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Statistical criteria for limiting the measurement of radionuclide activity by plastic scintillators

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Abstract

The paper is devoted to the estimation of the characteristic limits (statistical criteria) for the detection of small amounts of ionizing radiation by a measuring device under conditions of a natural radioactivity background of the environment: the decision threshold, the detection limit, the minimum detectable activity and the confidence interval. The assessment procedures were carried out in accordance with the national harmonized standard DSTU ISO 11929-3:2009.

The threshold for making a decision on the presence of ^{137}Cs and ^{60}Co radionuclides in objects of the external environment and the limit of their detection using a measuring device equipped with plastic scintillators manufactured by the Institute of Scintillation Materials of the National Academy of Sciences of Ukraine were estimated. The influence of the energy of the detected radiation, the dimensions of the scintillators and the geometry of the irradiation on the estimation of the characteristic limits were investigated.

Keywords: scintillator; decision threshold; detection limit; confidence interval; minimum detectable activity.

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1. Introduction

This work continues the topic [1] devoted to assessing the capabilities of a measuring device equipped with large plastic scintillators (PS) manufactured by the Institute of Scintillation Materials of the National Academy of Sciences of Ukraine (used in portal monitors) to detect small amounts of ionizing radiation against the background of the environment natural radioactive background. As characteristics that ensure the required accuracy in activity measuring by specific device are the characteristic limits of detection, introduced by Currie in 1968 [2]. These are statistical criteria related to the recorded background level and limiting the measuring device sensitivity: "decision threshold", "detection limit" and "confidence interval limits".

Decision-making threshold is the level of the recorded background (set in advance), above which it can be assumed that the measured sample or the environment contains some radionuclide. The criterion allows deciding on the presence of a physical effect and the need for measuring procedures. The detection limit indicates what the smallest true value of the measured quantity can be detected with a 95% probability using a given measuring device. That is, the criterion characterizes the minimum detectable activity (*MDA*) value of a particular device. Confidence limits include an interval containing the true value of the measured quantity with a probability of 95%. The ISO 11929-3:2000 standard [3] was developed on the base of Currie formulas. The harmonized DSTU ISO 11929-3:2009 [4] is in force in Ukraine. The correct definition of the limitation characteristics is necessary for making decisions on national and international regulations concerning permitted levels of radioactivity in environmental objects [5].

In the previous work, the various factors influence on the statistical and systematic uncertainties of measurement of the radionuclides detection limit (*MDA*) of a measuring device with PS was estimated.

The aim of this work is to obtain the same factors influence estimates on the statistical uncertainty of measuring the decision threshold and the confidence interval limits.

2. Evaluation of statistical criteria according to DSTU ISO 11929-3:2009

The procedure for estimating characteristic limits is based on the use of statistical methods for testing classical hypotheses [6] about the 1st and 2nd kind errors. It is assumed that the Poisson distribution of the impulses appearance probability can be approximated by a Gaussian distribution.

Under this assumption, the decision threshold is the value R_n^* that, if the average measured net (minus the background) pulse count rate R_n is exceeded, it is used as a sign of the activity presence in the object under study. With this definition R_n^*, a false alarm (assuming the presence of a contribution from the object, in the presence the background only) occurs

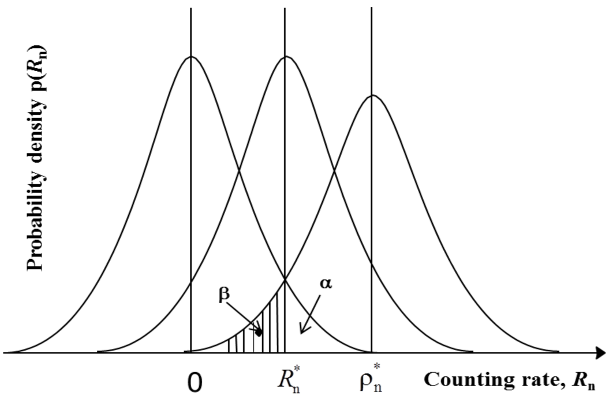

Fig. 1. Decision threshold and detection limit [7]

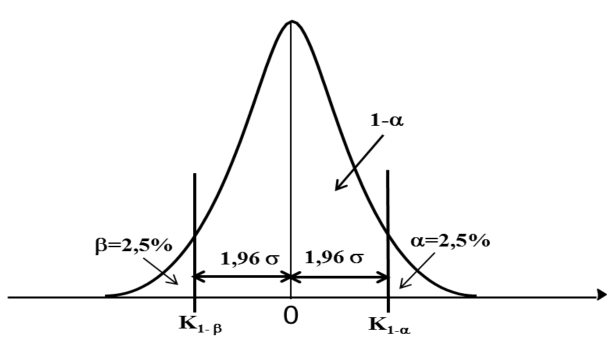

Fig. 2. Confidence interval for the probability P_c = 0.95 [8]

with probability α (error of the 1st kind – accepting background fluctuations as a useful signal).

The detection limit ρ_n^* is defined by [1] as the minimum value of the net pulse rate counting mathematical expectation ρ_n. With this definition ρ_n^*, false negation (the assumed absence of the object's contribution, but the presence of only the background), happens with probability β (error of the 2nd kind – the transmission signal, which is taken as background fluctuation).

Fig. 1 [7] presents the zero level of activity (background) and the levels of the decision threshold and the detection limit with indication of 1st and 2nd kind errors.

The numerical values of the decision threshold and the detection limit were calculated from simplified expressions (1) and (2):

$$R_n^* = (k_{1-\alpha})\sqrt{\frac{2R_0}{t}}, \quad (1)$$

$$\rho_n^* = (k_{1-\alpha} + k_{1-\beta})\sqrt{\frac{2\rho_0}{t}}, \quad (2)$$

where: $k_{1-\alpha}+k_{1-\beta}$ – quantiles of the standard normal distribution equal to 1.96 at a confidence level of P_c=0.95; α and β – probabilities of errors of the 1st or 2nd kind occurrence, equal to 0.025 at P_c = 0.95; R_0 is the background rate of the studied PS, in counts/sec; ρ_0 – mathematical expectation of R_0, in counts/sec; t is the exposure time.

Since the statistical variations in the measured value (pulse count rate or activity) are distributed according to the normal law and are symmetric about the most probable value, the confidence-probability interval for a 95% probability has the form shown in Fig. 2.

The numerical values of the confidence interval limits for ρ_n were calculated by the formula (3):

$$R_n - k_{1-\gamma/2}\sqrt{\frac{R_s}{t}+\frac{R_0}{t}} \le \rho_n \le R_n + k_{1-\gamma/2}\sqrt{\frac{R_s}{t}+\frac{R_0}{t}}, \quad (3)$$

where: R_s is the total counting rate of pulses from the studied PS; $k_{1-\gamma/2}$ – the quantile of the standard normal distribution, equal to 1.96 at a confidence level of P_c = 0.95.

3. Experiment

A general view of scintillators for portal monitors based on PS, a detailed description of the equipment and excitation circuit, as well as the justification for the choice of the indicated distances to the source and exposure time for calculations (t = 1 s) are given in [9]. The sources of gamma radiation ^{137}Cs (A = 99 kBq) and ^{60}Co (A = 32.3 kBq) were used. In the energy range of 20–2000 keV, the values of the total pulse count rate R_s from the PS and the background count rate R_0 were determined at a distance to the source h = 10 cm and h = 50 cm. Based on the data obtained, the values of the net counting rate R_n, the sensitivity coefficients of the setup η, the decision threshold R_n^* and the detection limit ρ_n^* were calculated. The confidence interval for ρ_n was also estimated.

4. Results and discussion

The obtained results of the characteristic limits characterizing the measuring device capabilities estimates are shown in Table 1. For comparison, the same

Table 1

Indicators of characteristic limits and *MDA* of PS

Vol, cm^3	Nuclide	R_s, c/sec	R_0, c/sec	h = 10 cm							R_s, c/sec	h = 50 cm					
				η, c/s×kBq	R_n^*, c/sec	R_n^*, kBq	ρ_n^*, c/sec	*MDA*, kBq	Conf. int., c/sec			η, c/s×kBq	R_n^*, c/sec	R_n^*, kBq	ρ_n^*, c/sec	*MDA*, kBq	Conf. int., c/sec
7500	^{137}Cs	4845	554	43.3	65.2	1.51	130.5	3.01	±144.0		1042	4.9	65.2	13.2	130.5	26.4	±78.3
	^{60}Co	4422	554	119.8	65.2	0.54	130.5	1.08	±138.3		1026	14.6	65.2	4.5	130.5	8.9	±77.9
12500	^{137}Cs	5484	872	47.2	81.9	1.73	163.7	3.47	±156.3		1552	6.9	81.9	11.9	163.7	23.8	±96.5
	^{60}Co	5572	872	145.0	81.9	0.56	163.7	1.13	±157.3		1602	22.8	81.9	3.6	163.7	7.2	±97.5

table shows the *MDA* values obtained by applying the calibration coefficient η to the detection limit.

Table 1 shows that the threshold for making a decision on the presence of ^{137}Cs radionuclide in the environment is 65-82 c/sec (1.5–1.7 kBq) at $h = 10$ cm and 65–82 c/sec (13–12 kBq) at $h = 50$ cm, for measurements with the studied PS. For the ^{60}Co nuclide, this criterion is 65–82 c/sec (0.5–0.6 kBq) at $h = 10$ cm and 65–82 c/sec (4.5–3.6 kBq) at $h = 50$ cm. The values in c/sec of the radionuclides detection limit by the measuring device for similar conditions are two times higher than the decision threshold values. The equivalent values, in kBq, (*MDA*) are for ^{137}Cs – 3.0–3.5 kBq at $h = 10$ cm and 26.4–23.8 kBq at $h = 50$ cm. For ^{60}Co this criterion is 1.1–1.3 kBq at $h = 10$ cm and 8.9–7.2 kBq at $h = 50$ cm.

5. Conclusions

It was found that the main factor influencing the value of the characteristic limits that determine the measuring device sensitivity is the environment background. The investigated measuring setup with a PS with a volume of 7500 cm^3 and 12500 cm^3, under natural background conditions, allows us to assume the presence of ^{137}Cs in objects at a registration level of 1.5–13.2 kBq for distances of 10–50 cm, and the presence of ^{60}Co at a registration level of 0.5–8.9 kBq.

It has been shown that with a probability of 95% one can declare the presence of ^{137}Cs or ^{60}Co in environmental objects at registration levels 2 times higher than the above.

It is shown that the confidence interval of the mathematical expectation of the ^{137}Cs or ^{60}Co net counting rate is R_n ±138–157 c/sec at a distance of 10 cm and R_n ±78–98 c/sec at a distance of 50 cm.

It was found that an increase in the PS volume practically does not give a gain in the results of measuring the characteristic limits, since an increase in the sensitivity coefficient (due to an increased counting rate) is leveled out by a simultaneous increase in the background counting rate.

Статистичні критерії обмеження вимірювання активності радіонуклідів пластмасовими сцинтиляторами

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Анотація

Роботу присвячено оцінюванню характерних меж (статистичних критеріїв) виявлення вимірювальною установкою малих кількостей іонізуючого випромінювання в умовах природного радіоактивного фону навколишнього середовища: порога прийняття рішення (decision threshold), межі виявлення (detection limit), мінімальної детектованої активності та довірчо-ймовірнісного інтервалу (confidence interval). Процедури оцінювання проводилися відповідно до національного гармонізованого стандарту ДСТУ ISO 11929-3:2009.

Проведено оцінки порога прийняття рішення про присутність в об'єктах зовнішнього середовища радіонуклідів ^{137}Cs і ^{60}Co та межі їх виявлення з використанням вимірювальної установки, оснащеної пластмасовими сцинтиляторами, що випускаються Інститутом сцинтиляційних матеріалів Національної академії наук України. Досліджено вплив енергії реєстрованого випромінювання, розмірів сцинтиляторів та геометрії опромінення на оцінку характерних меж.

Оцінювалися характерні межі виявлення при зміні розміру сцинтилятора від 500×300×50 мм (7500 см^3) до 500×500×50 мм (12500 см^3), зміні енергії реєстрованого випромінювання від 662 кеВ (^{137}Cs) до 1332 кеВ (^{60}Co) та зміні відстані від сцинтилятора до гамма-джерела від 10 до 50 см. Вимірювання чистої швидкості рахунку імпульсів та фонової швидкості сцинтиляторів проводилися в інтервалі енергій 20–2000 кеВ.

Показано, що основним чинником, який впливає на величину характерних меж, що визначають чутливість вимірювальної установки, є фон навколишнього середовища. Тому значення характерних меж, в імп/с, не залежать від зміни реєстрованої енергії та відстані до гамма-джерела, але злегка залежать від розміру сцинтилятора. Значення порога прийняття рішення для різних розмірів сцинтиляторів становлять 65–82 імп/с. Значення межі виявлення в два рази вище – 130,5–163,7 імп/с.

Ключові слова: сцинтилятор; поріг ухвалення рішення; межа виявлення; довірчий інтервал; мінімальна детектована активність.

Статистические критерии ограничения измерения активности радионуклидов пластмассовыми сцинтилляторами

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Аннотация

Работа посвящена оцениванию характерных пределов (статистических критериев) обнаружения измерительной установкой малых количеств ионизирующего излучения в условиях естественного радиоактивного фона окружающей среды: порога принятия решения (decision threshold), предела обнаружения (detection limit), минимальной детектируемой активности и доверительно-вероятностного интервала (confidence interval). Процедуры оценивания проводились в соответствии с национальным гармонизированным стандартом ДСТУ ISO 11929-3:2009.

Проведены оценки порога принятия решения о присутствии в объектах внешней среды радионуклидов ^{137}Cs и ^{60}Co и предела их обнаружения с использованием измерительной установки, оснащенной пластмассовыми сцинтилляторами, выпускаемыми Институтом сцинтилляционных материалов Национальной академии наук Украины. Исследовано влияние энергии регистрируемого излучения, размеров сцинтилляторов и геометрии облучения на оценку характерных пределов.

Ключевые слова: сцинтиллятор; порог принятия решения; предел обнаружения; доверительный интервал; минимальная детектируемая активность.

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