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Determination of the detection limit and decision threshold for ionizing radiation measurements —

Part 4: Fundamentals and application to measurements by use of linear-scale analogue ratemeters, without the influence of sample treatment

Détermination de la limite de détection et du seuil de décision des mesurages des rayonnements ionisants —

Partie 4: Principes fondamentaux et leur application aux mesurages réalisés à l'aide d'ictomètres analogiques à échelle linéaire, sans l'influence du traitement d'échantillon

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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

Attention is drawn to the possibility that some of the elements of this part of ISO 11929 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 11929-4 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiation protection*.

ISO 11929 consists of the following parts, under the general title *Determination of the detection limit and decision threshold for ionizing radiation measurements*:

— *Part 1: Fundamentals and application to counting measurements without the influence of sample treatment*

— *Part 2: Fundamentals and application to counting measurements with the influence of sample treatment*

— *Part 3: Fundamentals and application to counting measurements by high resolution gamma spectrometry, without the influence of sample treatment*

— *Part 4: Fundamentals and applications to measurements by use of linear-scale analogue ratemeters, without the influence of sample treatment*

— *Part 5: Fundamentals and applications to measurements of aerosols or gaseous or liquid effluents while running*

Annex A of this part of ISO 11929 is for information only.

Introduction

ISO 11929 gives basic information on the statistical principles for determination of the detection limit and decision threshold (and directives for specification of the confidence interval) for nuclear radiation measurements based on the principles defined by Altschuler and Pasternack [1], Nicholson [8], Currie [4].

This part of ISO 11929 applies to linear-scale analogue pulse-rate measurements as they are frequently used in the routine monitoring of clothes, hands, feet, body, surfaces, air filters, working places, desks and other flat materials, wipe-test papers, and other contamination checks in stationary use of equipment and sources. For scanning of surfaces, this measurement can be used when the detector is moved slowly enough for the surface to be measured to remain under the detector area for twice the time constant of the integrating circuit in the equipment.

ISO 11929-1 and ISO 11929-2 deal with integral counting measurements with or without consideration of the sample treatment. Specific problems which occur in case of spectrometric measurements or continuous monitoring of radioactive effluents are covered in ISO 11929-3 and ISO 11929-5.

This part of ISO 11929 deals with ionizing radiation measurements in which events, in particular pulses, are measured using linear-scale analogue ratemeters, without considering the influence of a sample treatment. It considers exclusively the random character of radioactive decay and of pulse-rate counting by use of a linear-scale analogue ratemeter, and ignores other influences (e.g. due to sample treatment, weighting, enrichment, or instability of the equipment). It is based on the assumption that the product of pulse rate and time constant of the meter is sufficient to permit approximation of the real pulse/time distribution by a normal standard distribution, and that dead-time losses are negligible. Wherever activities or specific activities are to be determined, it is assumed that the factors for the conversion of pulse rates into activities or specific activities have been determined with sufficient accuracy to ignore the influence of their uncertainty in the measurement.

This part of ISO 11929 should not be used for ratemeters with cyclic digital counters. In this case, ISO 11929-1 should be applied.

For this purpose, Bayesian statistical methods are used to specify values of statistics characterized by the following given error probabilities.

— The decision threshold, which allows a decision to be made for each measurement with a given probability of error as to whether the registered pulses include a contribution by the sample.

— The detection limit, which specifies the minimum sample contribution which can be detected with a given probability of error using the measuring procedure in question. This consequently allows a decision to be made as to whether a measuring method checked using this part of ISO 11929 satisfies certain requirements and is consequently suitable for the given purpose of measurement.

— The confidence limits, which define a confidence interval of the measurand with a given probability if the measured value exceeds the decision threshold.

NOTE The difference between using the decision threshold and using the detection limit is that measured values are to be compared with the decision threshold while the detection limit is to be compared with the guideline value.

Determination of the detection limit and decision threshold for ionizing radiation measurements —

Part 4: Fundamentals and application to measurements by use of linear-scale analogue ratemeters, without the influence of sample treatment

1 Scope

This part of ISO 11929 specifies suitable statistical values which allow an assessment of the detection capabilities in ionizing radiation measurements, without the influence of sample treatment, using linear-scale analogue ratemeters. For this purpose, statistical methods are used to specify statistical values characterizing given probabilities of error.

2 Terms and definitions

For the purposes of this part of ISO 11929, the following terms and definitions apply.

2.1
linear-scale analogue rate-meter
electronic device whose output increases suddenly with every incoming pulse, and decreases with a given time constant until the next pulse arrives

NOTE The pulses should be of equal electrical charge, and the time constant should be independent of the pulse rate.

2.2
measuring method
use of a linear-scale analogue ratemeter for pulse-rate measurements under specified conditions

2.3
decision threshold
critical value of a statistical test for the decision between the null hypothesis $\rho_\mathrm{s} = \rho_0$ and the alternative hypothesis $\rho_\mathrm{s} > \rho_0$

NOTE It should be the value R_n^* which, when exceeded by the determined value R_n, is taken to indicate that the null hypothesis should be rejected. The statistical test should be designed such that the probability of wrongly rejecting the null hypothesis (error of the first kind) is equal to a value α which is fixed prior to commencement of the measurement.

2.4
detection limit
smallest difference $\rho_n = \rho_\mathrm{s} - \rho_0$ associated with the statistical test concerned for the decision between the null hypothesis $\rho_\mathrm{s} = \rho_0$ and the alternative hypothesis $\rho_\mathrm{s} > \rho_0$ and having the following characteristic: if in reality $\rho_n \geqslant \rho_n^*$, the probability of wrongly not rejecting the null hypothesis $\rho_\mathrm{s} = \rho_0$ (error of the second kind) shall be at most equal to a value β which is fixed prior to commencement of the measurement

2.5
confidence interval
interval for ρ_n to be specified for the measured value obtained for R_n

NOTE This interval includes the true value of ρ_n in at least $(1 - \gamma) \times 100$ % of all cases.

2.6
sample
whole amount or an aliquot of a material, the content of radioactive nuclides of which has to be determined by ionizing radiation measurement

2.7
background effect
measured counting rate without radioactivity of interest in the sample

NOTE This covers radiation caused by external sources and detector noise.

2.8
gross effect
measured counting rate from the sample (sample contribution) and the background radiation

2.9
net effect
⟨sample contribution⟩ gross effect minus the background effect

2.10
guideline value
value which corresponds to scientific, legal or other requirements for which the measuring procedure is intended to assess, for example, as activity, specific activity, surface activity, or dose rate

3 Symbols

R_0 Ratemeter output without sample (background pulse rate)

ρ_0 Expectation value of R_0

R_s Ratemeter output with sample (gross effect pulse rate) R_n

ρ_s Expectation value of R_s

R_n Net counting rate (difference between gross and background pulse rate), $R_n = R_s - R_0$

ρ_n Expectation value of R_n

R_n^* Decision threshold for the net counting rate R_n

ρ_n^* Detection limit for the expectation value of the net counting rate R_n

s^2 Squared standard deviation

δ^2 Expectation value of s^2

α Error of the first kind; the probabilitiy of rejecting the null hypothesis $\rho_s = \rho_0$ for the alternative hypothesis $\rho_s > \rho_0$ when the null hypothesis is true

β Error of the second kind; the probability of accepting the null hypothesis $\rho_s = \rho_0$ against the alternative hypothesis $\rho_s > \rho_0$ when the null hypothesis is false

$1 - \gamma$ Confidence level of the confidence interval for ρ_n

τ Time constant of the ratemeter

τ_0 Time constant for background measurement

τ_s Time constant for sample measurement

$k_{1-\alpha}, k_{1-\beta}, k_{1-\gamma/2}$ Quantiles of the standard normal distribution (see Table 2)

4 Statistical values and confidence interval

4.1 Principles

4.1.1 General aspects

The definition of the statistical values for decision threshold, detection limit and confidence interval are based on the squared standard deviation of the measured results. They are dependent on the squared standard deviation caused by counting statistics. Measurement equipment instability normally can be neglected because usually it is small compared with the other influences. The contribution of counting statistics can be calculated by the Poisson equation in combination with the Campbell theorem [2].

4.1.2 Model

If device instabilities are neglected, the following model may be applied:

$$\rho_n = \rho_s - \rho_0$$

The pulse rate measured without a sample, R_0, is caused by background radiation (external sources and activity in detector and shielding). The gross pulse rate, R_s, measured with a sample is the sum of background counting rate and sample radiation (net counting rate):

$$R_s = R_0 + R_n$$

It is assumed that, for a constant radioactive emission rate and a given time constant, both the number of pulses counted in a measurement of the gross effect, as well as in an independent measurement of the background effect, follow a Poisson distribution. Therefore, the expectation values of the counting rates R_0 and R_s are ρ_0 and $\rho_s = \rho_0 + \rho_n$, and the variances are $s^2(R_0) = \rho_0/2\tau$ and $s^2(R_s) = \rho_s/2\tau$, respectively (Campbell theorem); τ = time constant.

The net counting rate $R_n = (R_s - R_0)$ has the expectation ρ_n and the variance

$$\text{Var}\,(R_n) = \text{Var}\,(R_0) + \text{Var}\,(R_s) \tag{1}$$

For $\rho_n = 0$ this variance is (with $\rho_s = \rho_0$)

$$\text{Var}\,(R_n = 0) = \rho_0 \left(\frac{1}{\tau_0} + \frac{1}{\tau_s} \right)$$

where

τ_0 is the time constant at background-effect measurement;

τ_s is the time constant at gross-effect measurement.

In this case, ρ_0 and ρ_s are unknown parameters.

4.2 Decision threshold

The decision threshold shall refer to the value R_n^* which, when exceeded by a measured net counting rate R_n, is taken to indicate that a sample contribution exists. Otherwise, it should be assumed that there is no sample contribution.

If this decision rule is observed, a wrong decision occurs with the probability α that there is a sample contribution when only a background effect exists (error of the first kind).

The decision threshold is given by

$$R_n^* = k_{1-\alpha}\sqrt{\text{Var}\,(R_n = 0)} = k_{1-\alpha}\sqrt{2s^2\,(R_0)} \tag{2}$$

If R_0 has been measured with higher precision than R_s

$$R_n^* = k_{1-\alpha}\sqrt{s^2\,(R_0)} \tag{3}$$

where $k_{1-\alpha}$ is a factor given in Table 2.

Equations for calculation of the decision threshold are given in Table 1.

4.3 Detection limit

The detection limit, ρ_n^*, refers to the smallest expectation of the net counting rate under given parameters for which a wrong decision occurs with probability β (if the decision rule as specified in 4.2 is applied) that there is no sample contribution but only a background effect (error of the second kind).

To check whether a measuring procedure is suitable for such measurements, the detection limit shall be compared with a specified guideline value (e.g. specified requirements on the sensitivity of the measuring procedure for scientific, legal or other reasons).

So, with α and β, the limit of detection is

$$\rho_n^* = R_n^* + k_{1-\beta}\sqrt{\text{Var}\,(R_n = \rho_n^*)} \tag{4}$$

$$= k_{1-\alpha}\sqrt{\text{Var}\,(R_n = 0)} + k_{1-\beta}\sqrt{\text{Var}\,(R_n = \rho_n^*)} \tag{5}$$

and for $s^2\,(R_n = 0) \approx s^2\,(R_n > 0)$, in most cases due to the high background counting rate of an unshielded detector

$$\rho_n^* = (k_{1-\alpha} + k_{1-\beta})\sqrt{\text{Var}\,(R_n = 0)} \tag{6}$$

If $\alpha = \beta$, the detection limit is

$$\rho_n^* = 2R_n^* \tag{7}$$

where $k_{1-\alpha}$ and $k_{1-\beta}$ are factors given in Table 2.

4.4 Confidence interval

Additional equations are given in Table 1 to assess a confidence interval for each measured value R_n on a specified confidence level $1 - \gamma$. This interval includes the true value of ρ_n in at least $(1 - \gamma) \times 100$ % of all cases.

5 Application of this part of ISO 11929

5.1 Specific values

The error probabilities α, β and the confidence level $1 - \gamma$ shall be specified in advance by the user of this part of ISO 11929. Frequently cited values are $\alpha = \beta =$ 0,05 and $\gamma =$ 0,10. If technically possible, the time constant τ shall be chosen such that the detection limit is below the guideline value.

5.2 Assessment of a measuring method

The decision as to whether a measuring method (2.2) satisfies certain requirements with respect to the detection limit shall be made by comparing the detection limit which has been determined with the specified guideline value (see 4.3).

This can be done either in advance, for the assessment of an intended measuring method on the basis of an experimentally determined background pulse rate by a separate measurement, or retrospectively using the background pulse rate then available from the measurement.

The detection limit can be calculated by means of the equations given in Table 1. If the detection limit thus determined is greater than the guideline value, the measuring procedure is not suitable for the measurement.

NOTE Under certain circumstances, a measuring procedure can be improved, for example, by preselecting an increased time constant, by using a mean pulse rate of multiple readings, by reducing the background effect, by increasing sample quantity or by chemical enrichment of the radioactivity.

5.3 Assessment of measured results

The decision threshold may be calculated by means of the equations in Table 1. A measured result shall be compared with the decision threshold thus obtained (see 4.2).

If a result is greater than the decision threshold, it is assumed to be a real sample contribution.

5.4 Documentation

The record of measurements in accordance with this part of ISO 11929 shall contain details of the error probabilities, the decision threshold and the detection limit. For established sample contributions, confidence intervals determined in accordance with the equations in Table 1 and the confidence level shall also be specified.

6 Figures and tables

Table 1 — Equations for the calculation of statistical values

Decision threshold

$$R_n^* = k_{1-\alpha}\sqrt{\frac{R_0}{\tau}} \tag{8}$$

and if R_0 has been measured with higher precision than R_s in the practical use of equipment

$$R_n^* = k_{1-\alpha}\sqrt{\frac{R_0}{2\tau}} \tag{9}$$

Detection limit

$$\rho_n^* = \left[k_{1-\alpha} + k_{1-\beta}\sqrt{1 + k_{1-\alpha}\sqrt{\frac{1}{\rho_0\tau}} + \frac{k_{1-\beta}^2}{4\rho_0\tau}}\right]\sqrt{\frac{\rho_0}{\tau}} + \frac{k_{1-\beta}^2}{2\tau} \tag{10}$$

Simplified equation if $\alpha = \beta$

$$\rho_n^* = (k_{1-\alpha} + k_{1-\beta})\sqrt{\frac{R_0}{\tau}} \tag{11}$$

and if R_0 has been measured with higher precision than R_s

$$\rho_n^* = (k_{1-\alpha} + k_{1-\beta})\sqrt{\frac{R_0}{2\tau}} \tag{12}$$

Confidence interval

$$R_n - k_{1-\gamma/2}\sqrt{\frac{R_\mathrm{s}}{2\tau}} \leqslant \rho_n \leqslant R_n + k_{1-\gamma/2}\sqrt{\frac{R_\mathrm{s}}{2\tau}} \tag{13}$$

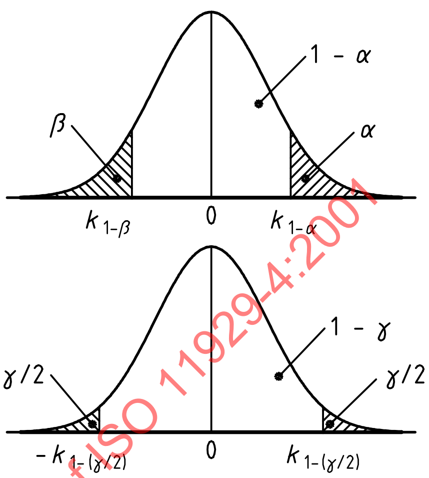
An estimate for ρ_0 is R_0 and for ρ_n it is R_n

NOTE 1 These equations are approximations, becoming more precise as the number $\tau\rho_0$ or τR_0 respectively increases. If the values $\alpha = \beta =$ 0,05 and $\gamma =$ 0,10 as recommended in this part of ISO 11929, and the true value of $\rho_0\tau$ is $\geqslant$ 12, the actual probability of an error of the first kind is nearly 0,057 and the actual probability of an error of the second kind is nearly 0,044 and the confidence probability is greater than 0,944.

NOTE 2 R_0 can be used as an estimate for ρ_0. The degree of approximation of ρ_0 can be improved by using an increased time constant if technically possible using a signal registered over a time gap which is ten times the time constant of the meter, or by using a mean of the results of ten readings of the meter. With smaller values of α, β, γ (e.g. α, $\beta <$ 0,05, $\gamma <$ 0,01), the actual probalities of error may deviate significantly more from the specified values. The user of this part of ISO 11929 should refer to advice given in [3] or his own statistical studies.

Table 2 — Values $k_{1-\alpha}$, $k_{1-\beta}$, $k_{1-\gamma/2}$ as a function of error probabilities α and β or confidence level $1-\gamma$ (quantiles of normal distribution)

Error probability α or β	Confidence level $1-\gamma$	$k_{1-\alpha}$, $k_{1-\beta}$, $k_{1-\gamma/2}$	Minimum $\rho_0\tau$ [a]
0,158 6	0,682	1,000	3 [b]
0,100 0	0,800	1,282	3 [b]
0,050 0	0,900	1,645	12
0,025 0	0,950	1,960	23
0,022 8	0,955	2,000	25
0,010 0	0,980	2,326	40
0,005 0	0,990	2,576	53
0,001 4	0,997	3,000	83
0,001 0	0,998	3,090	86



[a] Using the figures given in column 4, the quantiles of the standardized distribution of the measured results will not differ by more than $\pm$ 5 % from the standard normal distribution.

[b] Due to the correction terms in equation (8), this approximation is valid down to $\rho_0\tau \sim 3$. In the case where the true value of $\rho_0\tau$ is < 3, the approximations are not sufficiently correct. In this case, use of a meter with a cycling working digital counting microprocessor, and the application of ISO 11929-1, are recommended.

Annex A
(informative)

Example of application of this part of ISO 11929

A.1 General

With a time constant set to $\tau = 3$ s, a contamination monitor with a ratemeter shows, after 12 s, a background count rate of $R_0 = 10\ \text{s}^{-1}$ as a mean of ten readings.

A.2 Calculation of the decision threshold

The decision threshold R_n^* can be calculated using equation (8) in Table 1. R_0 will be taken as an estimate for ρ_0. With $\alpha = 0{,}05$, $k_{1-\alpha} = 1{,}645$ (Table 2, row 3), we obtain

$$R_n^* = 1{,}645 \times \sqrt{\frac{10}{3}}$$

which equals to a decision threshold of pulse rate of

$$A\left(R_n^*\right) = 2{,}99\ \text{s}^{-1} \approx 3{,}0\ \text{s}^{-1}$$

If R_0 has been measured with higher precision, it follows that

$$R_n^* = 1{,}645 \times \sqrt{\frac{10}{2 \times 3}}$$

and

$$A\left(R_n^*\right) = 2{,}12\ \text{s}^{-1} \approx 2{,}1\ \text{s}^{-1}$$

With the calibration factor of the meter $\eta = 0{,}29\ \text{s}^{-1}/\text{Bq}$, R_n^* corresponds to 10,3 Bq. So, if the net count rate exceeds 2,1 s^{-1} or the reading is $> \left(R_n^* + R_0\right) = 12{,}1\ \text{s}^{-1}$, a contamination has been detected at an error of the first kind of $\alpha = 5\ \%$.

A.3 Calculation of the detection limit

The detection limit ρ_n^* can be calculated using equations (10) or (11) in Table 1. R_0 will be taken as an estimate for ρ_0. With α or $\beta = 0{,}05$, $k_{1-\alpha}$, $k_{1-\beta} = 1{,}645$ (Table 2, row 3), equation (10) gives

$$\rho_n^* = \left[1{,}645 + 1{,}645 \times \sqrt{1 + 1{,}645 \times \sqrt{\frac{1}{10 \times 3} + \frac{1{,}645^2}{3 \times 4 \times 10}}}\right] \times \sqrt{\frac{10}{3}} + \frac{1{,}645^2}{2 \times 3}$$

$$\rho_n^* = 5{,}96\ \text{s}^{-1} \approx 6{,}0\ \text{s}^{-1}$$

Using the same parameters as above, the simplified equation (11) gives

$$\rho_n^* = 2 \times 1{,}645 \times \sqrt{\frac{10}{3}}$$

