https://doi.org/10.15407/scine17.03.049

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SPECTROMETER-IDENTIFIER BASED ON A SOLID DETECTOR FOR NFC FACILITIES

Introduction. *The Chornobyl accident resulted in radiation contamination of a large area. In order to prevent the release of radioactive elements into the environment and food, it is necessary to use specialized devices that allow monitoring of the radiation situation.*

Problem Statement. *One of the most effective ways to quickly detect and identify sources of ionizing radiation in the environment is to control the spread of radionuclides that are present in food and construction materials.*

Purpose. *The purpose is to develop modern domestic equipment for automated operational detection, identification, and monitoring of ionizing radiation sources in the environment in real time.*

Materials and Methods. *Methods of mathematical and computer modeling, full-scale modeling, machine design have been used. To study the specifications of the system and its features, field tests of its individual channels in the exclusion zone of the Chornobyl NPP have been carried out.*

Results. *An experimental system for automated operational detection, identification, and monitoring of ionizing radiation sources in the environment in real time, as well as for identification of detected radioactive isotopes and reliable estimate of their activity has been created and tested.*

Conclusions. *The created spectrometer-identifier is a new generation rapid response system based on advanced technologies, synthesis of principles of radiometry, spectrometry, and mathematical simulation. It is used for effective control of specific activity of liquid, viscous, bulk food and non-food samples and for identification of their radionuclide composition.*

The introduction of the spectrometer-identifier significantly reduces the time for operational mass study of food and non-food samples and identification of their radionuclide composition, which raises the environmental safety in the era of widespread operation of nuclear fuel cycle facilities.

Keywords: nuclear radiation accident, gamma radiation, spectrometer, radiation monitoring, and radiation safety.

Any facility of the nuclear fuel cycle (NFC) infrastructure, while operating, is a source of radionuclides that pollute the environment. The long-term operation of NFC facilities brings additional radioactivity to the adjacent territories, with its elemental composition being identical to the natural radioactivity accumulated in the environment. Most emis-

Citation: Zabulonov, Yu., Burtnyak, V., and Odukalets, L. Spectrometer-Identifier Based on a Solid Detector for NFC Facilities. *Sci. innov.* 2021. V. 17, no. 3. P. 49—55. https://doi.org/10.15407/scine17.03.049

sions because of a short half-life of radionuclides and their limited mobility in the environment have local or regional importance. Some radionuclides (^{3}H, ^{14}C, ^{129}J, etc.) are characterized by a long half-life and a high mobility [1].

Thus, as a result of human activity, the content of natural and artificial radionuclides in the environment has increased. The concentration of radionuclides in food also has grown. The level of food contamination depends on the intensity of radioactive fallout, their bioavailability, and on the soil and climatic conditions that determine the migration of radionuclides [2].

The separation of technogenic radioactivity from the background natural one that accumulated in the environment, for example, in the soil, is a rather complicated analytical task, and ways to solve it have not been sufficiently developed. Also, there have been no methods to correctly determine relative contributions into the pollution of each individual enterprise or a cluster of enterprises located within a limited area, which can be sources of additional radioactivity discharged into the environment.

Reliable information on the levels of radioactive contamination of the environment is a necessary condition for assessing the dose load on the population and for making decisions on measures to ensure radiation safety.

The estimation of radiation doses is an extremely complicated biological problem because of the difficulty of obtaining statistically significant values of dose loads, especially when they are less than 0.1 Gy (doses that do not lead to the development of clinically defined non-random effects on human or animal health). Irradiation in such doses may be dangerous because of delayed somatic and genetic effects characterized by probabilistic nature of their manifestation. There have been almost no reliable experimental data on small doses.

In order to prevent the ingress of radioactive elements into the environment and food, it is necessary to use specialized instruments and measuring systems for monitoring the radiation situation and, having analyzed it, for predicting and preventing emergencies.

This is especially relevant now, when the design resource of many NPPs has already been exhausted, and decisions are being made to extend it. That is, there is a need for specialized devices and measuring systems that allow monitoring the radiation situation.

The existing approaches, methods, and devices cannot be effectively used to detect and to identify sources of ionizing radiation. This is primarily because of a low functionality of existing technical systems, the ability to register only limited characteristics of radiation fields, unsatisfactory level of automation of control procedures, underdeveloped information exchange, and "closed" architecture. The limiting factors for the modernization of these systems and their integration into other monitoring systems are unsatisfactory level of identification of ionizing radiation sources, the inability to integrate them into a common system because of the lack of a common principle and method for their design.

Given the importance and urgency of controlling the radiation situation, researchers of the Nuclear Physics Department of IEG of the NAS of Ukraine have created a new generation measuring system that allows quick detection and identification of radionuclides in the measured sample.

The purpose of this research is to design, create, and to evaluate the parameters of a compact, inexpensive, wireless spectrometer-radiometer for real-time detection, identification, and monitoring of ionizing radiation sources in the environment.

1. Engineering solutions

The spectrometer-identifier may be considered as a rather sophisticated autonomous system that operates in real time. Like all such systems, it consists of disparate components: analog and digital electronic circuits, measurement algorithms, and structural elements, i.e. a set of hardware and software designed for automatic solution of the tasks assigned to them for effective identification of gamma radiation sources.

The spectrometer-identifier has a modular structure and consists of the following elements:

- detection unit;
- microcontroller for data control, collection, and pre-processing;
- unit for transmission and exchange of information with an external user;
- data selection and record unit; and
- power control unit.

A scintillation crystal of cesium iodide activated by thallium CsI (Tl) is used as a detector in the spectrometer-identifier. This crystal has the property of radioluminescence: charged particles and high-energy photons (X-ray and gamma range) excite the glow in it, with photons emitted as a short, about a microsecond, flash of light — scintillation. The scintillation crystals are chosen in as much as they can be compact, inexpensive, provide efficient record of gamma rays, and operate in spectrometric mode.

Typically, photoelectric multipliers (PEMs) the main advantage of which is a high sensitivity are used to capture such weak light pulses. The maximum sensitivity of PEM coincides with the maximum wavelength of the scintillator. However, PEM has several significant disadvantages:

- the need for high voltage power supply;
- large dimensions;
- high cost;
- the need for magnetic shielding.

Today, semiconductor photodetectors that are able to compete in sensitivity with PEMs, but do not have the above disadvantages have appeared on the market.

A multipixel silicon photodiode with p-i-n junctions, which has a maximum spectral sensitivity in the infrared region is used as a photodetector. Each pixel is a *p-n* junction to which a reverse bias voltage exceeding the breakdown voltage (<60 V) is applied. The charge gain of an individual pixel is ~ 10^6 and is determined by the amount of accumulated charge at the *p-n* junction of the pixel. The magnitude of the charge at the output of such a photomultiplier is determined by the sum of the charges of all its pixels triggered by the light flash of the scintillator. This photodetector has several advantages, in particular, a high internal gain, a low reverse bias voltage and a weak dependence of the internal gain on bias voltage and temperature variations. These advantages allow it to be used as a photodetector for scintillation detectors designed for solving spectrometric problems.

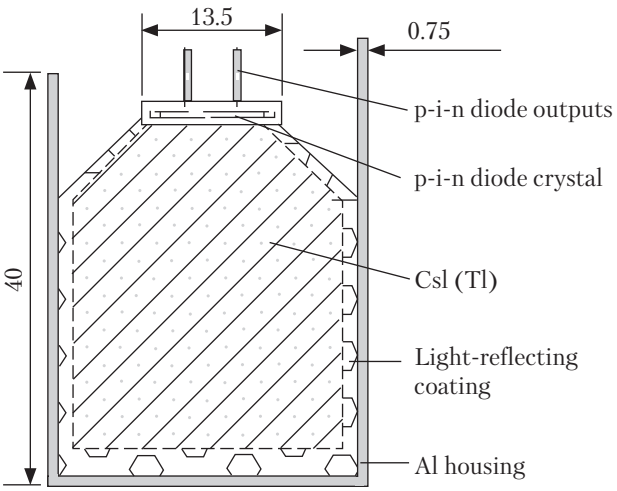

Fig. 1. Configuration of the detector

A solid photomultiplier with a total area of 1 × 1 mm² consists of 576 independent pixels, each having a size of ~ 40 × 40 μm.

The CsI (Tl) scintillator is coupled with a solid PEM with optical glue to remove the air gap between the crystal and the photodetector window, and to ensure maximum light collection by the photodetector. The crystal and solid PEM are surrounded from all sides by a reflector made of fluoroplastic powder. This coating has a very high diffuse reflection coefficient. To be protected against external influences, the detector is placed in a cylindrical aluminum housing that provides protection and water-proofing, since the cesium iodide crystal is sensitive to moisture that may destroy it (Fig. 1).

The detector has the following electric parameters:

Voltage, V	+ 5.0
Detector's maximum bias voltage, V	+ 5.0
Supply current, mA	100
Supply current, mA	24—27

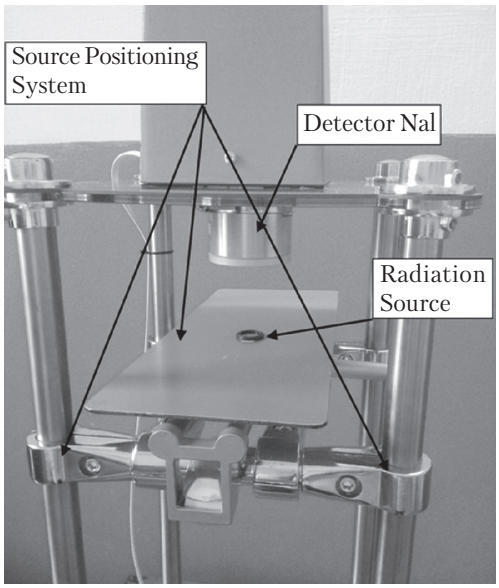

Fig. 2. Stand for gamma-spectrometric measurements

Amplifier conversion factor, mV / MeV	80
Front of the amplifier output signal, ns	~ 5
Gain ratio (adjustable).	20—20
Polarity of the output pulse at a positive bias on the detector.	Positive
Output pulse FWHM, μs	5.0
Maximum magnitude of output pulse, V	+ 3.2

The detection unit is built on the basis of a solid detector and has the following specifications:

Energy range, MeV	0.05—3
Relative resolution on 661 keV line (^{137}Cs), %	At most 7
Integral nonlinearity, %.	At most ±1
Instability for 8 hours of continuous operation, %	± 2
Maximum input static load, s^{-1}	50 000
Operating mode setting time, min	At most 30
Number of channels	1024
Operating temperature range, °C	from –10 to +40

The signals of required amplitude and duration from the detector are digitized, encoded, and stored in the form of a digital code in the memory of the microprocessor unit.

The microprocessor unit (MPU) provides collection and processing of information in real time, storage of information on a memory card (microSD), transfer of information to the host (personal computer or other device), execution of commands from it, support of the Ethernet network interface, various expansion modules (UEXT interface, Olimex-compatible), device power, and user interface. The MPU is based on a microcontroller of the Cortex M4 family with a core clock speed of 168 MHz, has 1 MB internal Flash memory and 196 KB RAM [3]. The MPU performs all control functions of other modules; it is a hardware platform for executing algorithms for processing and organizing the user interface.

2. Algorithm solutions

According to the measurement model used in the registration of particles with energy spectrum $\Phi(E)$, we obtain some signal distribution $U(V)$ that is called the hardware spectrum. The relationship between $\Phi(E)$ and $U(V)$ is described by the following integral relation

$$U(V) = \int_0^\infty G(V, E)\, \Phi(E) dE. \qquad (1)$$

When working with a spectrometer, the main task is to find the true energy spectrum $\Phi(E)$ based on the hardware spectrum U(V). In the general case, for this purpose it is necessary to know the response function of the detector $G(V, E)$ and to solve the above integral equation.

The problem of identifying the radioisotope composition of the spectrum $\Phi(E)$ is reduced to finding the peaks of full absorption in the spectrum $U(V)$ in the hardware spectrum.

From formula (1) it follows that the identification is based on a comparison of the energy distribution of the measured hardware spectrum $U(E)$ with the energy distribution of individual radionuclides $g_i(E)$.

The energy distribution of the sample to be analyzed may be represented as the sum of the distributions of radionuclides in the sample:

$$f_N^* = \sum_{i=1}^{N} \alpha_i g_i, \qquad (2)$$

where $g_i \subset \Phi$, $i = \overline{1, N}$ are basic expansion functions; $\alpha_i \in R$, $i = \overline{1, N}$ are coefficients of the series expansion; f_N^* is approximation of certain function y with the use of N various basic expansion

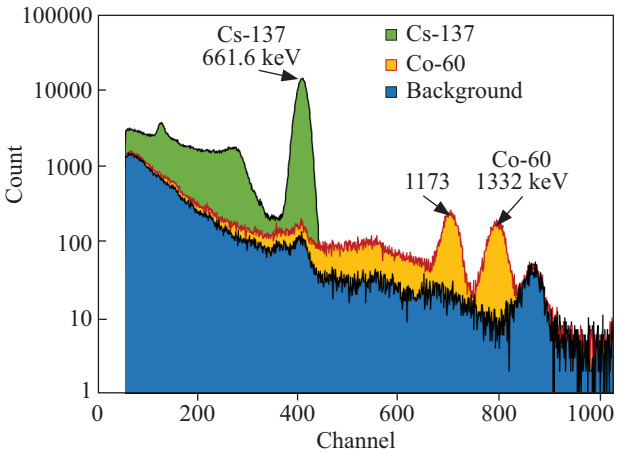

Fig. 3. Spectra of tested sources of 137Cs and 60Co

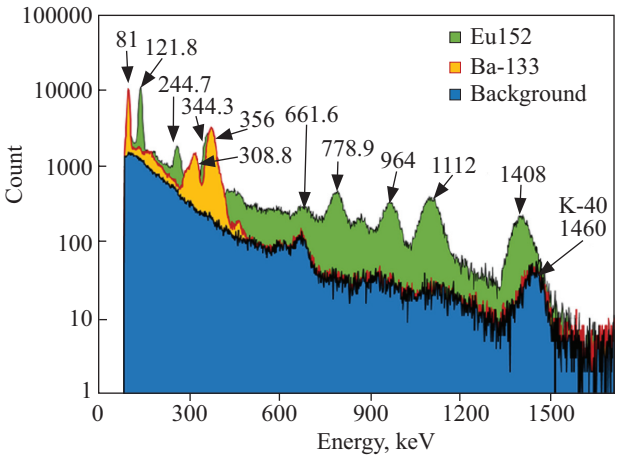

Fig. 4. Spectra of tested sources of 152Eu and 133Ba

functions from set Φ; $y = \{y_1, ..., y_L\}$is known function obtained from measurements; $M << N$ is the number of functions in set Φ.

It is necessary to choose basis $\{g_1, ..., g_N\} \subset \Phi$ and respective coefficients $\{a_1, ..., a_N\} \in R^N$ in such a way as to minimize the quadratic residual:

$$RSS = \|R_N\|^2 = \|y - f_N^*\|^2 = \sum_{i=1}^{L} (y_i - f_N^*(x_i)). \quad (3)$$

To ensure the (mathematically) optimal solution to this problem, it is necessary to search through T bases $\{g_1, ..., g_N\} \subset \Phi$ and to find T times the respective coefficients $\{a_1, ..., a_N\} \in R^N$, where T is defined from the formula

$$T = 2^N. \quad (4)$$

For an arbitrary basis, the respective coefficients that minimize the quadratic residual (3) have been found with the use of the least squares method, provided that the free term of the corresponding linear regression equation (2) is equal to zero [4].

3. Testing of solutions

A stand for gamma spectrometric measurements has been designed to verify and to test the solutions, algorithms, and software of the spectrometer-identifier.

The design of the stand consists of a spectrometer-identifier, a personal computer with a program for processing and visualization of spectra, and a positioning system for sources of ionizing radiation (Fig. 2).

Using radioisotope sources 241Am, 137Cs, 60Co, 152Eu, 133Ba, and 40K, the detection unit of the spectrometer-identifier has been tested.

According to the measurement results, the optimal forming time constant, in terms of signal / noise ratio, has been determined. Its value is $\tau = 1$ μs, despite the fact that the total illumination time of the scintillator CsI (Tl) is ~ 3—4 μs. Reducing the forming time constant allows increasing the record capacity of the detector based on the "slow" scintillator CsI (Tl). The discrete sensitivity (number of counted pulses per unit dose) of the detection unit may be adjusted both by selecting the detector volume together with varying the operating bias voltage and by varying the discrimination (or amplification) of the signal in the measuring path. Figs. 3—4 show the results of background radiation and test radionuclide record, which characterize the most typical energy regions of the detector hardware spectra. The range of their gamma radiation, from 81 keV (133Ba) to 1460 (40K), practically covers the range of gamma radiation of Chornobyl genesis radionuclides.

The energy resolution of the gamma spectrometer at an energy of 661.6 keV is 6.5%. The energy calibration of the gamma spectrometer has been validated by reference spectrometric gamma sources (RSGS) 137Cs and 60Co (Fig. 5).

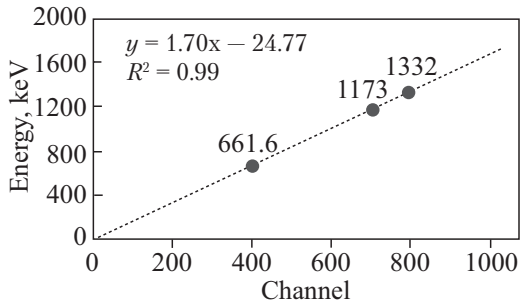

Fig. 5. Calibration curve of energy channel

The measurement is performed upon the operator's command; the measurement results are processed automatically. The implemented isotope identification algorithm has showed good results. For test samples, it unmistakably determines the available isotopes in the total spectrum (Table 1). The response functions of the detector have been obtained on the stand of gamma spectrometric measurements.

The high energy capacity of the detector (6.5%) increases the accuracy of radionuclide identification. The wide spectral range of measurements from 0.5 KeV to 3 MeV increases the ability to detect different types of radionuclides.

Conclusions

1. As a result of the research, an experimental sample of spectrometer-identifier based on a solid detector has been designed for real-time control and prevention of the spread of radionuclides that are present in food and construction materials, as well as for identification of detected radioactive isotopes and reliable determination of their activity.

2. Due to the use of a scintillation crystal with a high radiation detection as a detection unit and a PEM based on a semiconductor diode with a high quantum efficiency and readout speed, the gamma-ray spectrometer has excellent spectrometric and operational characteristics.

3. Modern element base and perfect circuitry, which are used in the creation of recording equipment (pre-amplifier, analog-to-digital converter, microprocessor unit), allow real-time obtainment of the spectra of any gamma radiation source with subsequent processing and analysis.

4. The microprocessor unit with a modern signal processor *Cortex*, on the basis of which the device is built, provides statistical processing of measurement results at the same rate as they come

Table 1. **Results of Gamma Spectra Processing**

Sample	Isotope	Energy, keV	Confidence	Identification error	Activity, Bq/sample
P-1	CS-137	661.66	1.0	1.1134806E-03	1.7200047E+02
	EU-154	123.07	0.998	5.7892155E-02	8.8093251E+01
		1274.43			
	EU-155	105.31	1.0	7.8731112E-01	1.2195589E+01
	AM-241	59.54	1.0	5.2484277E-03	8.2756083E+02
P-2	CS-137	661.66	0.992	8.281543E-003	3.951950E+002
	EU-154	123.07	0.988	1.070405E-002	4.626154E+000
		1274.43			
	AM-241	59.54	1.0	7.357731E-002	4.277017E+001
	CO-60	1173,24	0.996	1.817543E-003	2.619645E+002
		1332,5			
P-3	CS-137	661.66	0.992	8.281543E-003	3.951950E+002
	EU-154	123.07	0.988	1.070405E-002	4.626154E+000
		1274.43			
	AM-241	59.54	1.0	7.357731E-002	4.277017E+001

from the detector, prompt display of results, comparison of measurement results with the tolerances, alarming in the case where these results go beyond the established limits, and archiving of measurement results.

5. The resulting spectrometer-identifier based on a solid detector, which is designed for real-time control and prevention of the spread of radionuclides present in food and construction materials, as well as for identification of detected radioactive isotopes and reliable estimation of their activity, may be used as a basic element of the automated system for continuous safety control of radiation in the areas affected by the Chornobyl disaster.

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Received 29.01.2020
Revised 26.02.2020
Accepted 23.02.2021

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СПЕКТРОМЕТР-ІДЕНТИФІКАТОР НА ОСНОВІ ТВЕРДОТІЛЬНОГО ДЕТЕКТОРА ДЛЯ ОБ'ЄКТІВ ЯДЕРНО-ПАЛИВНОГО ЦИКЛУ

Вступ. Наслідком аварії на Чорнобильській АЕС стало радіаційне забруднення значної території. З метою запобігання потрапляння радіоактивних елементів в довкілля та продукти харчування необхідним є використання спеціалізованих приладів, що дозволяють здійснювати контроль радіаційної обстановки.

Проблематика. Одним з найбільш ефективних способів оперативного виявлення та ідентифікації джерел іонізуючого випромінювання в довкіллі є контроль за розповсюдженням радіонуклідів, присутніх у продуктах харчування та будівельних матеріалах.

Мета. Розробка сучасного вітчизняного обладнання для автоматизованого оперативного виявлення, ідентифікації та моніторингу джерел іонізуючого випромінювання в середовищі в режимі реального часу.

Матеріали й методи. Використано методи математичного та комп'ютерного моделювання, натурного макетування, машинного проєктування. Для дослідження технічних характеристик системи, її особливостей проведено натурні випробування окремих її каналів в зоні відчуження Чорнобильської АЕС.

Результати. Створено та апробовано експериментальну систему автоматизованого оперативного виявлення, ідентифікації та моніторингу джерел іонізуючого випромінювання в навколишньому середовищі в режимі реального часу, а також ідентифікації виявлених радіоактивних ізотопів та достовірної оцінки їхньої активності.

Висновки. Створений спектрометр-ідентифікатор є системою швидкого реагування нового покоління на базі сучасних технологій, синтезу принципів радіометрії, спектрометрії та математичного моделювання для ефективного контролю питомої активності рідких, в'язких, сипучих харчових і нехарчових проб, ідентифікації їхнього радіонуклідного складу.

Впровадження ідентифікатора-спектрометра сприятиме суттєвому скороченню часу на проведення оперативної масової перевірки харчових і нехарчових проб та ідентифікації їхнього радіонуклідного складу, що, в свою чергу, підвищить рівень екологічної безпеки населення в епоху широкої експлуатації об'єктів ядерно-паливного циклу.

Ключові слова: ядерно-радіаційна аварія, гамма-випромінювання, спектрометр, радіаційний моніторинг, радіаційна безпека.