counting time t_C considering a long half-life radionuclides $\left(t_{1/2} \gg t_T \right)$

t_C min	t_T min								
	1	**10**	**20**	**30**	**60**	**120**	**180**	**240**	**300**
1	1,3	7,4	14,2	21,3	41,5	82,5	123,5	164,4	205,4
5	4,8	9,7	16,3	23,1	43,6	84,5	125,5	166,4	207,4
10	9,3	13,3	19,4	26,0	46,2	87,1	128,0	169,0	210,0
20	18,3	21,6	26,6	32,4	51,9	92,4	133,2	174,2	215,1
30	27,3	30,3	34,7	39,9	58,1	98,0	138,6	179,4	220,3
40	36,3	39,3	43,1	47,9	64,9	103,8	144,1	184,8	225,6
50	45,3	48,3	51,8	56,2	72,2	109,8	149,8	190,3	231,0
60	54,3	57,3	60,7	64,7	79,8	116,1	155,6	195,9	236,5
120	108,3	111,3	114,6	118,0	129,3	159,6	194,6	232,3	271,4
180	162,3	165,3	168,6	171,9	182,0	207,9	239,3	273,8	310,3
240	216,2	219,2	222,6	225,9	235,9	258,6	287,2	319,1	353,3

Figure 8 shows shift between the activity concentration calculated by Formula (30) and displayed by curve 1 and the activity concentration calculated by Formula (34) and displayed by curve 2 because of the counting time t_C which adds an additional delay to this intrinsic response time.



Key

t time, in s

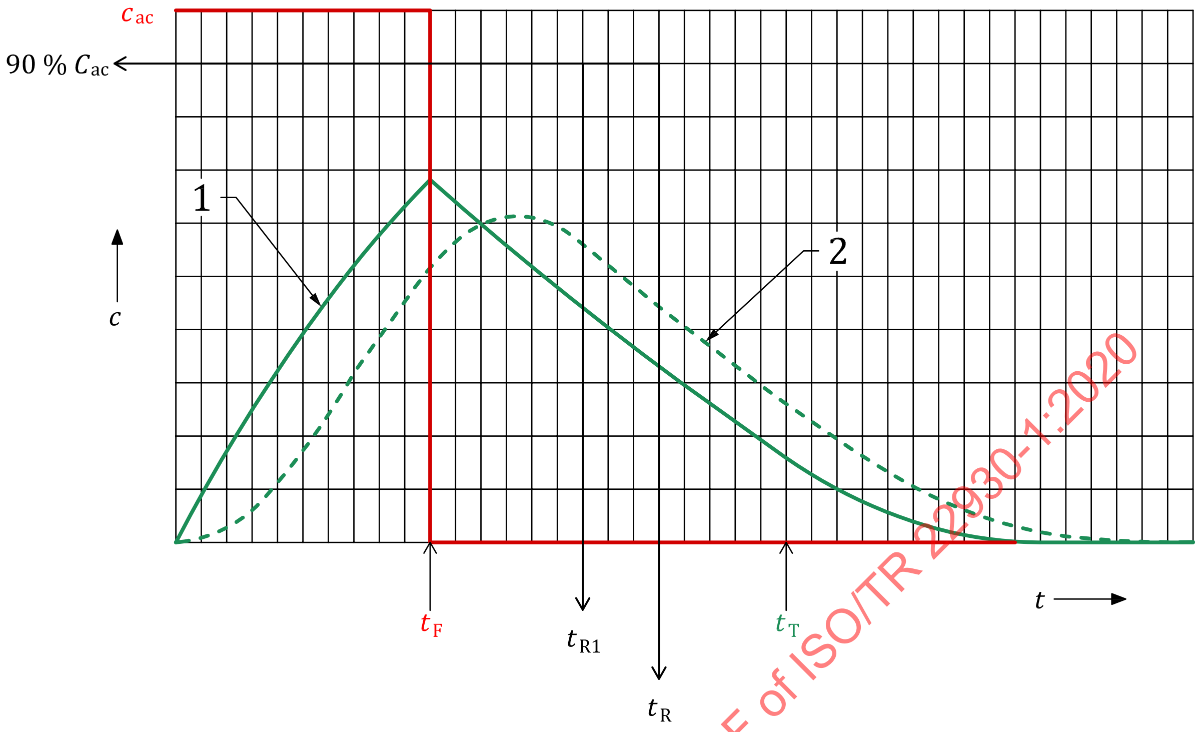
c activity concentration, in Bq·m^{-3}

1 activity concentration calculated according to Formula (30)

2 activity concentration calculated according to Formula (34)

Figure 8 — Response time of the moving filter model of evaluation

Figure 9 shows that in some case of puff release $(t_F < t_R)$ the value of the actual concentration c_{ac} cannot be measured by the CAM because its response time t_C is too long compared to the brief duration of release t_F.



Key

t time, in s

c activity concentration, in Bq·m^{-3}

1 activity concentration calculated according to Formula (30)

2 activity concentration calculated according to Formula (34)

Figure 9 — Dynamic behaviour of the moving filter model of evaluation in case of puff release

However in any case of release conditions, it ca be demonstrated that the integrated concentration which represents the total internal exposure due to inhalation always remains equal to the actual integrated concentration:

$$\int_0^{t \gg t_F} c(t)\,\mathrm{d}t = c_{ac} \cdot t_F$$

8 Evaluation of the characteristic limits

8.1 General

Direct measurements in real time often use complex algorithms of processing data protected by copyrights. The certification tests of such equipment are usually carried out in test laboratories with well-defined test conditions which do not necessarily reflect the environment in which the device is used and particularly the fluctuations of natural radioactivity.

To determine the characteristic limits (uncertainty, decision threshold and detection limit) related to this type of device it may be necessary to conduct tests in an environment representative of real conditions of use.

In most cases, CAM is used when radionuclides with important radiotoxicities are involved (small value of ALI). Those radionuclides have usually long half-life values. Thus, expressions of long half-life models of evaluation are used to determine the characteristic limits.

8.2 Fixed media filter model of evaluation

8.2.1 General

An example of application is given in Annex A.

8.2.2 Definition of the model

The activity concentration $c(t_j)$ at a time t_j of a long half-life radionuclide, according to Formula (18), is expressed as:

$$c\left(t_j\right)=\frac{r_g\left(t_j,t_C\right)-r_g\left(t_j-t_I,t_C\right)}{\varepsilon_D\cdot q\cdot t_I\cdot\delta} \tag{37}$$

To simplify the Formula, consider that

$$r_g\left(t_j,t_C\right)\rightarrow r_j,$$

$$r_g\left(t_j-t_I,t_C\right)\rightarrow r_{j-1},$$

$c\left(t_j\right)\rightarrow c_j$ and

$$w=\frac{1}{\varepsilon_D\cdot q\cdot t_I\cdot\delta}$$

Then Formula (37) becomes to

$$c_j=\left(r_j-r_{j-1}\right)\cdot w \tag{38}$$

Knowing the random characteristic of the count rates, the evaluation of c_j can also be carried out by the use of a linear regression method which make possible to determine $\frac{dr_g(t)}{dt}$ of Formula (14) from successive counting measurements[5]. The explanation and numerical example of this method are given in Annex D.

8.2.3 Standard uncertainty

The standard uncertainty, (c_j) is given by the following Formulae:

$$u^2\left(c_j\right)=\left(\frac{\partial c_j}{\partial r_j}\right)^2\cdot u^2\left(r_j\right)+\left(\frac{\partial c_j}{\partial r_{j-1}}\right)^2\cdot u^2\left(r_{j-1}\right)+\left(\frac{\partial c_j}{\partial w}\right)^2\cdot u^2\left(w\right) \tag{39}$$

then

$$u^2\left(c_j\right)=\frac{w\cdot c_j}{t_C}+\frac{2\boldsymbol{w}}{\boldsymbol{t}_C}\cdot\sum_{\boldsymbol{k}=1}^{\boldsymbol{l}=\boldsymbol{j}-1}\boldsymbol{c}_{\boldsymbol{k}}+2\cdot\frac{w^2}{t_C}r_0+\frac{u^2(w)}{w^2}.c_j^2=\frac{w\cdot c_j}{t_C}+\frac{2\boldsymbol{w}}{\boldsymbol{t}_C}\cdot\boldsymbol{r}_{\boldsymbol{j}-1}+\frac{u^2(w)}{w^2}\cdot c_j^2 \tag{40}$$

then

$$u^2\left(c_1\right)=\frac{w\cdot c_1}{t_C}+2\cdot\frac{w^2}{t_C}r_0+\frac{u^2(w)}{w^2}\cdot c_1^2 \tag{41}$$

with

r_0 initial gross count rate with a counting time t_C at the beginning of a measuring cycle (s-1)

8.2.4 Decision threshold

The decision threshold c^* is given by

$$c^* = k_{1-\alpha} \cdot u(0) \tag{42}$$

For $c_1 = ... = c_j = 0$ Formulae (40) and (41) lead to

$$u^2(0) = 2 \cdot \frac{w^2}{t_C} \cdot r_0 \quad \text{then}$$

$$c^* = k_{1-\alpha} \cdot w \cdot \sqrt{\frac{2 \cdot r_0}{t_C}} \tag{43}$$

NOTE 1 The decision threshold given in Formula (42) is only valid when there is no radiological event. If a radiological event occurs the decision threshold values increase as the activity settles on the media filter.

With regard to the real-time measurements of the artificial activity concentration, the presence of the natural radon and thoron radioactivity and, where appropriate, the ambient dose rate are such that the measured quantities of counting $\left(r_j, r_{j-1}, ..., r_0\right)$ are most often processed by algorithms in order to attenuate their influences and are also not explicitly known.

In that situation, the only data the user may have is directly the displayed activity concentration c and the decision threshold c^* cannot be calculated using Formula (42).

In that situation, the principle of the model of evaluation is known, but the input data are not accessible.

The measurement problem is to compare a series of indications $c_{0,i}$ (i = 1, ...,n) which are judged by the user to represent a background situation with a single indication c_g for another situation, called gross measurement of the activity concentration at a time t. Then the model of evaluation of the activity concentration can also be written as

$$c = c_g - \overline{c_0} = c_g - \frac{1}{n} \cdot \sum_{i=1}^{n} c_{0,i} \tag{44}$$

with

$$\overline{c_0} = \frac{1}{n} \cdot \sum_{i=1}^{n} c_{0,i} \tag{45}$$

and the standard deviation

$$s_0 = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(c_{0,i} - \overline{c_0}\right)^2} \tag{46}$$

and since no other information is available the $c_{0,i}$ (i = 1, ...,n) is assumed to be samples from Gaussian distributions with unknown expectations and variances. According to ISO/IEC Guide 98-3-1:2008, the arithmetic means $\overline{c_0}$ is the best estimate and the standard uncertainties associated with $\overline{c_0}$ is

$$u\left(\overline{c_0}\right)=\left(\frac{n-1}{n-3}\right)^{1/2}\cdot\frac{s_0}{\sqrt{n}} \qquad \text{with } n\geq 4 \tag{47}$$

then

$u^2(c)=u^2\left(c_g\right)+u^2\left(\overline{c_0}\right)$ and in the absence of the phenomenon to be measured ($c=0$) it is assumed that

$u^2\left(c_g\right)=s_0^2$ then

$$u^2(0)=s_0^2+u^2\left(\overline{c_0}\right)=s_0^2\left[1+\frac{n-1}{n\cdot(n-3)}\right] \tag{48}$$

and the decision threshold is given by

$$c^*=k_{1-\alpha}\cdot s_0\cdot\sqrt{1+\frac{n-1}{n\cdot(n-3)}} \tag{49}$$

NOTE 2 The determination of the decision threshold according to Formula (49) implies checking periodically that there is not significant variation of s_0.

8.2.5 Detection limit

The detection limit $c^\#$ is given by

$$c^\#=c^*+k_{1-\beta}\cdot u\left(c^\#\right) \tag{50}$$

then

$$c^\#=\frac{2\cdot c^*+\dfrac{k^2\cdot w}{t_C}}{1-k^2\cdot\dfrac{u^2(w)}{w^2}} \tag{51}$$

with $k=k_{1-\alpha}=k_{1-\beta}$

under the condition

$$k^2\cdot\frac{u^2(w)}{w^2}<1 \tag{52}$$

Otherwise the measurement method is not adapted.

8.2.6 Limits of the coverage interval

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

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

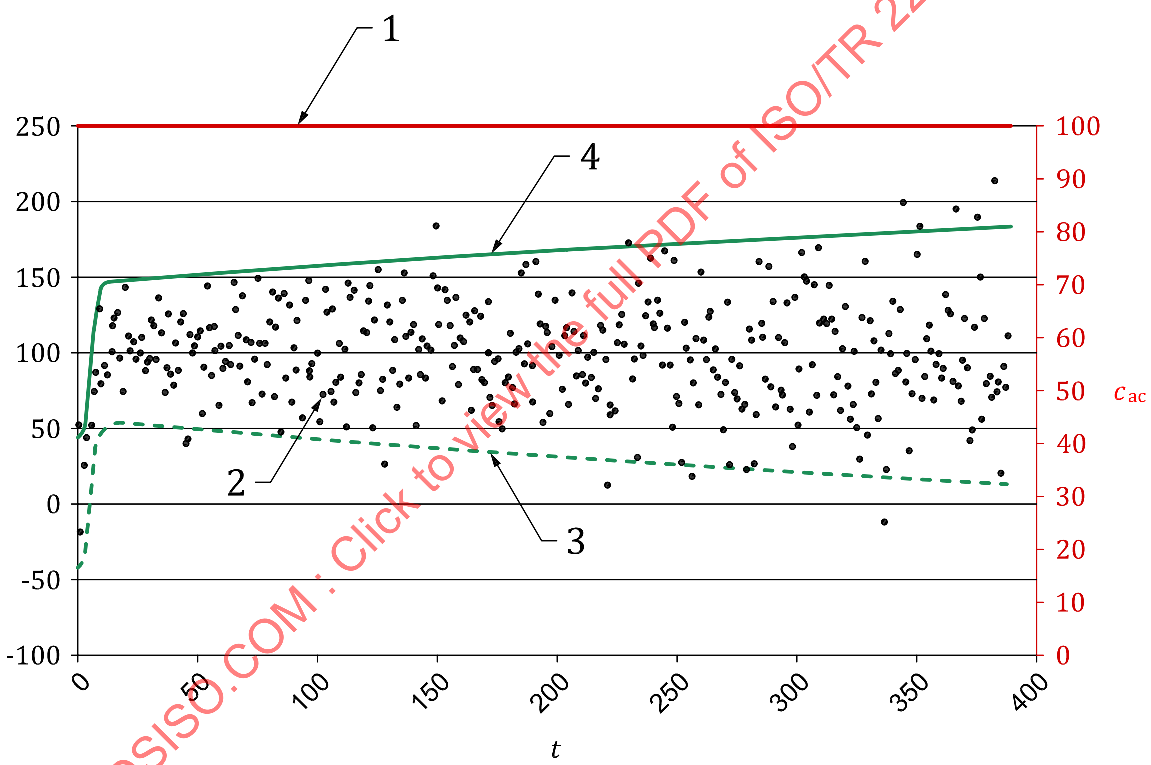
$$c^{\triangleleft} = c - k_{1-\frac{\gamma}{2}} \cdot u(c) \tag{53}$$

and

$$c^{\triangleright} = c + k_{1-\frac{\gamma}{2}} \cdot u(c) \tag{54}$$

The determination of c according to Formula (44) implies to check periodically that there is not significant variation of $\overline{c_0}$.

NOTE In the case of a continuous release, Formula (40) shows that due to the constant increase of activity on the media filter the uncertainties are getting important over time and the measurements results become quickly unusable because of the fluctuations as it is shown in the illustration given in Figure 10.



Key

t time, in s

c_{ac} actual activity concentration, in Bq·m^{-3}

1 actual activity concentration during the regarded time

2 measured activity concentration during the regarded time

3 lower limit of the coverage interval $c^{\triangleleft}$ of the measured activity concentration with a probability of 95 %

4 upper limit of the coverage interval $c^{\triangleright}$ of the measured activity concentration with a probability of 95 %

Figure 10 — Dynamic behaviour of the fixed media filter model of evaluation in case of continuous release, c_{ac}, with $t_C = t_I$ = 5 min

8.3 Moving filter model of evaluation

8.3.1 Definition of the measurand

In the case of a rectangular window deposition area, the activity concentration $c(t)$ at a time t of a long half-life radionuclide, according to Formula (32) is expressed as:

$$c(t)=\frac{2}{q\,\delta\,\varepsilon_{\mathrm{D}}\,t_{\mathrm{T}}}\left[r_{\mathrm{g}}(t,t_C)-r_0\right] \tag{55}$$

In the case of a circular window deposition area, according to Formula (33), Formula (55) becomes Formula (56)[3] as follow

$$c(t)=\frac{3\pi}{4\,q\,\delta\,\varepsilon_{\mathrm{D}}\,t_{\mathrm{T}}}\left[r_{\mathrm{g}}(t,t_C)-r_0\right] \tag{56}$$

with $t_{\mathrm{T}}=\frac{D}{v}$

To simplify the Formula:

$r_{\mathrm{g}}(t,t_C)\rightarrow r_{\mathrm{g}}$,

$c(t)\rightarrow c$ with

in the case of a rectangular window deposition area

$$w=\frac{2}{q\,\delta\,\varepsilon_{\mathrm{D}}\,t_{\mathrm{T}}} \tag{57}$$

and in the case of a circular window deposition area

$$w=\frac{3\pi}{4\,q\,\delta\,\varepsilon_{\mathrm{D}}\,t_{\mathrm{T}}} \tag{58}$$

Then Formulae (55) and (56) can be expressed as

$$c=w\cdot\left(r_{\mathrm{g}}-r_0\right) \tag{59}$$

8.3.2 Standard uncertainty

The standard uncertainty $u(c)$ is such that

$$u^2(c)=\left(\frac{\partial c}{\partial r_{\mathrm{g}}}\right)^2\cdot u^2\left(r_{\mathrm{g}}\right)+\left(\frac{\partial c}{\partial r_0}\right)^2\cdot u^2\left(r_0\right)+\left(\frac{\partial c}{\partial w}\right)^2\cdot u^2(w) \tag{60}$$

Assuming that $u^2\left(r_{\mathrm{g}}\right)=\frac{r_{\mathrm{g}}}{t_{\mathrm{C}}}$

Then

$$u^2(c)=(r_g\cdot w^2)/t_C+w^2\cdot u^2(r_0)+c^2.(u^2(w))/w^2$$

$$u^2(c)=\frac{\left(\frac{c}{w}+r_0\right)\cdot w^2}{t_C}+w\cdot u^2(r_0)+c^2\cdot\frac{u^2(w)}{w^2}$$

$$u^2(c)=\frac{c\cdot w}{t_C}+\frac{r_0\cdot w^2}{t_C}+w^2\cdot u^2(r_0)+c^2\cdot\frac{u^2(w)}{w^2}$$

$$u^2(c)=\frac{c\cdot w}{t_C}+\frac{r_0\cdot w^2}{t_C}+w^2\cdot u^2(r_0)+c^2\cdot\frac{u^2(w)}{w^2}$$

$$u^2(c)=\frac{c\cdot w}{t_C}+\left[\frac{r_0}{t_C}+u^2(r_0)\right]\cdot w^2+c^2\cdot\frac{u^2(w)}{w^2}=\frac{c\cdot w}{t_C}+u^2(0)+c^2\cdot\frac{u^2(w)}{w^2} \quad (61)$$

8.3.3 Decision threshold

For c = 0 Formula (57) leads to

$$u^2(0)=\left[\frac{r_0}{t_C}+u^2(r_0)\right]\cdot w^2$$ then according to Formula (42)

$$c^*=k_{1-\alpha}\cdot w\cdot\sqrt{\frac{r_0}{t_C}+u^2(r_0)}=k_{1-\alpha}\cdot w\cdot\sqrt{r_0\cdot\left(\frac{1}{t_C}+\frac{1}{t_0}\right)} \quad (62)$$

With regard to the real-time measurements of the artificial activity concentration, the presence of the natural radon and thoron radioactivity and, where appropriate, the ambient dose rate are such that the measured quantities of counting r_g are most often processed by algorithms in order to attenuate their influences.

These algorithms are usually black boxes protected by copyright and the certification tests of the measurement devices are generally carried out in test laboratories under well-defined test conditions which do not necessarily reflect the environment in which the device is used.

In that situation the only data the user may have is the displayed activity concentration c, then the decision threshold c^* cannot be calculated using Formula (60), but can be determined experimentally using Formula (49).

8.3.4 Detection limit

The detection limit $c^\#$ can be calculated in the same way as described in 8.2.5, then Formula (51) still applies with the condition (52).

8.3.5 Limits of the coverage interval

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

The lower limit of the coverage $c^{\triangleleft}$ and the upper limit of the coverage interval $c^{\triangleright}$ can be calculated in the same way as described in 8.2.6, then Formulae (53) and (54) still apply.

The determination of c according to Formula (44) implies to check periodically that there is not significant variation of $\overline{c_0}$.

9 Alarms setup, minimum detectable activity concentration and PME

The performance of a CAM is quantified by the decision threshold (and therefore the detection limit) and the associated response time. It could be tempted to setup the alarm on the basis of the decision threshold, but given the large number of measurements, this choice would lead to an unacceptable false alarm rates.

To avoid excessive false alarm it can be useful to setup the detection alarm level with a K value adjusted to an acceptable level of false alarm rate, instead of $k_{1-\alpha}$ value used to determine the decision threshold. Values of K as a function of false alarm rate are given in Table 8.

NOTE 1 The K values defined in Table 3 are related to the usual statistical fluctuations radioactivity measurements in the absence of the phenomenon to be measured and in a relatively stable radiological environment, but sources of instability may arise and if poorly compensated may lead to additional sources of false alarms. For example: fluctuations caused by significant variations in the activity concentration of radon progeny or the ambient dose rate. In this case, the value of K can be adjusted, at larger values, empirically according to the actual situations encountered.

This detection alarm level S0 (see Figure 11) is then given by

$$S0 = K \cdot u(0) = c_{\min} \tag{63}$$

which corresponds to the minimum detectable activity concentration $c_{\min}$ and its associated coverage intervals for a given probability $(1-\gamma)$.

The lower limit of the coverage interval $c_{\min}^{\triangleleft}$ and the upper limit of the coverage interval $c_{\min}^{\triangleright}$ are provided by:

$$c_{\min}^{\triangleleft} = c_{\min} - k_{1-\frac{\gamma}{2}} \cdot u(c_{\min}) \tag{64}$$

and

$$c_{\min}^{\triangleright} = c_{\min} + k_{1-\frac{\gamma}{2}} \cdot u(c_{\min}) \tag{65}$$

In order to be alerted when a measurement is likely to exceed the value of a chosen PME, an alarm level S1 can be set up. The value L1 of the PME is then the upper limit of the coverage interval for a given probability $(1-\gamma)$ of the activity concentration measurement corresponding to S1 (see Figure 11). Then S1 is set up according to

$$S1 = L1 - k_{1-\frac{\gamma}{2}} \cdot u(S1) \tag{66}$$

Table 8 — Alarm setup parameter *K* and its associated false alarm rate *X*

K	*X* %
1,282	10
1,645	5
1,960	2,5
2,327	1
3,091	0,1
3,720	0,01
4,267	0,001
4,756	0,000 1
5,203	0,000 01
K alarm setup parameter *X* false alarm rate, in %	

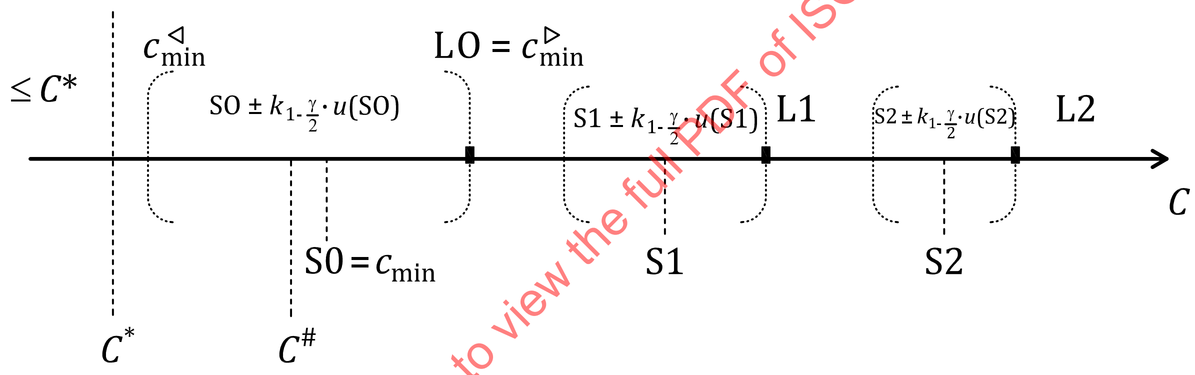
The minimum value of L0 of the PME (see Figure 11) that can be chosen with an acceptable false alarm rate corresponds to the upper limit of the coverage interval for a given probability (1−γ) of the activity concentration measurement corresponding to S0, which is

$$\mathrm{L0}=\mathrm{S0}+k_{1-\frac{\gamma}{2}}\cdot u(\mathrm{S0})=c_{\min}^{\triangleright} \qquad (67)$$

In order to be alerted when a measurement is likely to exceed the guideline or legal limit an alarm level S2 can be set up. The value L2 of the guideline or legal limit is then the upper limit of the coverage interval for a given probability (1−γ) of the activity concentration measurement corresponding to S2 (see Figure 11). Then S2 is set up according to

$$\mathrm{S2}=\mathrm{L2}-k_{1-\frac{\gamma}{2}}\cdot u(\mathrm{S1}) \qquad (68)$$

NOTE 2 Formulae (66) and (68) can be solved with the help of Formulae (40) or (61), either by iteration or by solving explicitly a second degree equation. The use of the Formula (40) assumes, in all cases, that $r_{j-1}=r_0$, which is wrong because in case of a constant atmospheric contamination r_{j-1} increases over time (see Figure 10). However it can be admitted, as a first approximation, that this assumption is true for a duration, of the same order of magnitude of the response time, after the beginning of the rejection.



Key

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}
S0	detection alarm level value related to an acceptable level of false alarm rate
$c_{\min}$	minimum detectable activity concentration, in Bq·m^{-3}
$\left[\mathrm{S0}\pm k_{1-\frac{\gamma}{2}}\cdot u(\mathrm{S0})\right]$	range of minimum detectable activity concentration for a given probability (1−γ)
L0	minimum value of the PME that can be chosen with an acceptable false alarm rate
$c_{\min}^{\triangleleft}$	lower limit of the coverage interval of $c_{\min}$ for a given probability (1−γ)
$c_{\min}^{\triangleright}$	upper limit of the coverage interval of $c_{\min}$ for a given probability (1−γ)
S1	alarm level value related to the chosen value L1 of the PME
L1	chosen value the PME
S2	alarm level value related to the guideline or legal concentration value L2
L2	guideline or legal concentration value

Figure 11 — Characteristic limits, alarms setup, minimum detectable activity concentration and PME

Annex A
(informative)

Numerical example of gross beta emitting activity concentration measurement on fixed filter

A.1 Description

This type of beta aerosol CAM measures the beta activity concentration of particles in the air with radon and thoron background compensation.

The air is drawn into the instrument by an external pump, and the air particles are deposited on the fixed filter. A silicon detector measures the beta radioactivity deposited on the fixed filter.

This type of generally mobile device can be used for monitoring dismantling work to be alerted in a reasonably short time when contamination levels exceed the limits of use of personal protective equipment.

A.2 CAM Parameters

Table A.1 — Parameters of the used CAM

Quantity	Value	Estimated standard uncertainty	Unit
t_c	600	Neglected	s
t_I	600	Neglected	s
ε_D	0,230[a]	0,007	$s^{-1}\cdot Bq^{-1}$
q	5,36 E-4	2,68 E-5	$m^3\cdot s^{-1}$
δ	1	0,05	
DAC	1 244[b]	Not applicable	$Bq\cdot m^{-3}$
$w=\frac{1}{\varepsilon_D \cdot q \cdot t_I \cdot \delta}$ [c]	13,52	1,04	$Bq\cdot m^{-3}\cdot s$

[a] ^{137}Cs.

[b] The dose coefficient for inhalation of ^{137}Cs at the workplace is assumed to be 6,7 E-9 $Sv\cdot Bq^{-1}$. Assuming that in one year there are 2 000 h, that the breathing rate of a worker is 1,2 $m^3\cdot h^{-1}$ and the annual effective dose limit for a worker is 20 mSv then $DAC=\frac{20\text{ E-3}}{1,2\cdot 2\,000\cdot 6,7\text{ E}-9}=1\,244\text{ Bq}\times m^{-3}$.

[c] Long half-life radionuclide evaluation model.

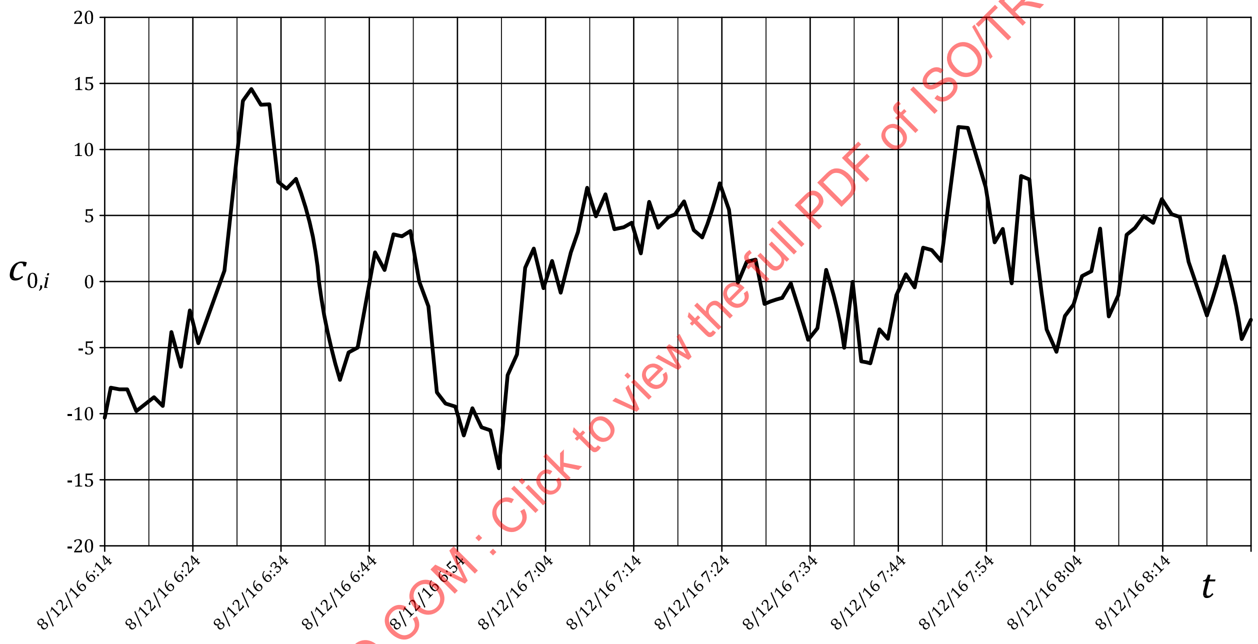
A.3 Measurement results in the absence of the activity concentration to be monitored in a given radiological background ambient level

Table A.2 — Measurement results of background measurements (n = 120)

Date/Time	$c_{0,i}$ in Bq·m^{-3}	Date/Time	$c_{0,i}$ in Bq·m^{-3}	Date/Time	$c_{0,i}$ in Bq·m^{-3}	Date/Time	$c_{0,i}$ in Bq·m^{-3}
08/12/2016 06:20	−8,69	08/12/2016 06:50	−0,11	08/12/2016 07:20	6,14	08/12/2016 07:50	6,79
08/12/2016 06:21	−9,40	08/12/2016 06:51	−1,88	08/12/2016 07:21	3,89	08/12/2016 07:51	11,69
08/12/2016 06:22	−3,74	08/12/2016 06:52	−8,38	08/12/2016 07:22	3,36	08/12/2016 07:52	11,62
08/12/2016 06:23	−6,40	08/12/2016 06:53	−9,23	08/12/2016 07:23	5,16	08/12/2016 07:53	9,53
08/12/2016 06:24	−2,16	08/12/2016 06:54	−9,40	08/12/2016 07:24	7,51	08/12/2016 07:54	7,42
08/12/2016 06:25	−4,64	08/12/2016 06:55	−11,66	08/12/2016 07:25	5,47	08/12/2016 07:55	3,00
08/12/2016 06:26	−2,68	08/12/2016 06:56	−9,51	08/12/2016 07:26	−0,07	08/12/2016 07:56	4,07
08/12/2016 06:27	−1,11	08/12/2016 06:57	−11,04	08/12/2016 07:27	1,54	08/12/2016 07:57	−0,09
08/12/2016 06:28	0,91	08/12/2016 06:58	−11,21	08/12/2016 07:28	1,73	08/12/2016 07:58	7,99
08/12/2016 06:29	6,84	08/12/2016 06:59	−14,08	08/12/2016 07:29	−1,66	08/12/2016 07:59	7,72
08/12/2016 06:30	13,64	08/12/2016 07:00	−7,07	08/12/2016 07:30	−1,40	08/12/2016 08:00	1,11
08/12/2016 06:31	14,62	08/12/2016 07:01	−5,48	08/12/2016 07:31	−1,21	08/12/2016 08:01	−3,59
08/12/2016 06:32	13,42	08/12/2016 07:02	1,14	08/12/2016 07:32	−0,14	08/12/2016 08:02	−5,32
08/12/2016 06:33	13,44	08/12/2016 07:03	2,60	08/12/2016 07:33	−2,17	08/12/2016 08:03	−2,59
08/12/2016 06:34	7,53	08/12/2016 07:04	−0,59	08/12/2016 07:34	−4,38	08/12/2016 08:04	−1,77
08/12/2016 06:35	7,03	08/12/2016 07:05	1,63	08/12/2016 07:35	−3,51	08/12/2016 08:05	0,47
08/12/2016 06:36	7,79	08/12/2016 07:06	−0,85	08/12/2016 07:36	0,91	08/12/2016 08:06	0,76
08/12/2016 06:37	5,98	08/12/2016 07:07	2,00	08/12/2016 07:37	−1,06	08/12/2016 08:07	4,07
08/12/2016 06:38	3,33	08/12/2016 07:08	4,00	08/12/2016 07:38	−4,91	08/12/2016 08:08	−2,55
08/12/2016 06:39	−1,67	08/12/2016 07:09	7,16	08/12/2016 07:39	−0,13	08/12/2016 08:09	−1,04
08/12/2016 06:40	−4,99	08/12/2016 07:10	4,86	08/12/2016 07:40	−6,02	08/12/2016 08:10	3,57
08/12/2016 06:41	−7,48	08/12/2016 07:11	6,63	08/12/2016 07:41	−6,19	08/12/2016 08:11	4,10
08/12/2016 06:42	−5,31	08/12/2016 07:12	3,96	08/12/2016 07:42	−3,56	08/12/2016 08:12	4,98
08/12/2016 06:43	−4,96	08/12/2016 07:13	4,08	08/12/2016 07:43	−4,37	08/12/2016 08:13	4,42

Table A.2 *(continued)*

Date/Time	$c_{0,i}$ in Bq·m⁻³	Date/Time	$c_{0,i}$ in Bq·m⁻³	Date/Time	$c_{0,i}$ in Bq·m⁻³	Date/Time	$c_{0,i}$ in Bq·m⁻³
08/12/2016 06:44	−1,45	08/12/2016 07:14	4,49	08/12/2016 07:44	−1,05	08/12/2016 08:14	6,27
08/12/2016 06:45	2,30	08/12/2016 07:15	2,13	08/12/2016 07:45	0,60	08/12/2016 08:15	5,12
08/12/2016 06:46	0,85	08/12/2016 07:16	6,03	08/12/2016 07:46	−0,45	08/12/2016 08:16	4,89
08/12/2016 06:47	3,57	08/12/2016 07:17	4,06	08/12/2016 07:47	2,62	08/12/2016 08:17	1,54
08/12/2016 06:48	3,43	08/12/2016 07:18	4,79	08/12/2016 07:48	2,43	08/12/2016 08:18	−0,27
08/12/2016 06:49	3,83	08/12/2016 07:19	5,15	08/12/2016 07:49	1,60	08/12/2016 08:19	−2,51



Key

t time, in day (DD)/month (MM)/year (YY)- hour (hh):minute (mm)

$c_{0,i}$ activity concentration of *i* gross measurements representing the background situation, in Bq·m⁻³

Figure A.1 — Illustration of the measurement results of background measurements

A.4 Monitoring requirements

Table A.3 — Requirements

Quantity	Value	Unit
Guideline value (L2)	100[a]	DAC
PME (L1)	50	DAC
[a] Maximum limit of use of personal protective equipment.		

A.5 Performance

Table A.4 — Performance

Quantity	Value	Unit
t_R [a]	15,5[e]	min
$\overline{c_0}$ [b]	0,83	$Bq \cdot m^{-3}$
c^* [c]	11,3[f]	$Bq \cdot m^{-3}$
$c^\#$ [d]	23,2[f]	$Bq \cdot m^{-3}$

a See Table 3.

b Formula (45).

c Formula (49).

d Formula (51).

e $t_C = t_I = 10$ min .

f $k_{1-\alpha} = k_{1-\beta} = k = 1,96$.
with $\alpha = \beta = 2,5\,\%$.

A.6 Alarms setup and minimum detectable activity concentration

There is a measurement every second which means there are daily 86 400 output data and if the alarm is set up at the decision threshold level, 2 160 false alarms per day (2,5 % of 86 400) can be expected which is not acceptable.

In order to avoid that situation the detection alarm level is set up with $K = 5$ to obtain a far less than one false alarm per day (see Table 8).

Table A.5 — Values for the alarm setup and minimum detectable activity concentration

Quantity	Value	Unit
Detection alarm level set up value with an acceptable false alarm rate = minimum detectable activity concentration: $S0 = c_{min}$ [a]	29 2,4 E-2	Bq·m^{-3} DAC
Lower limit of the coverage interval of c_{min} for a given probability (1−γ): $c_{min}^{\triangleleft}$ [e, g]	17 1,37 E-2	Bq·m^{-3} DAC
Upper limit of the coverage interval of c_{min} for a given probability (1−γ): $c_{min}^{\triangleright}$ [f, g]	41 3,3 E-2	Bq·m^{-3} DAC
Minimum value of the PME that can be chosen with an acceptable false alarm rate: $L0 = c_{min}^{\triangleright}$ [b]	41 3,3 E-2	Bq·m^{-3} DAC
Alarm set up value associated to the PME (L1): S1[c]	5,3 E4 43	Bq·m^{-3} DAC
Alarm set up value associated to the guideline value (L2): S2[d]	1,1 E5 87	Bq·m^{-3} DAC

[a] Formula (63).

[b] Formula (67).

[c] Formula (66).

[d] Formula (68)

[e] Formula (64).

[f] Formula (65).

[g] $k_{1-\gamma/2} = 1{,}96$
with γ = 5 % for a probability (1 − γ) = 95 %.

A.7 Discussion

The minimum detectable activity concentration c_{min} of 2,4 E-2 DAC is quite acceptable as it is well below the PME value L1 of 50 DAC and the guideline value L2 of 100 DAC. The associated response time t_R of 15,5 min seems also acceptable.

As there is a lot of margin on c_{min} compared to L2, the values of t_C and t_I can be reduced.

For example if $t_C = t_I$ = 5 min instead of $t_C = t_I$ = 10 min, then according to Formula (43), the corresponding decision threshold c^* as well as c_{min}, are multiplied by the ration $\frac{10\sqrt{10}}{5\sqrt{5}} = 2{,}83$. Then the minimum detectable activity concentration c_{min} becomes 6,8 E-2 DAC which is still quite acceptable with a better corresponding response time t_R of 7,8 min according to Table 3.

Annex B
(informative)

Numerical example of gross alpha emitting activity concentration measurement on moving filter

B.1 Description

This type of beta aerosol CAM measures the alpha activity concentration of particles in the air with radon and thoron background compensation. The air is drawn into the instrument by an external pump, and the air particles are deposited on the moving filter. A silicon detector measures the alpha radioactivity deposited on the moving filter.

This type of CAM is typically used to monitor a very dusty atmosphere that can cause frequent clogging of a fixed filter system.

B.2 Parameters

Table B.1 — Parameters of the used CAM

Quantity	Value	Estimated standard uncertainty	Unit
t_C	600	Neglected	s
t_0	600	Neglected	s
r_0	7	0,11[a]	s^{-1}
$L = D$	2,5 E-2	5,0 E-4	m
v	1,39 E-6	2,78 E-8	$m \cdot s^{-1}$
ε_D	0,2[b]	0,01	$s^{-1} \cdot Bq^{-1}$
q	8,33 E-4	4,17 E-5	$m^3 \cdot s^{-1}$
δ	1	0,05	
$t_T = \frac{L}{v} = \frac{D}{v}$	1,8 E4	5,09 E2	s
$w = \frac{2}{q\,\delta\,\varepsilon_D\,t_T}$ [c]	6,67 E-1	6,1 E-2	$Bq \cdot m^{-3} \cdot s$
$w = \frac{3\pi}{q\,\delta\,\varepsilon_D\,t_T}$ [d]	7,86 E-1	7,2 E-2	$Bq \cdot m^{-3} \cdot s$

[a] $u(r_0) = \sqrt{\frac{r_0}{t_C}}$.

[b] ^{239}Pu.

[c] Rectangular deposition area long half-life radionuclide model of evaluation. Formula (57).

[d] Circular deposition area long half-life radionuclide model of evaluation. Formula (58).

[e] The dose coefficient for inhalation of ^{239}Pu at the workplace is assumed to be 1,6 E-5 $Sv \cdot Bq^{-1}$. Assuming that in one year there are 2 000 h, that the breathing rate of a worker is 1,2 $m^3 \cdot h^{-1}$ and the annual effective dose limit for a worker is 20 mSv then $DAC = \frac{20\text{ E-3}}{1{,}2 \cdot 2\,000 \cdot 1{,}6\text{ E}-5} = 0{,}52\ Bq \times m^{-3}$

Table B.1 *(continued)*

Quantity	Value	Estimated standard uncertainty	Unit
DAC	0,52[e]	Not applicable	$Bq·m^{-3}$

a $u(r_0)=\sqrt{\frac{r_0}{t_C}}$.

b ^{239}Pu.

c Rectangular deposition area long half-life radionuclide model of evaluation. Formula (57).

d Circular deposition area long half-life radionuclide model of evaluation. Formula (58).

e The dose coefficient for inhalation of ^{239}Pu at the workplace is assumed to be 1,6 E-5 $Sv·Bq^{-1}$. Assuming that in one year there are 2 000 h, that the breathing rate of a worker is 1,2 $m^3·h^{-1}$ and the annual effective dose limit for a worker is 20 mSv then $DAC=\frac{20\text{ E-3}}{1,2\cdot 2\,000\cdot 1,6\text{ E}-5}=0,52\text{ Bq}\times\text{m}^{-3}$

B.3 Performance

Table B.2 — Performance

Quantity	Value	Unit
t_R[a]	210[d]	min
c^*[b] (rectangular deposition)	0,2[e]	$Bq·m^{-3}$
c^*[b] (circular deposition)	0,24[e]	$Bq·m^{-3}$
$c^\#$[c] (rectangular deposition)	0,42[e]	$Bq·m^{-3}$
$c^\#$[c] (circular deposition)	0,49[e]	$Bq·m^{-3}$

a See Table 7.

b Formula (62).

c Formula (51).

d $t_C=10\text{ min}$.

$t_T=300\text{ min}$.

e $k=k_{1-\alpha}=k_{1-\beta}=1,96$

with $\alpha=\beta=2,5\,\%$.

B.4 Monitoring requirements

Table B.3 — Requirements

Quantity	Value	Unit
Guideline value (L2)	100[a]	DAC
PME (L1)	50	DAC

a Maximum limit of use of personal protective equipment.

B.5 Alarms setup and minimum detectable activity concentration

There is a measurement every second which means there are daily 86 400 output data and if the alarm is set up at the decision threshold level, 2 160 false alarms per day (2,5 % of 86 400) can be expected which is not acceptable.

In order to avoid that situation the detection alarm level is set up with $K = 5$ to obtain a far less than one false alarm per day (see Table 8).

Table B.4 — Values for the alarm setup and minimum detectable activity concentration in the case of a rectangular deposition area

Quantity	Value	Unit
Detection alarm level set up value with an acceptable false alarm rate = minimum detectable activity concentration: $S0=c_{min}$ [a]	5,1 E-1 9,8 E-1	$Bq·m^{-3}$ DAC
Lower limit of the coverage interval of c_{min} for a given probability (1−γ): $c_{min}^{\triangleleft}$ [e, g]	0,29 0,55	$Bq·m^{-3}$ DAC
Upper limit of the coverage interval of c_{min} for a given probability (1−γ): $c_{min}^{\triangleright}$ [f, g]	0,73 1,4	$Bq·m^{-3}$ DAC
Minimum value of the PME that can be chosen with an acceptable false alarm rate: $L0=c_{min}^{\triangleright}$ [b]	0,73 1,4	$Bq·m^{-3}$ DAC
Alarm set up value associated to the PME (L1): S1[c]	22 42	$Bq·m^{-3}$ DAC
Alarm set up value associated to the guideline value (L2): S2[d]	44 85	$Bq·m^{-3}$ DAC

a Formula (63).

b Formula (67).

c Formula (66).

d Formula (68).

e Formula (64).

f Formula (65).

g $k_{1-\gamma/2} = 1,96$ with γ = 5 % for a probability (1−γ) = 95 %.

Table B.5 — Values for the alarm setup and minimum detectable activity concentration in the case of a circular deposition area

Quantity	Value	Unit
Detection alarm level set up value with an acceptable false alarm rate = minimum detectable activity concentration: $S0 = c_{min}$ [a]	6,0 E-1 1,2	$Bq \cdot m^{-3}$ DAC
Lower limit of the coverage interval of c_{min} for a given probability (1−γ): $c_{min}^{\triangleleft}$ [e, g]	0,34 0,65	$Bq \cdot m^{-3}$ DAC
Upper limit of the coverage interval of c_{min} for a given probability (1−γ): $c_{min}^{\triangleright}$ [f, g]	0,87 1,7	$Bq \cdot m^{-3}$ DAC
Minimum value of the PME that can be chosen with an acceptable false alarm rate: $L0 = c_{min}^{\triangleright}$ [b]	0,87 1,7	$Bq \cdot m^{-3}$ DAC
Alarm set up value associated to the PME (L1): S1[c]	22 42	$Bq \cdot m^{-3}$ DAC
Alarm set up value associated to the guideline value (L2): S2[d]	44 85	$Bq \cdot m^{-3}$ DAC

[a] Formula (63).

[b] Formula (67).

[c] Formula (66).

[d] Formula (68).

[e] Formula (64).

[f] Formula (65).

[g] $k_{1-\gamma/2} = 1{,}96$
with γ = 5 % for a probability (1−γ) = 95 %.

B.6 Discussion

The minimum detectable activity concentrations c_{min} of 0,98 DAC for rectangular deposition and c_{min} of 1,2 DAC for circular deposition are quite acceptable as they are well below the PME value L1 of 50 DAC and the guideline value L2of 100 DAC. On the other hand, the associated response time t_R of 210 min does not seem reasonable.

To reduce the response time t_R to a reasonable value, for example 13,3 min, keeping $t_C = t_0 = 600\,s$ (10 min), Table 7 indicates that the transit time t_T should be then equal to 10 min, which also mean a moving filter speed v of 15 cm per hour.

Then according to (62), the corresponding decision threshold c^*as well as c_{min} are multiplied by the ratio of the transit times $\frac{300\,\text{min}}{10\,\text{min}} = 30$. Then the minimum detectable activity concentrations become 29 DAC for rectangular deposition and 36 DAC for circular deposition which are still acceptable compared to the PME value L1 of 50 DAC and the guideline value L2 of 100 DAC.

Annex C
(informative)

Numerical example of iodine 131 activity concentration gamma spectrometry measurement on fixed charcoal cartridge

C.1 Description

This type CAM measures the activity concentration in the air of the gaseous form of iodine.

The air is drawn into the instrument by an external pump, and the iodine gas is trapped within a fixed charcoal cartridge. A scintillator NaI type measures the iodine radioactivity deposited within the charcoal cartridge.

This type of CAM is used to monitor workplaces where there is a risk of radioactive iodine dispersion in gaseous form, in order to alert workers without personal protective equipment in a reasonably short time in case of an unexpected release.

C.2 CAM Parameters

Table C.1 — Parameters of the used CAM

Quantity	Value	Estimated standard uncertainty	Unit
t_c	600	Neglected	s
t_I	600	Neglected	s
r_0	0,4	0,026[a]	s^{-1}
ε_D	0,04[b]	0,002	$s^{-1} \cdot Bq^{-1}$
q	1,67 E-3	8,35 E-5	$m^3 \cdot s^{-1}$
δ	1	0,05	
$w = \frac{1}{\varepsilon_D \cdot q \cdot t_I \cdot \delta}$ [c]	24,95	2,16	$Bq \cdot m^{-3} \cdot s$
DAC	555[d]	Not applicable	$Bq \cdot m^{-3}$

[a] $u(r_0) = \sqrt{\frac{r_0}{t_c}}$.

[b] ^{131}I.

[c] Long half-life radionuclide evaluation model.

[d] The dose coefficient for inhalation of ^{131}I (organic form) at the workplace is assumed to be 1,5 E-8 $Sv \cdot Bq^{-1}$. Assuming that in one year there are 2 000 h, that the breathing rate of a worker is 1,2 $m^3 \cdot h^{-1}$ and the annual effective dose limit for a worker is 20 mSv then $DAC = \frac{20\ E\text{-}3}{1,2 \cdot 2\,000 \cdot 1,5\ E-8} = 555\ Bq \times m^{-3}$.

C.3 Performance

Table C.2 — Performance

Quantity	Value	Unit
t_R[a]	15,5[d]	min
c^*[b]	1,8[e]	$Bq·m^{-3}$
	3,2 E-3	DAC
$c^\#$[c]	3,8[e]	$Bq·m^{-3}$
	6,9 E-3	DAC

[a] See Table 3.

[b] Formula (49).

[c] Formula (51).

[d] $t_C = t_I = 10 \text{ min}$.

[e] $k = k_{1-\alpha} = k_{1-\beta} = 1{,}96$ with $\alpha = \beta = 2{,}5\ \%$.

C.4 Monitoring requirements

Table C.3 — Requirements

Quantity	Value	Unit
Legal value (L2)	1[a]	DAC
PME (L1)	0,1	DAC

[a] Maximum level of concentration allowed in the area.

C.5 Alarms setup and minimum detectable activity concentration

There is a measurement every second which means there are daily 86 400 output data and if the alarm is set up at the decision threshold level, 2 160 false alarms per day (2,5 % of 86 400) can be expected which is not acceptable.

In order to avoid that situation, the detection alarm level is set up with K = 5 to obtain a far less than one false alarm per day (see Table 8).

