TECHNICAL REPORT

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# Evaluating the performance of continuous air monitors —

## Part 2:
## Air monitors based on flow-through sampling techniques without accumulation

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

*Partie 2: Moniteurs d'air basés sur des techniques d'échantillonnage par circulation sans 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.

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# 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 flow-through sampling techniques without accumulation.



# Evaluating the performance of continuous air monitors —

## Part 2: Air monitors based on flow-through sampling techniques without accumulation

## 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 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.

This document describes

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

— the determination of the characteristic limits (decision threshold, detection limit, limits of the coverage interval), and

— a possible way to determine the minimum detectable activity concentration and the alarms setup.

Finally 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 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*

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*



## 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 https://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 $\alpha$.

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$^3$·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, $\beta$, 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 concentration**
time-integrated activity concentration or activity concentration measurements and their associated coverage intervals for a given probability $(1-\gamma)$ corresponding to the first 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

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).

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

## 4 Symbols

| | |
|---|---|
| $a(t)$ | Activity going through the detection volume at a time $t$, in Bq |
| $c$ | Activity concentration, in Bq·m$^{-3}$ |
| $c_{ac}$ | Actual 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 $(1-\gamma)$, in Bq·m$^{-3}$ |
| $c^{\triangleright}$ | Upper limit of the coverage interval of the activity concentration for a given probability $(1-\gamma)$, in Bq·m$^{-3}$ |
| $c(t)$ | Activity concentration measured at a time $t$, in Bq·m$^{-3}$ |
| $c_{\mathrm{ac}}(t)$ | Actual activity concentration measured at a time $t$, in Bq·m$^{-3}$ |
| $c_{\mathrm{g}}$ | Gross primary measurement of the activity concentration, in Bq·m$^{-3}$ |
| $c_{\min}$ | 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 $(1-\gamma)$, in Bq·m$^{-3}$ |
| $c_{\min}^{\triangleright}$ | Upper limit of the coverage interval the minimum detectable activity concentration for a given probability $(1-\gamma)$, in Bq·m$^{-3}$ |
| $c_{0,i}$ | Activity concentration of the $i^{\mathrm{th}}$ 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$^{-3}$ |



| | |
|---|---|
| $I_{min}$ | Minimum amount of current registered by the measuring detector (with $I_{min}=\frac{Q_{min}}{t_C}$ in A |
| $I_{min,cd}$ | Minimum amount of current registered by the compensating detector (with $I_{min,cd}=\frac{Q_{min,cd}}{t_{C,cd}}$), in A |
| $I_g(t)$ | Instantaneous gross current of the measuring detector at a time $t$, in A |
| $I_g(t,t_C), I_g$ | Gross current during the counting time $t_C$ of the measuring detector at a time $t$, in A |
| $I_{g,cd}(t)$ | Instantaneous gross current of the compensating detector at a time $t$, in A |
| $I_{g,cd}(t,t_{C,cd}), I_{g,cd}$ | Gross current during the counting time $t_{C,cd}$ of the compensating detector at a time $t$, in A |
| $I_0$ | Background current of the measuring detector, in A |
| $I_{0,cd}$ | Background current of the compensating detector, in A |
| $K$ | 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 ($1-\alpha$), dimensionless |
| $k_{1-\beta}$ | Quantile of a standard normal distribution for a probability ($1-\beta$), dimensionless |
| $k_{1-\frac{\gamma}{2}}$ | Quantile of a standard normal distribution for a probability $\left(1-\frac{\gamma}{2}\right)$, dimensionless |
| $N$ | Number of atoms on the media filter, dimensionless |
| $n_g(t,t_C)$ | Gross count during the counting time $t_C$ of the measuring detector at a time $t$, dimensionless |
| $Q_{min}$ | Minimum amount of electric charge that induces a pulse registered by the measuring detector, in C |
| $Q_{min,cd}$ | Minimum amount of electric charge that induces a pulse registered by the compensating detector, in C |
| $q$ | Flow rate, in $m^3 \cdot s^{-1}$ |
| $r_g(t)$ | Instantaneous gross count rate of the measuring detector at a time $t$, in $s^{-1}$ |
| $r_g(t,t_C), r_g$ | Gross count rate during the counting time $t_C$ of the measuring detector at a time $t$, in $s^{-1}$ |
| $r_{g,cd}(t)$ | Instantaneous gross count rate of the compensating detector at a time $t$, in $s^{-1}$ |
| $r_{g,cd}(t,t_{C,cd}), r_{g,cd}$ | Gross count rate during the counting time $t_{C,cd}$ of the compensating detector at a time $t$, in $s^{-1}$ |
| $r_0$ | Background count rate of the measuring detector, in $s^{-1}$ |
| $r_{0,cd}$ | Background count rate of the compensating detector, in $s^{-1}$ |
| $s_0$ | Standard deviation of the activity concentration at a series of $i$ measurements which represent a background situation |



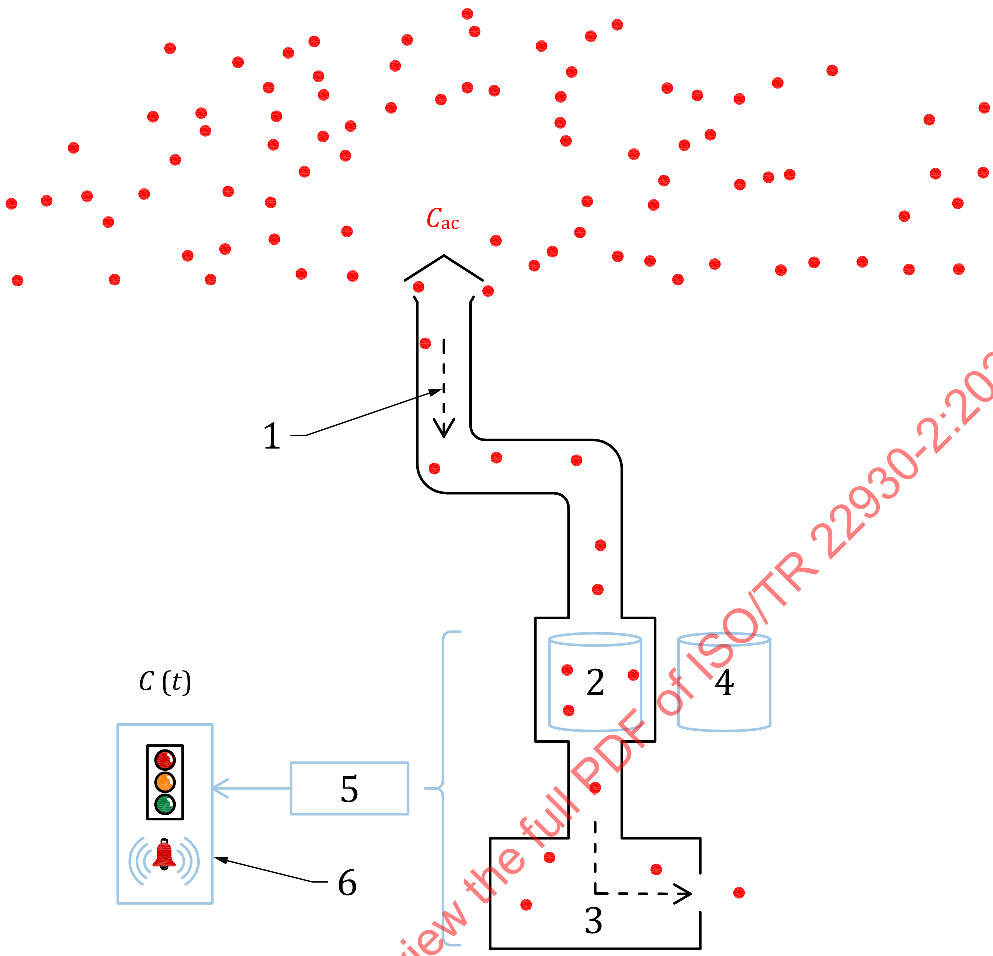
| | |
|---|---|
| $t_C$ | Counting time of the measuring detector, in s |
| $t_{C,cd}$ | Counting time of the compensating detector, in s |
| $t_F$ | Duration of airborne release, in s |
| $t_R$ | Response time, in s |
| $t_{RI}$ | Intrinsic response time, in s |
| $t_0$ | Counting time of the measuring detector for background measurement, in s |
| $t_{0,\,cd}$ | Counting time of the compensating detector for background measurement, in s |
| $t_{1/2}$ | Half-life, in s |
| $V$ | Detection volume, in $m^3$ |
| $w$ | Calibration factor, in $Bq \cdot m^{-3} \cdot s$ or $Bq \cdot m^{-3} \cdot A^{-1}$ |
| $\delta$ | Correction factor related to sampling (sampling point representativity, radioactive decay, ...), dimensionless |
| $\varepsilon_D$ | Detector efficiency, in $Bq^{-1} \cdot s^{-1}$ or $A \cdot Bq^{-1}$ |
| $\lambda$ | Decay constant, in $s^{-1}$ |

## 5 Measuring principle

A representative sample of ambient air to be monitored containing an activity concentration $c_{ac}(t)$ at a time t is continuously captured through a transport line then goes through a detection volume without being retained. In parallel, a detector continuously measures the activity going through the detection volume. Then a processing algorithm calculates the activity concentration $c(t)$ and the suited alarms on the basis of the evolution of the activity going through the detection volume of air sampled and the installation or not of an ambient compensating detector. The processing algorithm can also, if necessary, take into account influence quantities 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 Study of dynamic behaviour

This clause 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 $t_R$ 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 activity going through the detection volume, the renewal rate of the detection volume 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 $t_F$:

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

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

The differential equations describing the number of atoms $N$ of the radionuclide considered in the detection volume of the detector can be formulated as a function of the concentration $c_{ac}$ at the sampling point according to the following relationships:

$$\frac{dN(t)}{dt}=\frac{q\,\delta\,C_{ac}}{\lambda}-\lambda N(t)-\frac{N(t)\,q}{V} \qquad \text{when } 0 \leq t < t_F \qquad (3)$$

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

and

$$\frac{dN(t)}{dt}=-\lambda N(t)-\frac{N(t)\,q}{V} \qquad \text{when } t \geq t_F \qquad (4)$$

Moreover, the evolution of the activity present in the detection volume is given by the relationship

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

NOTE 2 The detector efficiency $\varepsilon_D$ is supposed to be constant meaning that at any time the activity is distributed uniformly throughout the detection volume.

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

$$r_g(t)-r_0=\varepsilon_D\,\lambda N(t)=\frac{\varepsilon_D\,q\,\delta\,c_{ac}}{\lambda+\frac{q}{V}}\left[1-e^{-\left(\lambda+\frac{q}{V}\right)t}\right] \qquad \text{when } 0 \leq t < t_F \qquad (6)$$

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

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

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

When an ionization detector is used, instead of the count rate, the current may be the output. Then the model of evaluation of the activity concentration becomes to

$$c(t)=\frac{\lambda+\frac{q}{V}}{\varepsilon_D\,\delta\,q}\left[I_g(t)-I_0\right] \qquad (9)$$



with

$$c(t)=c_{ac}\left[1-e^{-\left(\lambda+\frac{q}{V}\right)t}\right] \quad \text{when } 0\le t<t_F \tag{10}$$

$$c(t)=c_{ac}\left[1-e^{-\left(\lambda+\frac{q}{V}\right)t_F}\right]e^{-\left(\lambda+\frac{q}{V}\right)(t-t_F)} \quad \text{when } t\ge t_F \tag{11}$$

The evolution of the ratio of the activity concentration and the actual one according to Formula (10) by considering an infinite duration release ($t_F \to \infty$) is given in Table 1.

**Table 1 — Evolution of the ratio $\frac{c(t)}{c_{ac}(t)}$ of the measured activity concentration and the actual one according to Formula (10)**

| Ratio<br>% | Time<br>s |
|---|---|
| 0 | 0 |
| 50 | $\frac{0,69}{\lambda+\frac{q}{V}}$ |
| 90 | $\frac{2,3}{\lambda+\frac{q}{V}} \sim t_{RI}$ |
| 95 | $\frac{3}{\lambda+\frac{q}{V}}$ |
| 99 | $\frac{4,61}{\lambda+\frac{q}{V}}$ |
| 99,9 | $\frac{6,91}{\lambda+\frac{q}{V}}$ |

Table 1 shows that, according to Formula (10), the higher the detection volume renewal rate $\frac{q}{V}$ the better the intrinsic response time $t_{RI}$ is.

The evolutions of the activity concentration $c(t)$ as defined in Formulae (10) and (11) assume that the gross count rate $r_g(t)$ 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 therefore the following relationships are obtained:

a) when $0<t\le t_C$:

$$r_g(t,t_C)-r_0=\frac{1}{t_C}\int_0^t\left[r_g(t)-r_0\right]dt=\frac{\varepsilon_D\, q\,\delta\, c_{ac}}{t_C\left(\lambda+\frac{q}{V}\right)}\left[t+\frac{e^{-\left(\lambda+\frac{q}{V}\right)t}-1}{\lambda+\frac{q}{V}}\right] \tag{12}$$

b) when $t_C<t\le t_F$:

$$r_g(t,t_C)-r_0=\frac{1}{t_C}\int_{t-t_C}^{t}\left[r_g(t)-r_0\right]dt=\frac{\varepsilon_D\, q\,\delta\, c_{ac}}{\lambda+\frac{q}{V}}\left[1+\frac{1-e^{-\left(\lambda+\frac{q}{V}\right)t_C}}{t_C\left(\lambda+\frac{q}{V}\right)}e^{-\left(\lambda+\frac{q}{V}\right)t}\right] \tag{13}$$

c) when $t_F<t\le(t_F+t_C)$ and $t_C\le t_F$:

$$r_g(t,t_C)-r_0=\frac{1}{t_C}\int_{t-t_C}^{t_F}\left[r_g(t)-r_0\right]dt+\frac{1}{t_C}\int_{t_F}^{t}\left[r_g(t)-r_0\right]dt=$$

$$=\frac{\varepsilon_D\, q\,\delta\, c_{ac}}{t_C\left(\lambda+\frac{q}{V}\right)}\left\{t_F-t+t_C+\frac{e^{-\left(\lambda+\frac{q}{V}\right)t_F}-e^{-\left(\lambda+\frac{q}{V}\right)(t-t_C)}}{\lambda+\frac{q}{V}}+\frac{1-e^{-\left(\lambda+\frac{q}{V}\right)t_F}}{\lambda+\frac{q}{V}}\left[1-e^{-\left(\lambda+\frac{q}{V}\right)(t-t_F)}\right]\right\} \tag{14}$$

d) when $t_F<t\le t_C$:

$$r_g(t,t_C)-r_0=\frac{1}{t_C}\int_{0}^{t_F}\left[r_g(t)-r_0\right]dt+\frac{1}{t_C}\int_{t_F}^{t}\left[r_g(t)-r_0\right]dt=$$

$$=\frac{\varepsilon_D\, q\,\delta\, c_{ac}}{t_C\left(\lambda+\frac{q}{V}\right)}\left\{t_F+\frac{e^{-\left(\lambda+\frac{q}{V}\right)t_F}-1}{\lambda+\frac{q}{V}}+\frac{1-e^{-\left(\lambda+\frac{q}{V}\right)t_F}}{\lambda+\frac{q}{V}}\left[1-e^{-\left(\lambda+\frac{q}{V}\right)(t-t_F)}\right]\right\} \tag{15}$$

e) when $t_C<t\le(t_C+t_F)$ and $t_C>t_F$:

$$r_g(t,t_C)-r_0=\frac{1}{t_C}\int_{t-t_C}^{t_F}\left[r_g(t)-r_0\right]dt+\frac{1}{t_C}\int_{t_F}^{t}\left[r_g(t)-r_0\right]dt=$$

$$=\frac{\varepsilon_D\, q\,\delta\, c_{ac}}{t_C\left(\lambda+\frac{q}{V}\right)}\left\{t_F+t_C-t+\frac{e^{-\left(\lambda+\frac{q}{V}\right)t_F}-e^{-\left(\lambda+\frac{q}{V}\right)(t-t_C)}}{\lambda+\frac{q}{V}}+\frac{1-e^{-\left(\lambda+\frac{q}{V}\right)t_F}}{\lambda+\frac{q}{V}}\left[1-e^{-\left(\lambda+\frac{q}{V}\right)(t-t_F)}\right]\right\} \tag{16}$$

f) when $t>(t_C+t_F)$:

$$r_g(t,t_C)-r_0=\frac{1}{t_C}\int_{t-t_C}^{t_F}\left[r_g(t)-r_0\right]dt=$$

$$=\frac{\varepsilon_D\, q\,\delta\, c_{ac}}{t_C\left(\lambda+\frac{q}{V}\right)^2}\left[1-e^{-\left(\lambda+\frac{q}{V}\right)t_F}\right]\left[e^{\left(\lambda+\frac{q}{V}\right)t_C}-1\right]e^{-\left(\lambda+\frac{q}{V}\right)(t-t_F)} \tag{17}$$

Taking account of the counting time $t_C$ the model of evaluation of the activity concentration given in the Formulae (10) and (11) becomes:

$$c(t)=\frac{\lambda+\frac{q}{V}}{\varepsilon_D\, q\, \delta}\left[r_g(t,t_C)-r_0\right] \tag{18}$$

The use of Formulae (12) to (17) applied to Formula (18) makes it possible to quantify the dynamic behaviour of the evaluation model in all release conditions knowing $\lambda$ (or $t_{1/2}$), $\frac{q}{V}$ and $t_C$ and so to determine the corresponding response time $t_R$. Table 2 gives the response time for the measurement of the activity concentration as a function of the detection volume renewal rate $\frac{q}{V}$ plus decay constant $\lambda$ and the counting time $t_C$. An example of use of Table 2 is given in the Annexes A and B.

**Table 2 — Response time $t_R$ of the model of evaluation of activity concentration as a function of the detection volume renewal rate $\frac{q}{V}$ plus decay constant $\lambda$ and the counting time $t_C$**

| $t_C$ | $\lambda+\frac{q}{V}$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1 h⁻¹** | **5 h⁻¹** | **10 h⁻¹** | **20 h⁻¹** | **50 h⁻¹** | **100 h⁻¹** | **200 h⁻¹** | **300 h⁻¹** | **400 h⁻¹** | **500 h⁻¹** | **600 h⁻¹** |
| **1 s** | 137,9 min | 27,6 min | 13,8 min | 6,9 min | 2,8 min | 1,4 min | 42 s | 28 s | 21 s | 17 s | 12 s |
| **10 s** | 138,2 min | 27,7 min | 13,9 min | 7,0 min | 2,9 min | 1,5 min | 47 s | 33 s | 26 s | 22 s | 18 s |
| **30 s** | 138,4 min | 27,9 min | 14,1 min | 7,2 min | 3,0 min | 1,7 min | 59 s | 46 s | 39 s | 36 s | 33 s |
| **1 min** | 138,4 min | 28,1 min | 14,3 min | 7,4 min | 3,3 min | 2,0 min | 1,3 min | 1,1 min | 1,1 min | 1,0 min | 1,0 min |
| **5 min** | 140,4 min | 30,2 min | 16,5 min | 9,7 min | 6,0 min | 5,1 min | 4,8 min | 4,7 min | 4,7 min | 4,6 min | 4,6 min |
| **10 min** | 142,9 min | 32,9 min | 19,5 min | 13,2 min | 10,2 min | 9,6 min | 9,3 min | 9,2 min | 9,2 min | 9,1 min | 9,1 min |
| **20 min** | 148,1 min | 38,9 min | 26,4 min | 21,2 min | 19,2 min | 18,6 min | 18,3 min | 18,2 min | 18,2 min | 18,1 min | 18,1 min |
| **30 min** | 153,5 min | 45,6 min | 34,1 min | 30,0 min | 28,2 min | 27,6 min | 27,3 min | 27,2 min | 27,2 min | 27,1 min | 27,1 min |
| **40 min** | 159,0 min | 52,7 min | 42,4 min | 39,0 min | 37,2 min | 36,6 min | 36,3 min | 36,2 min | 36,1 min | 36,1 min | 36,1 min |
| **50 min** | 164,6 min | 60,3 min | 51,1 min | 48,0 min | 46,2 min | 45,6 min | 45,3 min | 45,2 min | 45,1 min | 45,1 min | 45,1 min |
| **60 min** | 170,4 min | 68,2 min | 60,0 min | 57,0 min | 55,2 min | 54,6 min | 54,3 min | 54,2 min | 54,1 min | 54,1 min | 54,1 min |
| NOTE In most cases $\lambda \ll \frac{q}{V}$, then the response time is mainly due to the detection volume renewal rate $\frac{q}{V}$. | | | | | | | | | | | |

When an ionization detector is used, instead of count rate, current may be the output then the model of evaluation of the activity concentration becomes

$$c(t)=\frac{\lambda+\frac{q}{V}}{\varepsilon_D\, q\, \delta}\left[I_g(t,t_C)-I_0\right] \tag{19}$$

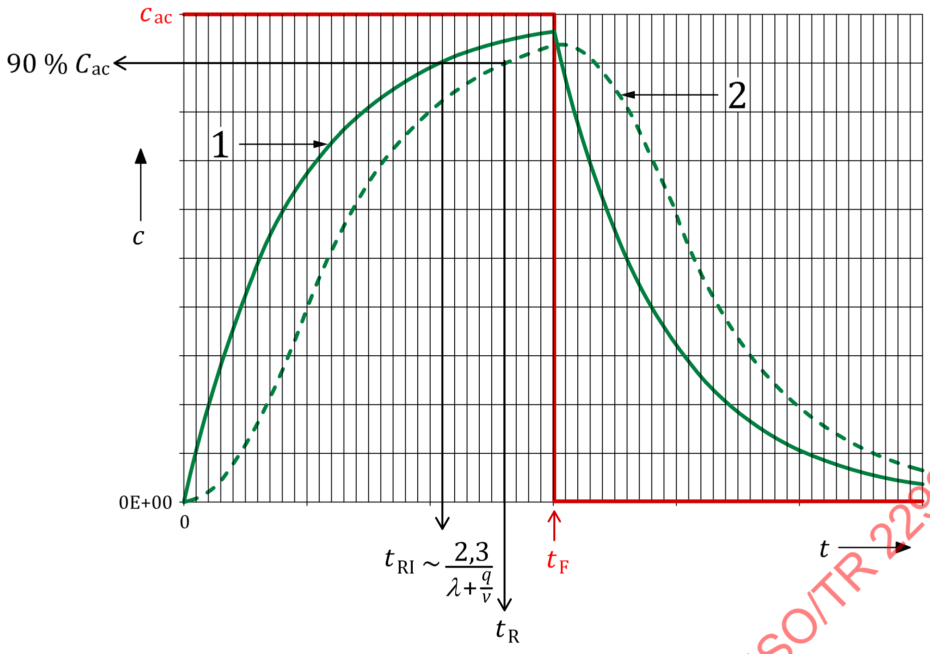
The relation between the count rate $r$ and the current $I$ is given by

$$I=r\cdot Q \tag{20}$$

Figure 2 shows shift between Formula (8) respectively Formula (9) displayed by curve 1 and Formula (18) respectively Formula (19) displayed by curve 2 because of the counting time $t_C$ which adds an additional delay to the intrinsic response time $t_{RI}$.






**Key**

$t$ time, in s

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

1 activity concentration calculated according to Formula (8) respectively Formula (9)

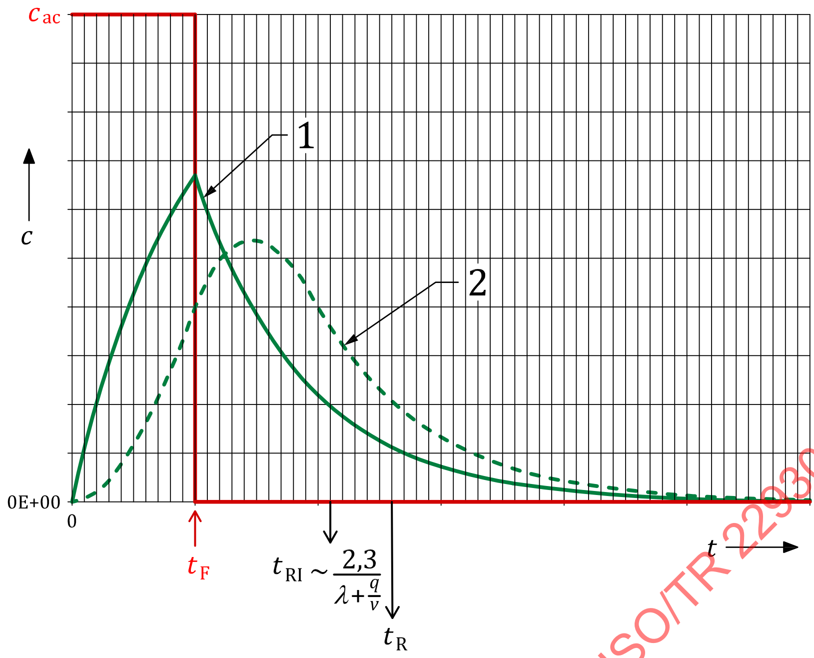
2 activity concentration calculated according to Formula (18) respectively Formula (19)

**Figure 2 — Response time of the model of evaluation**

Figure 3 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 $t_R$ is too long compared to the brief duration of release $t_F$.






**Key**

$t$ time, in s

$c$ activity concentration, in $Bq \cdot m^{-3}$

1 activity concentration calculated according to Formula (8) respectively Formula (9)

2 activity concentration calculated according to Formula (18) respectively Formula (19)

**Figure 3 — Dynamic behaviour of the model of evaluation in case of puff release**

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:

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

## 7 Evaluation of the characteristic limits

### 7.1 General

Direct measurements in real time use most of the time complex systems of processing data (processing algorithm, etc.) protected by copyrights. The certification tests of such equipment are usually carried out in test laboratories with well-defined test conditions which does not necessarily reflect the environment in which the device is used and particularly the fluctuations of natural radioactivity and the radiological environment.

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.

### 7.2 Single detector

#### 7.2.1 General

The measuring principle is given in Figure 1 without the compensating detector.



### 7.2.2 Definition of the model

From the models of evaluation given in Formulae (18) and (19) and considering for simplification that

$r_g(t,t_C)\to r_g$,

$I_g(t,t_C)\to I_g$,

$c(t)\to c$ and

$$w=\frac{\lambda+\frac{q}{V}}{\varepsilon_D\, q\,\delta}$$

the following Formulae for the activity concentration $c$ can be obtained:

a) for the count rate mode: $c=(r_g-r_0)\cdot w$ (21)

b) for the current mode: $c=(I_g-I_0)\cdot w$ (22)

### 7.2.3 Standard uncertainty

a) For the count rate mode, the standard uncertainty can be written as:

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

Assuming that $u^2(r_g)=\frac{r_g}{t_C}$, the Formula above can be transformed:

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

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

This leads to the standard uncertainty $u(c)$ given in Formula (23):

$$u^2(c)=\frac{c\cdot w}{t_C}+u^2(0)+c^2\cdot\frac{u^2(w)}{w^2} \qquad (23)$$

b) For the current mode, the standard uncertainty can be written as:



$$u^2(c) = \left(\frac{\partial c}{\partial I_g}\right)^2 \cdot u^2(I_g) + \left(\frac{\partial c}{\partial I_0}\right)^2 \cdot u^2(I_0) + \left(\frac{\partial c}{\partial w}\right)^2 \cdot u^2(w)$$

from Formula (20):

$$u^2(I_g) = \left(\frac{\partial I_g}{\partial r_g}\right)^2 \cdot u^2(r_g) + \left(\frac{\partial I_g}{\partial Q_{min}}\right)^2 \cdot u^2(Q_{min})$$

And assuming that $u(Q) \sim 0$,

$$u^2(I_g) = \left(\frac{\partial I_g}{\partial r_g}\right)^2 \cdot u^2(r_g) = Q_{min}{}^2 \cdot \frac{r_g}{t_C} = \frac{Q_{min}}{t_C} \cdot I_g = I_{min} \cdot I_g$$

NOTE Usually the parameter $I_{min} = \frac{Q_{min}}{t_C}$ is given by the manufacturer of the ionization detector.

Then the following transformations in regard to the standard uncertainty $u(c)$ can be done:

$$u^2(c) = I_{min} \cdot I_g \cdot w^2 + w^2 \cdot u^2(I_0) + c^2 \cdot \frac{u^2(w)}{w^2} = \left[I_{min} \cdot I_g + u^2(I_0)\right] \cdot w^2 + c^2 \cdot \frac{u^2(w)}{w^2} =$$

$$= \left[I_{min} \cdot \left(\frac{c}{w} + I_0\right) + u^2(I_0)\right] \cdot w^2 + c^2 \cdot \frac{u^2(w)}{w^2} =$$

$$= c \cdot w \cdot I_{min} + \left[I_{min} \cdot I_0 + u^2(I_0)\right] \cdot w^2 + c^2 \cdot \frac{u^2(w)}{w^2}$$

The standard uncertainty $u(c)$ can be written according to Formula (24):

$$u^2(c) = c \cdot w \cdot I_{min} + u^2(0) + c^2 \cdot \frac{u^2(w)}{w^2} \tag{24}$$

### 7.2.4 Decision threshold

The decision threshold $c^*$ is given, for both modes, by the expression

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

Regarding $c = 0$ the decision threshold

a) for the count rate mode is:

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

$$c^* = k_{1-\alpha} \cdot w \cdot \sqrt{\frac{r_0}{t_C} + u^2(r_0)} = k_{1-\alpha} \cdot w \cdot \sqrt{r_0 \cdot \left(\frac{1}{t_C} + \frac{1}{t_0}\right)} \tag{25}$$

NOTE 1 If $t_0 = t_C$ then $c^* = k_{1-\alpha} \cdot w \cdot \sqrt{2 \cdot \frac{r_0}{t_C}}$.

NOTE 2 If $t_0 \gg t_C$ or if $r_0$ are mean values determined experimentally from such a number of observations that $u^2(r_0) \ll \frac{r_0}{t_C}$, then the decision threshold can be expressed as $c^* = k_{1-\alpha} \cdot w \cdot \sqrt{\frac{r_0}{t_C}}$.

b) for the current mode is:

$$u^2(0)=\left[I_{\min}\cdot I_0+u^2(I_0)\right]\cdot w^2$$

$$c^*=k_{1-\alpha}\cdot w\cdot\sqrt{I_{\min}\cdot I_0+u^2(I_0)}=k_{1-\alpha}\cdot w\cdot\sqrt{I_0\cdot\left(\frac{Q_{\min}}{t_C}+\frac{Q_{\min}}{t_0}\right)} \tag{26}$$

NOTE 3 If $\frac{Q_{\min}}{t_0}=\frac{Q_{\min}}{t_c}$, then $c^*=k_{1-\alpha}\cdot w\cdot\sqrt{2\cdot I_{\min}\cdot I_0}$.

NOTE 4 If $\frac{Q_{\min}}{t_0}\gg\frac{Q_{\min}}{t_c}$ or if $I_0$ are mean values determined experimentally from such a number of observations that $u^2(I_0)\ll I_{\min}\cdot I_0$, then the decision threshold can be expressed as $c^*=k_{1-\alpha}\cdot w\cdot\sqrt{I_{\min}\cdot I_0}$.

However, in some cases, $r_0$ or $I_0$ are not explicitly known. In that situation, the only data the user may have is directly the estimate of the activity concentration *c*.

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" instantaneous situation at a time *t*. Then the activity concentration at a time *t* is given by the expression

$$c=c_g-\overline{c_0} \tag{27}$$

with

$$\overline{c_0}=\frac{1}{n}\cdot\sum_{i=1}^{n}c_{0,i} \tag{28}$$

and the standard deviation

$$s_o=\sqrt{\frac{1}{n-1}\cdot\sum_{i=1}^{n}\left(c_{0,i}-\overline{c_0}\right)^2} \tag{29}$$

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 [1] the arithmetic means $\overline{c_0}$ is the best estimate and the standard uncertainties associated with $\overline{c_0}$ is

$$u\left(\overline{c_0}\right)=\left(\frac{n-1}{n-3}\right)^{1/2}\cdot\frac{s_0}{\sqrt{n}} \qquad \text{with } n\geq 4 \tag{30}$$

Then

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

$u^2(c_g)=s_0^2$ then

$$u^2(0) = s_0^2 + u^2(\overline{c_0}) = s_0^2 \left[1 + \frac{n-1}{n \cdot (n-3)}\right] \quad (31)$$

And the decision threshold is given by

$$c^* = k_{1-\alpha} \cdot s_0 \cdot \sqrt{1 + \frac{n-1}{n \cdot (n-3)}} \quad (32)$$

NOTE 5 The determination of the decision threshold according to Formula (32) implies checking periodically that there is not significant variation of $s_0$.

### 7.2.5 Detection limit

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

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

With $k = k_{1-\alpha} = k_{1-\beta}$ and under the condition $k^2 \cdot \frac{u^2(w)}{w^2} < 1$, the detection limit $c^\#$ is

a) for the count rate mode: $$c^\# = \frac{2 \cdot c^* + \frac{k^2 \cdot w}{t_C}}{1 - k^2 \cdot \frac{u^2(w)}{w^2}} \quad (33)$$

b) for the current mode: $$c^\# = \frac{2 \cdot c^* + k^2 \cdot I_{min} \cdot w}{1 - k^2 \cdot \frac{u^2(w)}{w^2}} \quad (34)$$

Otherwise the measurement method is not adapted.

### 7.2.6 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:

$$c^\triangleleft = c - k_{1-\frac{\gamma}{2}} \cdot u(c) \quad (35)$$

and

$$c^\triangleright = c + k_{1-\frac{\gamma}{2}} \cdot u(c) \quad (36)$$

NOTE The determination of $c$ according to Formula (27) implies to check periodically that there is not significant variation of $\overline{c_0}$.

## 7.3 Double detector

### 7.3.1 General

The measuring principle is given in Figure 1 with the compensating detector.

### 7.3.2 Definition of the model

Considering for simplification that

$r_g(t,t_C) \rightarrow r_g$, $\quad r_{g,cd}(t,t_{C,cd}) \rightarrow r_{g,cd}$,

$I_g(t,t_C) \rightarrow I_g$ $\quad I_{g,cd}(t,t_{C,cd}) \rightarrow I_{g,cd}$

$c(t) \rightarrow c$ and

$$w = \frac{\lambda + \frac{q}{V}}{\varepsilon_D \, q \, \delta}$$

the following Formulae for the activity concentration $c$ can be obtained:

a) for the count rate mode: $c = \left[\left(r_g - r_{g,cd}\right) - \left(r_0 - r_{0,cd}\right)\right] \cdot w$ (37)

b) for the current mode: $c = \left[\left(I_g - I_{g,cd}\right) - \left(I_0 - I_{0,cd}\right)\right] \cdot w$ (38)

### 7.3.3 Standard uncertainty

a) For the count rate mode, the standard uncertainty $u(c)$ can be written as:

$$u^2(c) = \left(\frac{\partial c}{\partial r_g}\right)^2 \cdot u^2(r_g) + \left(\frac{\partial c}{\partial r_{g,cd}}\right)^2 \cdot u^2(r_{g,cd}) + \left(\frac{\partial c}{\partial r_0}\right)^2 \cdot u^2(r_0) + \left(\frac{\partial c}{\partial r_{0,cd}}\right)^2 \cdot u^2(r_{0,cd}) + \left(\frac{\partial c}{\partial w}\right)^2 \cdot u^2(w)$$

Assuming that $u^2(r_g) = \frac{r_g}{t_C}$ and $u^2(r_{g,cd}) = \frac{r_{g,cd}}{t_{C,cd}}$, the Formula above can be transformed into:

$$u^2(c) = \frac{c \cdot w}{t_C} + \left[ r_{g,cd} \cdot \left(\frac{1}{t_C} + \frac{1}{t_{C,cd}}\right) + \frac{r_0 - r_{0,cd}}{t_C} + u^2(r_0) + u^2(r_{0,cd}) \right] \cdot w^2 + c^2 \cdot \frac{u^2(w)}{w^2}$$

This leads to the standard uncertainty $u(c)$ given in Formula (39):

$$u^2(c) = \frac{c \cdot w}{t_C} + u^2(0) + c^2 \cdot \frac{u^2(w)}{w^2} \tag{39}$$

b) For the current mode, the standard uncertainty can be written as:

$$u^2(c) = \left(\frac{\partial c}{\partial I_g}\right)^2 \cdot u^2(I_g) + \left(\frac{\partial c}{\partial I_{g,cd}}\right)^2 \cdot u^2(I_{g,cd}) + \left(\frac{\partial c}{\partial I_0}\right)^2 \cdot u^2(I_0) + \left(\frac{\partial c}{\partial I_{0,cd}}\right)^2 \cdot u^2(I_{0,cd}) + \left(\frac{\partial c}{\partial w}\right)^2 \cdot u^2(w)$$

Knowing that $u^2(I_g) = I_{min} \cdot I_g$ with $I_{min} = \frac{Q_{min}}{t_C}$ and $u^2(I_{g,cd}) = I_{min,cd} \cdot I_{g,cd}$ with $I_{min,cd} = \frac{Q_{min,cd}}{t_{C,cd}}$. Then the following transformations in regard to the standard uncertainty $u(c)$ can be done:

$$u^2(c) = I_{min} \cdot I_g \cdot w^2 + I_{min,cd} \cdot I_{g,cd} \cdot w^2 + w^2 \cdot u^2(I_0) + w^2 \cdot u^2(I_{0,cd}) + c^2 \cdot \frac{u^2(w)}{w^2} =$$

$$= w^2 \cdot I_{min} \cdot \left(\frac{c}{w} + I_{g,cd} + I_0 - I_{0,cd}\right) + I_{min,cd} \cdot I_{g,cd} \cdot w^2 + w^2 \cdot u^2(I_0) + w^2 \cdot u^2(I_{0,cd}) + c^2 \cdot \frac{u^2(w)}{w^2} =$$



$$=w\cdot I_{\min}\cdot c+w^2\cdot\left[I_{\min}\cdot\left(I_0-I_{0,\mathrm{cd}}\right)+\left(I_{\min}+I_{\min,\mathrm{cd}}\right)\cdot I_{\mathrm{g,cd}}\right]+w^2\cdot\left[u^2\left(I_0\right)+u^2\left(I_{0,\mathrm{cd}}\right)\right]+c^2\cdot\frac{u^2(w)}{w^2}$$

The standard uncertainty $u(c)$ can be written according to Formula (40):

$$u^2(c)=c\cdot w\cdot I_{\min}+u^2(0)+c^2\cdot\frac{u^2(w)}{w^2} \tag{40}$$

### 7.3.4 Decision threshold

The decision threshold $c^*$ is given, for both modes, by the expression

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

Regarding $c=0$, the decision threshold

a) for the count rate mode is:

$$u^2(0)=\left[\frac{r_0-r_{0,\mathrm{cd}}}{t_\mathrm{C}}+r_{\mathrm{g,cd}}\cdot\left(\frac{1}{t_\mathrm{C}}+\frac{1}{t_{\mathrm{C,cd}}}\right)+u^2\left(r_0\right)+u^2\left(r_{0,\mathrm{cd}}\right)\right]\cdot w^2$$

$$c^*=k_{1-\alpha}\cdot w\cdot\sqrt{\frac{r_0-r_{0,\mathrm{cd}}}{t_\mathrm{C}}+r_{\mathrm{g,cd}}\cdot\left(\frac{1}{t_\mathrm{C}}+\frac{1}{t_{\mathrm{C,cd}}}\right)+u^2\left(r_0\right)+u^2\left(r_{0,\mathrm{cd}}\right)} \tag{41}$$

NOTE 1 If $r_0$ and $r_{0,\mathrm{cd}}$ are mean values determined experimentally from such a number of observations that, $\left[u^2\left(r_0\right)+u^2\left(r_{0,\mathrm{cd}}\right)\right]\ll\left[r_{\mathrm{g,cd}}\cdot\left(\frac{1}{t_\mathrm{C}}+\frac{1}{t_{\mathrm{C,cd}}}\right)+\frac{r_0-r_{0,\mathrm{cd}}}{t_\mathrm{C}}\right]$ then the decision threshold can be expressed as: $c^*=k_{1-\alpha}\cdot w\cdot\sqrt{\frac{r_0-r_{0,\mathrm{cd}}}{t_\mathrm{C}}+r_{\mathrm{g,cd}}\cdot\left(\frac{1}{t_\mathrm{C}}+\frac{1}{t_{\mathrm{C,cd}}}\right)}$.

NOTE 2 Formula (41) shows that the decision threshold $c^*$ varies according to $r_{\mathrm{g,cd}}$ which represent the ambient level in the absence of the phenomenon to be measured.

b) for the current mode is:

$$u^2(0)=\left[I_{\min}\cdot\left(I_0-I_{0,\mathrm{cd}}\right)+I_{\mathrm{g,cd}}\cdot\left(I_{\min}+I_{\min,\mathrm{cd}}\right)+u^2\left(I_0\right)+u^2\left(I_{0,\mathrm{cd}}\right)\right]\cdot w^2$$

$$c^*=k_{1-\alpha}\cdot w\cdot\sqrt{I_{\min}\cdot\left(I_0-I_{0,\mathrm{cd}}\right)+I_{\mathrm{g,cd}}\cdot\left(I_{\min}+I_{\min,\mathrm{cd}}\right)+u^2\left(I_0\right)+u^2\left(I_{0,\mathrm{cd}}\right)} \tag{42}$$

NOTE 3 If $I_0$ and $I_{0,\mathrm{cd}}$ are mean values determined experimentally from such a number of observations that $\left[u^2\left(I_0\right)+u^2\left(I_{0,\mathrm{cd}}\right)\right]\ll\left[I_{\min}\cdot\left(I_0+I_{0,\mathrm{cd}}\right)+I_{\mathrm{g,cd}}\cdot\left(I_{\min}+I_{\min,\mathrm{cd}}\right)\right]$, then the decision threshold can be expressed as: $c^*=k_{1-\alpha}\cdot w\cdot\sqrt{I_{\min}\cdot\left(I_0-I_{0,\mathrm{cd}}\right)+I_{\mathrm{g,cd}}\cdot\left(I_{\min}+I_{\min,\mathrm{cd}}\right)}$.

NOTE 4 Formula (42) shows that the decision threshold $c^*$ varies according to $I_{\mathrm{g,cd}}$ which represent the ambient level in the absence of the phenomenon to be measured.

However in some cases, $r_0$, $r_{0,cd}$ and $r_{g,cd}$ respectively $I_0$, $I_{0,cd}$ are not explicitly known. In that situation, the only data the user may have is the displayed activity concentration *c*. In those situations, Formulae (27) to (32) apply.

NOTE 5 The determination of the decision threshold according to Formula (32) implies checking periodically that there is not significant variation of $s_0$.

### 7.3.5 Detection limit

The detection limit $c^{\#}$ can be calculated in the same way as described in 7.2.5, then Formula (34) still applies.

### 7.3.6 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−*γ*).

The lower limit of the coverage interval $c^{\triangleleft}$ and the upper limit of the coverage interval $c^{\triangleright}$ can be calculated in the same way as described in 7.2.6, then Formulae (35) and (36) still apply.

NOTE The determination of *c* according to Formula (27) implies to check periodically that there is not significant variation of $\overline{c_0}$.

## 8 Alarms setup, minimum detectable concentration and potential missed exposure

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 3.

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 (if not the object of measurement) 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.

**Table 3 — Alarm setup parameter *K* and its associated false alarm rate *X***

| *K* | *X*<br>% |
|---|---|
| 1,282 | 10 |
| 1,645 | 5 |
| 1,960 | 2,5 |
| 2,327 | 1 |
| 3,091 | 0,1 |
| 3,720 | 0,01 |

*K* Alarm setup parameter.
*X* False alarm rate, in %.



**Table 3** *(continued)*

| $K$ | $X$<br>% |
|---|---|
| 4,267 | 0,001 |
| 4,756 | 0,000 1 |
| 5,203 | 0,000 01 |
| $K$ Alarm setup parameter. | |
| $X$ False alarm rate, in %. | |

This detection alarm level (see Figure 4) is then given by

$$S0 = K \cdot u(0) = c_{\min} \quad (43)$$

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:

$$c_{\min}^{\triangleleft} = c_{\min} - k_{1-\frac{\gamma}{2}} \cdot u(c_{\min}) \quad (44)$$

and

$$c_{\min}^{\triangleright} = c_{\min} + k_{1-\frac{\gamma}{2}} \cdot u(c_{\min}) \quad (45)$$

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 4). Then S1 is set up according to

$$S1 = L1 - k_{1-\frac{\gamma}{2}} \cdot u(S1) \quad (46)$$

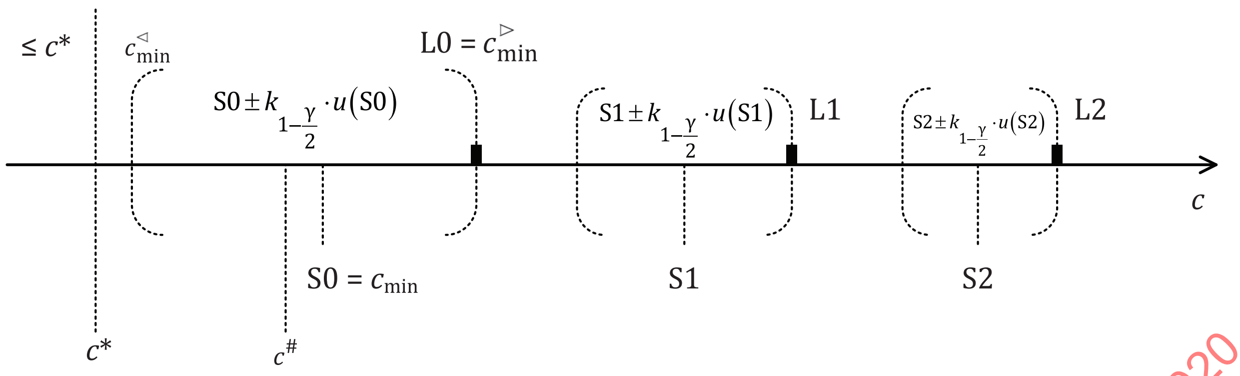
The minimum value of L0 of the PME (see Figure 4) that can be chosen with an acceptable false alarm rate corresponds to the upper limit of the coverage interval for a given probability (1−$\gamma$) of the activity concentration measurement corresponding to S0, which is

$$L0 = S0 + k_{1-\frac{\gamma}{2}} \cdot u(S0) = c_{\min}^{\triangleright} \quad (47)$$

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−$\gamma$) of the activity concentration measurement corresponding to S2 (see Figure 4). Then S2 is set up according to

$$S2 = L2 - k_{1-\frac{\gamma}{2}} \cdot u(S1) \quad (48)$$

NOTE 2 Formulae (46) and (48) can be solved with the help of Formulae (23), (24) or (40), either by iteration or by solving explicitly a second degree equation.




**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$^{-3}$ |
| $\left[S0 \pm k_{1-\frac{\gamma}{2}} \cdot u(S0)\right]$ | range of minimum detectable activity concentration for a given probability $(1-\gamma)$ |
| 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 $(1-\gamma)$ |
| $c_{min}^{\triangleright}$ | upper limit of the coverage interval of $c_{min}$ for a given probability $(1-\gamma)$ |
| 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 4 — Characteristic limits, alarms setup, minimum detectable activity concentration and PME**

# Annex A
(informative)

# Application example: Single detector with a proportional counter

## A.1 Description

This type of CAM measures noble gas activity concentration in the air. After being filtered to remove particles, the air is drawn into the instrument by an external pump and flows through a measuring chamber.

The measuring detector is equipped with one large area proportional counter tubes xenon sealed and surrounded by 2 cm of a lead shield to minimize the background as much as possible and there is no compensation detector.

## A.2 CAM Parameters

**Table A.1 — Parameters of the used CAM**

| Quantity | Value | Estimated uncertainty | Unit |
|---|---|---|---|
| $t_C$ | 600 | Neglected | s |
| $t_0$ | 600 | Neglected | s |
| $r_0$ | 6[a] | 0,1[b] | $s^{-1}$ |
| $V$ | 0,01 | 0,000 57 | $m^3$ |
| $\varepsilon_D$ | 0,028[c] | 0,001 4 | $s^{-1}\cdot Bq^{-1}$ |
| $q$ | 1,11 E-3 | Useless | $m^3\cdot s^{-1}$ |
| $\delta$ | 1 | 0,05 | |
| $\lambda$ | 2,05 E-9[c] | Neglected | $s^{-1}$ |
| $w=\dfrac{\lambda+\dfrac{q}{V}}{\varepsilon_D\cdot q\cdot\delta}$ | 3 571 | 324 | $Bq\cdot m^{-3}\cdot s^{-1}$ |
| DAC | 1,1 E7[d] | Not applicable | $Bq\cdot m^{-3}$ |

a 2 cm lead shielding.

b $u(r_0)=\sqrt{\dfrac{r_0}{t_0}}$.

c $^{85}Kr$.

d The effective dose rate per unit air concentration of $^{85}Kr$ is equal to 2,2 E-11 $Sv\cdot d^{-1}/(Bq\cdot m^{-3})$ or 2,02 E-12 $Sv\cdot h^{-1}/(Bq\cdot m^{-3})$. Assuming that in one year, there are 2 000 h and the annual effective dose limit for a worker is 20 mSv, then $DAC=\dfrac{20\,E-3}{2\,000\cdot 2{,}02\,E-12}\,Bq\cdot m^{-3}=1{,}1\,E7\,Bq\cdot m^{-3}$.

## A.3 Monitoring requirements

**Table A.2 — Requirements**

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

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

## A.4 Performance

**Table A.3 — Performance**

| Quantity | Value | Unit |
|---|---|---|
| $t_R$ [a] | 9,2[d] | min |
| $c^*$ [b] | 990[e]<br>9,0 E-5 | $Bq \cdot m^{-3}$<br>DAC |
| $c^\#$ [c] | 2 068[e]<br>1,9 E-4 | $Bq \cdot m^{-3}$<br>DAC |

[a] See Table 2.

[b] Formula (25).

[c] Formula (33).

[d] $\lambda + \frac{q}{V} \sim 350\ h^{-1}$ ; $t_C$ = 10 min

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

## A.5 Alarms setup and minimum detectable 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 first alarm level is set up with $K$ = 5 to obtain a far less than one false alarm per day (see Table 3).

**Table A.4 — 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] | 2,5 E3<br>2,3 E-4 | $Bq \cdot m^{-3}$<br>DAC |

[a] Formula (43).

[b] Formula (47).

[c] Formula (46).

[d] Formula (48).

[e] Formula (44).

[f] Formula (45).

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

**Table A.4** *(continued)*

| Quantity | Value | Unit |
|---|---|---|
| Lower limit of the coverage interval of $c_{min}$ for a given probability $(1-\gamma)$: $c^{\triangleleft}_{min}$ [e, g] | 1,4 E3<br>1,3 E-4 | $Bq{\cdot}m^{-3}$<br>DAC |
| Upper limit of the coverage interval of $c_{min}$ for a given probability $(1-\gamma)$: $c^{\triangleright}_{min}$ [f, g] | 3,6 E3<br>3,3 E-4 | $Bq{\cdot}m^{-3}$<br>DAC |
| Minimum value of the PME that can be chosen with an acceptable false alarm rate: $L0=c^{\triangleright}_{min}$ [b] | 3,6 E3<br>3,3 E-4 | $Bq{\cdot}m^{-3}$<br>DAC |
| Alarm set up value associated to the PME (L1): S1[c] | 9,3 E5<br>8,5 E-2 | $Bq{\cdot}m^{-3}$<br>DAC |
| Alarm set up value associated to the legal value (L2): S2[d] | 9,3 E6<br>8,5 E-1 | $Bq{\cdot}m^{-3}$<br>DAC |

[a] Formula (43).

[b] Formula (47).

[c] Formula (46).

[d] Formula (48).

[e] Formula (44).

[f] Formula (45).

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

## A.6 Discussion

The minimum detectable activity concentration $c_{min}$ of 2,3 E-4 DAC is quite acceptable as it is well below the PME value L1 of 0,1 DAC and the guideline value L2 of 1 DAC. The associated response time $t_R$ of 9,2 min seems also acceptable.

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

For example, if $t_C$ is 1 min instead of $t_C$ = 10 min, then according to (25), the corresponding decision threshold $c^*$ as well as $c_{min}$, are multiplied by 2,34. Then the minimum detectable activity concentration $c_{min}$ becomes 5,4 E-4 DAC which is still quite acceptable with a better corresponding response time $t_R$ of 1 min according to Table 2.

# Annex B
(informative)

# Application example: Double detector in current mode

## B.1 Description

This type of CAM measures noble gas activity concentration in the air. After being filtered to remove particles, the air is drawn into the instrument by an external pump and flows through a measuring chamber.

The measuring and the compensation detectors are equipped with the same type of ionization chamber.

## B.2 CAM Parameters

**Table B.1 — Parameters of the used CAM**

| Quantity | Value | Estimated uncertainty | Unit |
|---|---|---|---|
| $t_C$ | 60 | Neglected | s |
| $I_{min} = I_{min,cd}$ [a] | 3 E-18 | Not applicable | A |
| $V$ [a] | 0,000 18 | Not used | m³ |
| $q$ | 5 E-4 | Useless | m³·s⁻¹ |
| $\delta$ | 1 | 0,05 | |
| $\lambda$ | 2,05 E-9[c] | Neglected | s⁻¹ |
| $w = \frac{\lambda + \frac{q}{V}}{\varepsilon_D \cdot q \cdot \delta}$ [b] | 5,2 E19 | 3,7 E18 | Bq·m⁻³·A⁻¹ |
| DAC | 1,1 E7[d] | Not applicable | Bq·m⁻³ |

[a] Applicable to both measuring and the compensating detectors.

[b] $w$ is directly characterized without knowing $\varepsilon_D$ and $V$.

[c] $^{85}Kr$.

[d] The effective dose rate per unit air concentration of $^{85}Kr$ is equal to 2,2 E-11 Sv·d⁻¹/(Bq·m⁻³) or 2,02 E-12 Sv·h⁻¹/(Bq·m⁻³). Assuming that in one year there are 2 000 h and the annual effective dose limit for a worker is 20 mSv, then $\text{DAC} = \frac{20\,\text{E}-3}{2\,000 \cdot 2{,}02\,\text{E}-12}\,\text{Bq}\cdot\text{m}^{-3} = 1{,}1\,\text{E}7\,\text{Bq}\cdot\text{m}^{-3}$.

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

**Table B.2 — Results of background measurements ($i$ = 120)**

| Date/Time | $c_{0,i}$ Bq·m⁻³ | Date/Time | $c_{0,i}$ Bq·m⁻³ | Date/Time | $c_{0,i}$ Bq·m⁻³ | Date/Time | $c_{0,i}$ Bq·m⁻³ |
|---|---|---|---|---|---|---|---|
| 16/11/2016 00:01 | −86 024 | 16/11/2016 00:31 | −82 815 | 16/11/2016 01:01 | −72 197 | 16/11/2016 01:31 | −74 979 |