Development of a method for automatic compensation of energy dependence of the sensitivity

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Abstract. One of the main tasks of radiation safety is to determine the degree of exposure to ionizing radiation (IR) on a substance and a person, due to the exposure dose (ED) and the power of the exposure dose (PED). The solution of this problem imposes certain requirements for the accuracy of measurements, which is numerically represented as the calculation of absolute and relative error. The paper analyzes the normative documents regulating the accuracy of ED and PED determination, and calculates the components of measurement error.

1. Introduction
Until recently, the level of gamma radiation was taken to be measured by means of measurement of exposure dose or the exposure dose. Currently, in accordance with the recommendations of commissions of various levels, gamma radiation levels are measured by the absorbed or equivalent dose [1]. Previously, it was pointed out that the specifics of measuring gamma radiation is a large error due to the energy dependence of sensitivity (EDS) due to unaccounted systematic errors in practical measurements [2].

For dosimetric control devices in accordance with GOST 14337-87 [3] in force on the territory of the Russian Federation, their energy dependence is defined as the dependence of the sensitivity of measuring instruments (MI) on the energy of the measured radiation. The currently existing MI of gamma radiation levels have a high error, the main contribution to which, in addition to the main error of about 20 %, is made by the EDS of primary measuring converters, in some cases reaching a value of about 1500 % [4].

2. Problem statement
In order to develop new and improve existing MI that perform radiation monitoring of gamma radiation levels, it is necessary to develop a method for compensating for EDS in the entire energy range of measurement.

The purpose of this work is to develop a method for automatic compensation of EDS in the energy range of measuring gamma radiation levels from 0.01 to 10 MeV. To achieve this goal, it is necessary to analyze the detector's EDS in various operating modes, and consider existing methods of EDS compensation.
3. Methods and results

When designing and verifying dosimetric control devices, due to their peculiarity—the dependence of their sensitivity on the energy of ionizing radiation $E_{\gamma}$, in metrological laboratories, the sensitivity of devices is determined by exemplary energy $E_{\gamma}^s$, which usually uses the energy of either the Cs-137 ($E_{\gamma}^s = 0.662\text{ MeV}$) isotope or the Co-60 isotope ($E_{\gamma}^s = 1.25\text{ MeV}$). However, as it becomes obvious, in cases where measurements are made at other energies, the sensitivity of the detector changes, which introduces an additional error, which in some cases can reach a value of about 1500 %.

The ratio of the detector sensitivity $\eta$ at a given radiation energy $E_{\gamma}$, to the sensitivity $\eta$ at a standard energy $E_{\gamma}^s$, depends on the gamma radiation energy $E_{\gamma}$:

$$E_{\gamma} \frac{E_{\gamma}}{E_{\gamma}^s} \frac{\eta(E_{\gamma})}{\eta(E_{\gamma}^s)}$$  \quad (1)

In accordance with regulatory documents, the use of MI is possible only at energies at which the total error of the main and additional errors does not exceed the specified value of about 30%. The additional error can reach several orders of magnitude, so it determines the energy range of dosimetric devices, which leads to a significant narrowing of it.

There are several factors that determine the value of the EDS of a particular MI of radiation control. The main one is the difference in the energy transfer coefficients for the substance of the detector and the measuring instrument and the air:

1. $Z_m > Z_d$. The ratio $\mu_{\text{mnc}} / \mu_{\text{ma}}$ in the area of small energies of gamma radiation decreases with increasing energy. This is due to the effect of the photo effect. The dependence $\mu_{\text{mnc}} / \mu_{\text{ma}}$ on energy is determined by the effective atomic numbers of the detector material and the air. With an increase in the energy of gamma radiation, the role of the photo effect decreases sharply and the main role is played by the Compton effect. The electronic coefficients of energy transfer do not depend on the atomic number of the substance, but only on the energy of gamma quanta, so the ratio $\mu_{\text{mnc}} / \mu_{\text{ma}} = 1$.

2. $Z_m = Z_d$. The ratio $\mu_{\text{mnc}} / \mu_{\text{ma}}$ in the area of small energies of gamma radiation increases with increasing energy, while in the area of large energies it decreases. In the area of average energy values $\mu_{\text{mnc}} / \mu_{\text{ma}} = 1$.

3. $Z_m < Z_d$. The ratio $\mu_{\text{mnc}} / \mu_{\text{ma}}$ in the area of small energies, gamma radiation increases with increasing energy, while in the area of large energies it decreases.

In connection with the above, the detector material is selected from the so-called "air-equivalent" materials with $Z_m$, close to $Z_d = 7.64$.

Since the value $E_{\gamma}$ changes by three orders of magnitude, counter detectors have a very large amount of additional error. The influence of these three factors leads to different EDS for current and pulse devices.

To cover the entire required energy range of 0.01...10 MeV, it is more profitable to use a scintillation detector. Let's calculate the EDS for scintillators operating in current and pulse modes.

For a scintillation counter in pulse mode [5]

$$E_{\gamma} \frac{E_{\gamma}}{E_{\gamma}^s} \frac{\mu_{\text{mnc}} \cdot E_{\gamma}}{\mu_{\text{mnc}} \cdot E_{\gamma}^s}$$  \quad (2)

where $\mu_{\text{mnc}}, \mu_{\text{mce}}, \mu_{\text{as}}, \mu_{\text{at}}$ – values of linear coefficients of gamma radiation attenuation in the detector material or in the air for energy $E_{\gamma}$, and for energy of standard $E_{\gamma}^s$;

$h$ – thickness of the scintillator.

For a scintillation counter in current mode [6]
Figure 1 shows the EDS for a scintillation detector in pulse and current mode.

$$EDS = \frac{1 - e^{-\mu_{\text{tot}}}}{1 - e^{-\mu_{\text{tot}}}} \cdot \mu_{\text{tot}}.$$  \hspace{1cm} (3)

Figure 1. EDS for scintillation detector in pulse and current mode of operation.

When selecting a compensation filter, each value of the sensitivity of the "naked" detector is multiplied by the filtration coefficient $f_K$ of filter [8]:

$$F = \frac{EDS_f}{EDS_n},$$

where $EDS_f$ and $EDS_n$ – EDS with a filter and a "naked" detector.

As an example of a compensation filter we use one layer of aluminum and one layer of iron 1 mm thick each (figure 2).

Figure 2. EDS detector with a combination of various compensation filters with perforation.
Fig. 2 clearly illustrates that in the case of using a compensation filter made of aluminum at a given thickness, the lower limit of the measurement range begins with 50 keV, and in the case of using a material for a compensation filter made of iron - with 80 keV, which is unacceptable for solving the problems under consideration.

The calculations show that the use of a compensation filter with holes can reduce the influence of EDS in the area of low energies. However, the result is still unsatisfactory.

If you use multiple compensation filters (4), it will look like

\[ F = \prod_{i=1}^{n} \left( \frac{S_{perf}}{S_f} + \frac{1 - S_{perf}}{S_f} \cdot \exp\left(-\mu_{p_i} \cdot h_i \right) \right) \]

where \( n \) – number of filters.

After analyzing the presented graph, we can conclude that the highest EDS, and, consequently, the greatest error detectors have at low energies of gamma radiation. Therefore, at the design stage of detectors, additional compensating filters are currently being introduced from a substance with a larger Z. They weaken soft radiation more than hard radiation, and reduce the error, thereby extending the energy range of the device. Calculation of the characteristics of the EDS is performed when designing the device.

Figure 3 shows the interface of the developed software product that calculates filter parameters and correction coefficients [5].

A cardinal solution to the EDS problem is the introduction of a spectrometer into the device, which measures the energy of each gamma quantum and makes an adjustment to the EDS of the detector [3, 5, 9]. A model of a probabilistic wide-range gamma-ray spectrometer of increased accuracy, built in Multisim, implementing the proposed principle, is shown in Fig. 4.
Figure 4. Model of a high-precision wide-range gamma-ray spectrometer in a Multisim environment.

The proposed method of automatic compensation of EDS is reduced to the calculation of correction coefficients for a detector with specified characteristics according to the formula (5) and further loading them into the developed circuit device – a wide-range gamma-spectrometer of increased accuracy [6 – 9]. The proposed method of automatic compensation of EDS allows not only to increase the accuracy of measuring gamma radiation levels, but also to expand the energy range of measuring gamma radiation levels-from 0.01 to 10 MeV [3, 10].

Using the advantages of the probabilistic data representation form allowed us to build a scheme for a serial and parallel probabilistic wide-range gamma-ray spectrometer of high accuracy, which has a small hardware volume, increased noise immunity and the ability to work on a real-time scale [6, 10 - 13].

4. Conclusion
The main factor affecting the EDS is the difference in the energy transfer coefficients for the substance of the detectors of the measuring instrument and the air and, as a result, the occurrence of three effects: the Compton effect, the photo effect and the effect of vapor formation. These effects determine the non-linearity of the EDS in the entire energy range under consideration.

The existing methods of adjusting the EDS are reduced to selecting a compensating filter with the calculated parameters - the filter material and the degree of perforation. It is possible to combine several compensating filters with different parameters. However, this approach makes it possible to compensate for ESR only in a very narrow energy range.

A cardinal solution to the EDS problem is proposed by introducing EDS correction coefficients in the entire selected energy range from 10 keV to 10 MeV.

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