Improving the accuracy of gamma radiation measurements in radiation monitoring

D V Moiseev and L I Lukina
Sevastopol state university, 33 Universitetskaya str., Sevastopol, 299053, Russia
E-mail: dmitriymoiseev@mail.ru

Abstract. The article suggests the use of unmanned vehicles for monitoring the radiation situation. The paper analyzes data on the radiation situation at nuclear power plants and identifies the main factors of external radiation exposure. It is shown that the existing means of measuring gamma radiation in real conditions have to be used in an extended energy range. To improve the measurement accuracy while simultaneously expanding the energy range of gamma radiation levels, a method is proposed for automatically compensating for additional error due to the energy dependence of the sensitivity over the entire measurement range in real time by introducing pre-calculated correction coefficients. Simulation of the proposed circuit design is performed.

1. Introduction
The practice of NPP operation shows that the main factor of external radiation exposure to personnel is gamma radiation, which by its nature is a high-frequency electromagnetic radiation with a wavelength of less than $10^{-11}$ m, with a high penetrating power. It determines the degree of danger to the environment and health not only of the NPP personnel, but also of the population [1, 2].

In this regard, to reduce the impact of gamma radiation on humans, the environment and technology, it is necessary to carry out measures on nuclear, radiation, physical safety at nuclear power plants and radioecological monitoring of natural objects together with ensuring control of working conditions [2].

Along with the improvement of the technological process, there is a problem of improving the means, methods and techniques for measuring radiation levels, increasing the accuracy and reliability of their measurements, the solution of which is relevant today [3, 4].

In solving this problem, an important role is played by the use of information and measurement systems (IMS) designed to obtain initial information, process it and generate control signals on this basis [5-7].

2. Problem statement
The purpose of this research is to formalize the main methods for improving the accuracy of measuring gamma radiation levels in radiation monitoring. To achieve this goal, it’s necessary to solve the following tasks:

- determine the contribution of gamma radiation to the total activity in various operating modes,
- determine the real energy range of gamma radiation at nuclear power plants;
• analyze the metrological characteristics of modern gamma radiation measuring instruments (MI);
• develop a method for improving the accuracy of measuring the dose and dose rate of gamma radiation by automatically compensating the energy dependence of the sensitivity (EDS) of the primary converter (PC);
• develop new MI levels of gamma radiation based on the developed method to improve the accuracy of measuring the dose and dose rate of gamma radiation by automatically compensating the EDS PC on a real-time scale;
• improve the methodology for applying the probabilistic form of data representation for use in IMS in order to reduce their hardware volume, improve accuracy, noise protection and performance.

3. Methods and results
As the experience of NPS operation shows, the radiation dose of personnel is mainly due to gamma radiation from the nuclear power plant and its technological equipment. Personnel are exposed to other types of ionizing radiation only when performing repairs in the central hall of the reactor. At the same time, neutron irradiation accounts for no more than 15%, while the remaining 85% is accounted for by gamma radiation [1, 2].

As you know, gamma radiation is a high-energy photon radiation that occurs when the energy state of the atomic nucleus changes, nuclear transformations or particle annihilation. The energy of gamma quanta formed during these processes covers the range from 0.01 MeV to 10 MeV, and the corresponding wavelength is from $10^{-11}$ m to $10^{-16}$ m [2].

The position of the gamma radiation spectrum in the general spectrum of ionizing electromagnetic radiation is shown in figure 1.

![Figure 1. Range of gamma radiation in the spectrum of ionizing electromagnetic radiation.](image)

However, the normalized energy range for measuring gamma radiation levels is from 0.01 MeV to 3 MeV, which is significantly less than the actual range (from 0.01 MeV to 10 MeV).

Thus, the applied means of measuring technology (MMT) of gamma radiation during radiation monitoring in real conditions have to be used in an extended energy range, which, in turn, leads to additional measurement errors, dispersion of results, significant errors when performing calibration and verification operations [3].

Until recently, gamma radiation levels were commonly measured using MI exposure dose or exposure dose rate. Currently, in accordance with the recommendations of commissions of various levels, the intensity of gamma radiation is measured by the absorbed or equivalent dose [8]. 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 [4].

For dosimetric control devices in accordance with GOST 14337 – 87 [9], их энергетическая their energy dependence is defined as the dependence of the sensitivity of MME from the energy of the measured radiation. The currently existing MMT 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 error due to the EDS of primary measuring converters, in some cases reaching a value of up to 1500 % [3-5].

As is known, the peculiarity of dosimetric MI is the dependence of their sensitivity on the radiation energy \( E_{\gamma} \).

In the design and verification of SI in metrological laboratories, the sensitivity is determined for some exemplary energy \( E_{\gamma} \), which is usually used as energy Cs-137 (\( E_{\gamma} = 0.662 \) MeV), or Co-60 (\( E_{\gamma} = 1.25 \) MeV).

The gamma radiation energy \( E_{\gamma} \), in turn, determines the ratio of the sensitivity of the MI \( \eta_{x} \) at a given radiation energy \( E_{\gamma} \) to the sensitivity \( \eta_{s} \) at exemplary energy \( E_{\gamma} \) [4]:

\[
EDS(E_{\gamma}) = \frac{\eta(E_{\gamma})}{\eta(E_{\gamma})}. \tag{1}
\]

In accordance with regulatory documents, the use of MMT is possible only at energies at which the total error of the main and additional errors does not exceed the set value of 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 radiation control MMT. The main one is the difference in the energy transfer coefficients for the substance of the detector of the measuring instrument and air - \( \mu_{am}\), \( \mu_{ma}\).

In this case, the values of the effective atomic numbers of the detector material \( Z_{m} \) and air \( Z_{a} \) play a large role. The effective atomic number of a complex substance is the atomic number of such a conditional simple substance for which the electronic coefficient of radiation energy transfer is the same as for this complex substance [4].

In connection with the above, the detector material is selected from the so-called "air-equivalent" materials with \( Z_{m} \) which is closed to \( Z_{a} = 7.64 \). Graphically, this relationship looks as shown in figure 2 [4].

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.
The actual energy range of gamma radiation at a NPP from 0.01 MeV to 10 MeV most fully covers the scintillation primary converter operating in pulse mode, for which the EDS value is calculated using the formula [4]:

$$EDS = \frac{\left(1 - e^{-\mu_{s,h}}\right)\mu_{as}E_{xs}}{\left(1 - e^{-\mu_{s,h}}\right)\mu_{max}E_{xs}},$$ (2)

where $\mu_{as}, \mu_{max}, \mu_{s}, \mu_{h}$ – values of linear coefficients of gamma radiation attenuation in the detector material or in the air for energy $E_{xs}$ and for exemplary energy $E_{ys}$.

To reduce the impact of EDS, compensation filters are currently used to reduce the value of additional error due to EDS to a specified level in a given energy range. However, the use of this method leads to insensitivity of the MMT to components of the spectrum with low energy, which, in turn, leads to a narrowing of the measured energy range. The use of compensation filters with through holes allows to increase sensitivity to low-energy quanta, but, in turn, worsens the detector's EDS due to the fact that the thickness of the compensation filters is selected based on the value of one energy that gives the maximum error, and the influence of other energies is not taken into account. The highest EDS, and, consequently, the highest error (60 %) of primary converter are at low gamma radiation energies - less than 0.05 MeV [4].

To calculate the EDS with a combination of various compensation filters with through holes, the formula (2) will take the form:

$$F = \prod_{i=1}^{n} \frac{S_{hole}}{S_f} + \left(1 - \frac{S_{hole}}{S_f}\right) \exp\left(-\mu_{fs} \cdot h_f\right),$$ (3)

where $\frac{S_{hole}}{S_f}$ – the ratio of the area of the holes and the filter;

$\mu_{fs}, \mu_{fa}$ – linear coefficients of attenuation of gamma radiation by the filter substance at energies $E_{xs}$ and $E_{ys}$;

$h_f$ – the thickness of the filter.

Figure 3 shows the dependence of the EDS in the case of using different compensation filters.

The graph shows that when using compensation filters made of aluminum at a given thickness, the lower limit of the measurement range begins with 0.03 MeV, and iron - with 0.08 MeV.

The combination of compensating filters made of various materials with holes allows to compensate for the EDS, however, only in a fairly narrow energy range from 0.05 to 1.00 MeV.

Thus, the existing methods of adjusting the EDS are reduced to the selection of a compensation filter with the calculated parameters-the filter material and the degree of perforation. Therefore, to cover the entire proposed energy range from 0.01 to 10 MeV, we currently have to use several detectors designed to operate in different energy ranges.
Figure 3. EDS PC with various compensation filters and their combination.

- EDS of primary converter (PC) without filter;
- EDS PC with aluminum filter, 1 mm;
- EDS PC with iron filter, 1 mm;
- EDS PC with a combination of lead and aluminum filters, 1 mm.

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 [5].

The proposed method of automatic compensation of EDS is reduced to the calculation of correction coefficients for a detector with the specified characteristics according to the formula (3) and further loading them into the developed circuit device – a wide-range gamma-spectrometer of increased accuracy [3, 5, 10]. 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].

A circuit solution has been developed – an amplitude analyzer of a wide-range gamma-ray spectrometer of high accuracy, which implements the proposed method for increasing the accuracy of measuring gamma-radiation levels, allowing to measure the spectrum, dose and dose rate of gamma radiation in the entire energy range from 0.01 MeV to 10 MeV with a given accuracy in real time [3].

The solution of the technical problem is achieved by using a probabilistic form of data representation, which, in turn, allowed to significantly reduce the hardware volume of the device under development and increase its noise immunity due to the property of integrating interference [5, 10].

The proposed functional scheme of the probabilistic amplitude analyzer of the scintillation spectrometer is shown in figure 4 [11-13].

The structure of the scheme includes:

- analog comparison scheme (ACS);
- clock pulse generator (CPG);
- Q bit digital comparison scheme (DCS);
- generator of pseudo-random evenly distributed numbers (GPEDN);
- counter for the number of tests;
- multiplexing unit (MU), consisting of Q logic elements «OR» on L inputs;
- the real-time counter (RTC);
- L logic elements that perform summation modulo 2 (mod2);
- Block of logic elements;
- L memory registers for Q digits that store correction coefficients in the digital position code (Rg);
- L+2 binary cumulative counters,

where L – the number of measurement sub-ranges.

Figure 4. Functional diagram of a probabilistic amplitude analyzer of a wide-range gamma-ray spectrometer of high accuracy.

The work of the developed amplitude analyzer of a wide-range gamma-ray spectrometer of increased accuracy is simulated, the results of which are fully consistent with theoretical research [5, 3].

The simulated high-precision wide-range spectrometer has 32 energy channels and is constructed according to the scheme shown in [5], the energy measurement range is from 0.01 MeV to 10 MeV.

Each energy channel corresponds to its own energy range. Thus, by measuring the activity in each energy channel, we determine the spectrum, dose, and dose rate of gamma radiation. To improve the accuracy of measuring the dose and dose rate of gamma radiation, it is necessary to take into account the additional error due to the EDS, which, as previously shown, can both overestimate and underestimate the value of activity in the energy channel.

Figure 5 shows the correction of the energy spectrum of the input signal according to the algorithm of operation of the proposed spectrometer in the entire range using pre-calculated values in accordance with the developed method for improving the accuracy of gamma radiation measurements during radiation monitoring [3-6].
On the graph (figure 5), the light columns correspond to the energy spectrum before the EDS correction, and the output spectrum after the EDS autocompensation in the entire energy range is marked in dark color.

![Figure 5. Energy spectrum of the original and corrected signal.](image)

As can be seen from figure 5, the efficiency of using the proposed high-precision wide-range spectrometer, which implements the proposed method for increasing the accuracy of measuring the dose and dose rate of gamma radiation, is shown in the entire energy range, which makes it possible to design a gamma radiation MMT with an extended energy range. One of the tasks of object control is to measure metrics of information states of objects based on small-volume samples based on specified criteria and make decisions to assess the information situation. It is proposed to use the Kullback distance as an informational measure [14-16].

4. Conclusion
The paper solves an important scientific and practical problem of improving the accuracy of gamma radiation measurement in radiation monitoring at nuclear power plants based on the developed wide-range gamma spectrometer of increased accuracy, which implements the method of automatic compensation of ESR in the entire energy range of measurement (0.01-10.0) MeV, works on a real-time scale and has a small hardware volume. Based on the research, the following scientific and practical results were obtained:

- It is established that the main factor of external radiation exposure at NPPs in normal operation and in emergency situations is gamma radiation with a total contribution to the total radioactivity of ≈ 85 %, with a continuous energy spectrum in the range from 0.01 MeV to 10 MeV, in which it is proposed to perform radiation monitoring.
- It is found that the existing fleet of gamma radiation MMT often does not cover even the standard energy range (0.01 – 3.0) MeV. If the MMT are used to measure the dose and dose rate of gamma radiation in the proposed energy range, this leads to additional measurement errors, dispersion of results, and significant errors in calibration and verification operations.
- It is proved that the existing methods of correction of EDS are reduced to the selection and combination of compensation filters with the calculated parameters-the filter material and the
degree of perforation, but this approach allows to compensate for EDS only in a very narrow energy range and does not cover the entire necessary range from 0.01 MeV to 10 MeV.

- A method has been developed for automatic compensation of EDS in the entire proposed energy range from 0.01 MeV to 10 MeV by introducing correction coefficients, which allows increasing the measurement accuracy by more than 200%. A software package has been developed that implements this method in order to calculate the correction coefficients of EDS for detectors with specified characteristics.
- A circuit solution is proposed and implemented – an amplitude analyzer of a wide-range gamma-ray spectrometer of high accuracy, which allows measuring the spectrum, dose and dose rate of gamma radiation in the entire proposed energy range from 0.01 MeV to 10 MeV with a given accuracy on a real-time scale.

The application of a probabilistic form of data representation is proposed, which significantly reduces the hardware volume of a probabilistic wide-range gamma-ray spectrometer of high accuracy and thus provides the possibility of its application when using unmanned vehicles for radiation monitoring.

Acknowledgments
This work was supported by the Russian Foundation for Basic Research (projects № 19-29-06023/19).

References
[1] Nosovsky A V 2009 Decontamination (Kiev:Basis)
[2] Nosovsky A V 1998 Questions of dosimetry and radiation safety at the NPP (Slavutich:Ukratomizdat)
[3] Afanasyev A V, Sapozhnikov N E and Moiseev D V 2008 Ways to solve the problem of analysis of the isotopic composition of radioactive inert gases and aerosols in the practice of radiation safety, Collection of scientific papers SNUYaEp 4 63-7
[4] Moiseev D V and Lukina L I 2017 Method of automatic compensation of the energy dependence of sensitivity when measuring gamma radiation levels, Environmental, Industrial and Energy Security 2 916-20
[5] Moiseev D and Lukina L To the question of the radiation control at the enterprises of the nuclear-fuel cycle, Integrated problems of technospheric security 1 344-7
[6] Moiseev D 2019 Methodology of Probabilistic Representation and Transformation of Information, International Multi-Conference on Industrial Engineering and Modern Technologies FarEastCon 19229264 DOI: 10.1109/fareastcon.2019.8934304
[7] Vasiliev A B, Boyko A U, Lipovsky D D and Denisenya Y A 2015 Implementation of radiation, chemical and biological protections using robot appliances and chairs, Bulletin of the academy of military sciences 3 163-8
[8] Lukina L I, Moiseev D V and Frolova M A 2016 Radioecological monitoring of the radiation status of soils of the Chernobyl exclusion zone, Power installations and technologies 1 88-92
[9] 1989 USSR National Committee on Standards 27451-87 Ionizing radiation measuring means. General specifications (Moskov)
[10] Lukina L I and Moiseev D V 2016 Analysis of the sources and types of gamma radiation at nuclear power plants and description of their contribution to the total activity Current issues of nuclear technologies and environmental safety 1 195-200
[11] Sapozhnikov N E, Moiseev D V and Chuzikova-Proskurnina O D 2016 Comparison of various forms of not position probabilistic display of information Environmental monitoring systems 4 66-73
[12] Sapozhnikov N, Polyakov A and Moiseev D 2019 Advantages of Using the Probabilistic Form of Information Representation in Information-Control Systems International Science and Technology Conference "EastConf" 2 1-6 DOI: 10.1109/EastConf.2019.8725406
[13] Sapozhnikov N, Bryukhovetskii A, Polyakov A and Moiseev D 2018 Modeling performing
calculations over the data presented in a probabilistic form, *MATEC Web of Conferences* **224** 32-39 DOI: 10.1051/matecconf/201822404019

[14] Skatkov A, Bryukhovetskiy A and Moiseev D 2019 Adaptive intellectual decision support system for assessing changes in information states of objects in cloud computing environments *International Science and Technology Conference "EastConf"* **18724505** 1-5 DOI: 10.1109/EastConf.2019.8725339

[15] Skatkov A V, Bryukhovetskiy A A, Moiseev D V and Litvinova R A 2018 Detecting changes simulation of the technological objects’ information states *MATEC Web Conf.* **224** 02072 DOI: https://doi.org/10.1051/matecconf/201822402072

[16] Skatkov A V, Bryukhovetskiy A A and Moiseev D V 2017 Effectiveness analysis of the kulback’s information measure in the technological objects monitoring *MATEC Web Conf.* **129** 03025 DOI: https://doi.org/10.1051/matecconf/201712903025