ВІЙСЬКОВА ТЕХНІКА І ТЕХНОЛОГІЇ ПОДВІЙНОГО ПРИЗНАЧЕННЯ

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METHODS AND MEANS OF CONTROL OF NUCLEAR MATERIALS AND STATUS OF PROTECTIVE BARRIERS AT NPP IN WARTIME CONDITIONS

The level of development and application radiations technologies is largely determined by the state of nuclear instrumentation. In a relatively short period of time, this industry went through several stages of development, and each them was marked by the appearance of various devices that register and measure the parameters of ionizing radiation nuclear materials: gas discharge counters, scintillators, semiconductor detectors, and others.

The appearance of modern semiconductor radiation sensors for the first time connected nuclear instrumentation and electronics into a single complex - a semiconductor detector. It combines a semiconductor primary converter of ionizing radiation (sensor), a secondary converter of information from the sensor (electronics) and software for processing this information, which are interconnected by the problem to be solved and parameters. However, the development of atomic energy, spread of nuclear technologies in various industries has put forward new requirements for the control and metrology of ionizing radiation, which cannot be fully satisfied by modern level of nuclear instrumentation and applied nuclear physics research. The new generation radiation sensors and measurement systems based on them created in this work open up previously unknown opportunities in solving the problems of nuclear fuel analysis, increasing the accuracy and efficiency of monitoring technological parameters and the state of protective barriers in nuclear power plants, and creating means for MASATE inspections.

In the work, the use of algebraic reconstructive passive tomography (APT) methods for the reconstruction of the image of the internal structure of heat-emitting assemblies is proposed for the first time. For this purpose, a new algorithm for passive tomography of nuclear fuel was developed using the example of VVER-1000, which uses the method of angular projections own radiation of heat-emitting assemblies (HEA). Computer tomography experiments of this object showed that radiation intensity measurements at 360 points of the detector location relative to HEA axis are optimal for two or more values of the gamma radiation energy of the reference isotope ^{134}***Cs. In this case, the proposed APT method makes it possible to identify defective tvels cells with a leakage level of more than 30% on restored tomograms, as well as the absence of tvels cells in HEA.***

Key words: radiation sensors, ionizing radiation of nuclear materials, passive tomography, tvels

Introduction. The key problem of nuclear power engineering – radiation safety – is solved by ensuring the reliability of protective barriers of the main objects of the technological process of AES operation: tvels, fuel assemblies (FA), coolant transfer circuits, etc.

To implement the algorithm of computed tomography of WCPR-1000 nuclear fuel, a modern CdZnTe-detector with high resolution or a set of spatially distributed detectors, a digital gamma-spectrometric path and a medium-performance computer for processing and interpreting the tomography results are required. There are several possible ways to form spatial projections of FA self-radiation field: discrete angular movement of the controlled FA around its own axis, placement of a sufficiently large number of detectors around the controlled FA, placement of gamma-detector matrices at several angular positions around the FA. Regardless of the method of implementing computed tomography, radial movement of the gamma detector or the controlled FA seems to be very complex from a design point of view. Therefore, further computer tomography of nuclear fuel is studied only for angular projections of the fuel assembly's own radiation [1-3].

Analysis of previous studies. Methods of tomographic analysis of objects of various physical nature, i.e. reconstruction of the physical structure of an object by physical fields measured outside the object, as a rule, on a closed surface, originated in the 1970s in connection with the construction of X-ray tomographic images of human organs [1,2]. In the 1980s, tomographic methods were already widely used in industry for flaw detection [3-5]. Most of the methods developed to date, as a rule, use active tomography, which assumes the presence of a radiation source passing through the object being examined, and a receiver (or group of receivers) recording the radiation passed through the object. To analyze the state of nuclear fuel (NF), in particular, fuel assemblies, it is advisable to use passive emission tomography based on recording the intrinsic gamma radiation of fission products (FP) of NF with subsequent determination of their activity inside the studied FA.

Formation of the problem. In recent years, some attention has been paid to the use of high-energy microparticles in solid-state electronics: fast electrons and neutrons, protons, gamma-quanta. The diversity of nature of such microparticles in itself indicates a wide range of possibilities for controlling (modifying) the parameters of solid-state electronics products with their help. However, the prejudice caused by the destructive effect of such microparticles under nuclear explosion conditions, the danger of their flows for operators and the associated problems of using generators - all these are factors that hinder the development of this scientific and technical direction.

Results. To implement the developed algorithm for computed tomography of WCPR -1000 nuclear fuel (NF), a modern high-resolution CdZnTe-detector or a set of spatially distributed detectors, a digital gamma-spectrometric path, and a medium-performance computer for processing and interpreting the tomography results are required. Several methods are possible for forming spatial projections of FA self-radiation field: discrete angular movement of the monitored FA around its own axis, placement of a sufficiently large number of detectors around the monitored FA, placement of gamma-ray detector matrices at several angular positions around the FA. Regardless of the method for implementing computed tomography, radial movement of the gamma detector or the monitored FA seems to be very complex from a design point of view. Therefore, further computed tomography of NF is studied only for angular projections of FA self-radiation [7, 9].

When the detector is located at *n*-th observation point at a distance R_n from FA axis, the measured gamma-radiation intensity of *i*-th isotope with energy $E\gamma_j$ at the detector location point is equal to:

$$I_n^i = \sum_m A_{mi} k_{i_j} w_{mn} \varepsilon(E_{\gamma_j}), \tag{1}$$

where A_{mi} – activity of *i*-th isotope for *m*-th fuel element taking into account its actual state; k_{i_j} – yield of the gamma line with number *j* for *i*-th isotope; w_{mn} – contribution coefficient of *m*-th fuel element to the radiation intensity of *i*-th isotope with energy $E\gamma_j$, taking into account the attenuation effects during propagation of the gamma radiation beam from *m*-th fuel element to *n*-th observation point; $\varepsilon(E_{\gamma_j})$ – detection efficiency of the detector for energy $E\gamma_j$, m=1, …, *M*, where *M* – is the total number of fuel elements in the fuel assembly.

When measuring in the selected peak of total absorption of a specific reference isotope, the constants can be omitted k_{i_j}, $\varepsilon(E_{\gamma_j})$ and expression (1) can be written in a simplified form:

$$I_n = \sum_m A_m w_{mn} . \tag{2}$$

The principle of tomographic study of fuel assemblies consists of performing *n* measurements of γ-radiation intensity for different mutual arrangements of the detector and fuel assemblies, in particular, for different angular positions of the detector. This makes it possible to form a system of *n* equations of the form (2), which is usually called a projection system in algebraic reconstructive tomography, in this case - angular.

The task of algebraic reconstructive tomography is to reconstruct *m* values of the activity of fuel elements A_m inside the fuel assembly for the selected reference isotope by solving the resulting system of equations. In this formulation, in this paper (in contrast to [7, 8]), we formulate tomography problem according to the principle of"one fuel element - one pixel of the reconstructed tomogram". More detailed tomography is possible - by dividing the cross-sectional area of fuel element into several pixels in accordance with the specific geometry of the fuel assembly. However, the modeling results presented below show that this is not practically necessary.

When solving the problem of reconstructing the fuel assembly tomogram and modeling field formation at the detector location, a number of assumptions were used:

– problem is considered in a flat section of the fuel assembly and fuel rods, i.e. vertical non-uniformity of the fission product activity distribution over fuel rods is not taken into account;

– fuel rod is considered as a homogeneous cylinder with gamma-activity A_m;

– effects of radiation scattering on the fuel assembly structural elements are not taken into account;

– of practical interest are sufficiently large distances of the detector from the fuel assembly axis (about 25 cm), therefore the geometric effects of the collimator are not taken into account; at the specified distances, the assembly is visible from the detector location at a sufficiently small angle (less than 300), therefore it can be assumed that the radiation passes through the collimator without geometric losses.

To solve the problem, a rectangular coordinate system XOY with the origin in the geometric center of the fuel assembly was introduced (fig. 1). All fuel elements and rod guides are numbered in horizontal rows, starting from the upper left. The coordinates of each fuel element or rod hole (x_m, y_m) are found based on the correct triangular symmetry of the structure, with a period of 12.75 mm.

The detector coordinates are initially specified in polar coordinates (ρ, θ) (the pole θcoincides with the origin 0, the angle is measured counterclockwise), and then converted to rectangular (x_0, y_0). The further steps of the algorithm are as follows.

Step 1. For each *n*-th detector (x_{0n}, y_{0n}) position and each *m*-th fuel element with the coordinate of the center, the equation of the straight line passing through the detector location point and the center of *m*-th fuel element is found:

$$Ax+By+C=0. \tag{3}$$

The coefficients of this line are determined by relations:

$$A=-(y_{0n}-y_m), \tag{4}$$

$$B=x_{0n}-x_m, \tag{5}$$

$$C=-y_m(x_{0n}+x_m)+x_m(y_{0n}+y_m). \tag{6}$$

Step 2. For each *i*-th fuel element with coordinates of the center (x_i, y_i), through which gamma radiation from fuel element m passes, the distances along the normal from its center to the line $Ax+By+C=0$ are calculated:

$$d_i = \frac{Ax_i + By_i + C}{\sqrt{A^2+B^2}} . \tag{7}$$

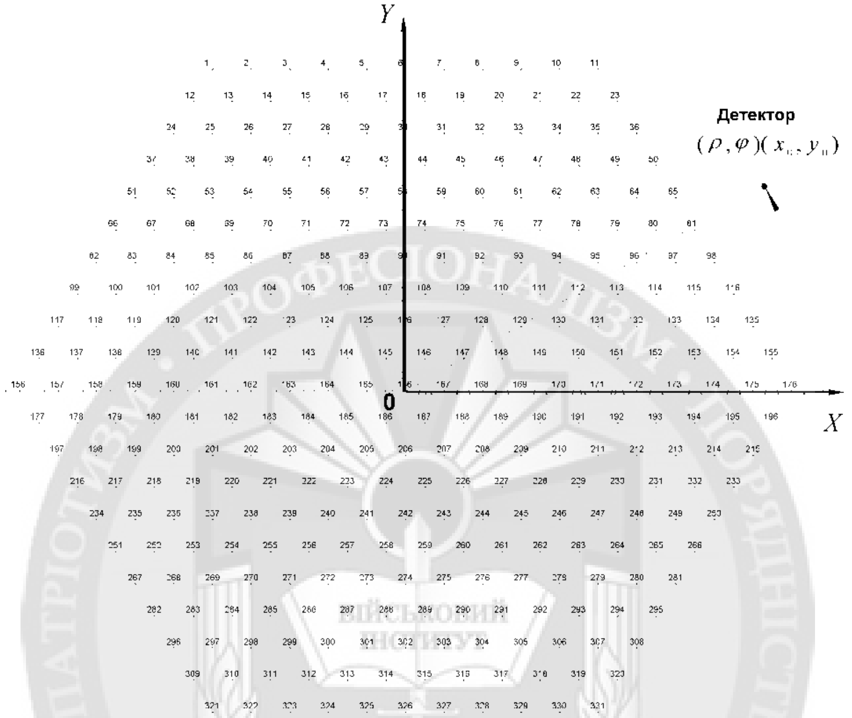


Figure 1 – Cartogram FA. Geometry of tomogram reconstruction problem

Step 3. The fuel elements through which the radiation from a given fuel element passes on its way to the detector are determined. These fuel elements must satisfy two conditions:

– fall within the “corridor” equal to the radius of the fuel element (0.455 cm);

– be located at a distance from the detector no greater than the emitting fuel element.

Step 4. For each of the fuel elements located in the radiation path, the free path in material of the zirconium cladding of the fuel element is found:

$$L_{\mathrm{Zr}i} = 2\sqrt{R_н{}^2 - d_i^2} - 2\sqrt{R_{вн}{}^2 - d_i^2} , \tag{8}$$

where $R_н$ and $R_{вн}$ – are outer and inner radii of the fuel element, respectively; d_i – distance along the normal from the center of the fuel element to the line $Ax+By+C=0$.

And in uranium dioxide:

$$L_{\mathrm{UO}_2 i} = 2\sqrt{R_{вн}{}^2 - d_i^2} . \tag{9}$$

Step 5. If there are core holes among the fuel elements found according to condition of point 3, then values of the mean free paths in them are excluded from array { $L_{\mathrm{Zr}i}, L_{\mathrm{UO}_2 i}$ }.

Step 6. For all fuel elements, the sums L_{Zri} and $L_{UO_2 i}$ are found, which are the total values of the mean free path of radiation in Zr and UO2. The total attenuation of radiation from *m*-th fuel element on the way to the detector in the fuel element materials will be:

$$P_{\Sigma}^{(m)} = \exp(-(\mu_{\mathrm{Zr}} \sum_i L_{\mathrm{Zr}i} + \mu_{\mathrm{UO}_2} \sum_i L_{\mathrm{UO}_2 i})) . \qquad (10)$$

Step 7. The total mean free path of gamma beam from emitting fuel element to the detector is:

$$\sqrt{(x_m^2 - x_{0n}^2)^2 + (y_m^2 - y_{on}^2)^2} . \qquad (11)$$

Step 8. The mean free path in water (both inside the assembly and outside it) will be:

$$\sqrt{(x_m^2 - x_{0n}^2)^2 + (y_m^2 - y_{on}^2)^2} - \sum_i L_{\mathrm{Zr}i} - \sum_i L_{\mathrm{UO}_2} , \qquad (12)$$

and the total attenuation of radiation of a single *m*-th fuel element in water, respectively, is:

$$P_{H_2O}^{(m)} = \exp(-\mu_{\mathrm{H_2O}}(\sqrt{(x_m^2 - x_{0n}^2)^2 + (y_m^2 - y_{on}^2)^2} - \sum_i L_{\mathrm{Zr}i} - \sum_i L_{\mathrm{UO}_2})) . \qquad (13)$$

Step 9. The contribution coefficient of each *m*-th fuel element is calculated as:

$$w_{mn} = \frac{S_{\mathrm{det}} P_{\Sigma}^{(m)} P_{H_2O}^{(m)}}{4\pi R_{mn}^2} . \qquad (14)$$

When modeling the tomography algorithm, the modeled activity distribution over the fuel elements inside fuel assembly is specified A_m, *m* =1,..., 312, and the radiation intensity at *n*-th point of the detector location is calculated:

$$I_n = \sum_m w_{mn} A_m . \qquad (15)$$

Algorithm for calculating the Moore-Penrose pseudoinverse matrix.

A matrix X of dimensions nxm is called the Moore-Penrose pseudoinverse matrix for the matrix A *(m*x*n),* if it satisfies the following four conditions:

1. AXA=A.
2. XAX=X.
3. AX is symmetric.
4. XA is symmetric.

It can be shown that such a matrix always exists and is unique [10]. The pseudoinverse matrix is denoted by A$^{\#}$. The pseudoinverse matrix is calculated using the singular value decomposition algorithm (SVD-decomposition, SVD-algorithm) [10,11].

The singular value decomposition of a real matrix A *(m*x*n)* is any factorization of the form:

$$A=U\Sigma V^{T}, \tag{16}$$

where U – is an orthogonal (*mxm*) matrix; V is an orthogonal (*nxn*) matrix; Σ – is a diagonal (*mxn*) matrix, whose singular values $\sigma_{ij}=0$ at $i\neq j$ and $\sigma_{ii}=\sigma_i\geq 0$.

Taking into account the above definitions, the pseudoinverse matrix can be calculated using the SVD-decomposition algorithm by the relation:

$$A^{\#}=V\Sigma^{\#}U^{T}. \tag{17}$$

The pseudoinverse matrix is related to the problem of least squares method (LSM) by the fact that vector *x* of the smallest length, minimizing form ||Ax-b||, can be expressed as $x=A^{\#}b$ in the sense of minimum residual LSM. Such a calculation is a regularizing procedure, which is convenient for solving ill-posed problems that are very sensitive to measurement noise. The problem of reconstructive emission tomography of fuel assemblies is one of such problems. Thus, by using Moore-Penrose pseudoinverse matrix to solve a system of projection equations, we not only organize an effective computational procedure, but also apply a regularization algorithm that smooths out measurement noise to a certain extent.

If the last relation $A^{\#}=V\Sigma^{\#}U^{T}$ is written out element by element for *i*=1,…,*n* and j=1,…,*m*, we obtain a direct algorithm for calculating the elements of pseudoinverse matrix [14,15]:

$$a_{ij}=\sum_{\sigma_k\neq 0}\frac{v_{ik}u_{jk}}{\sigma_k}. \tag{18}$$

To study the process of restoring the fuel element activities, a series of experiments were conducted in which the initial data contained a defective fuel element. The decrease in the activity of such a fuel element was set within the range from 10 to 50% of the nominal value.

During the experiments, systems of equations of the form (3) were formed for different energies, noise levels and the number of measurements. Then these systems were solved using the SVD decomposition method.

A preliminary analysis of the obtained tomograms showed that there are no generally accepted criteria for assessing the quality of determining the fuel element activity. Therefore, it was decided to study the reconstructed tomograms in terms of the relative dispersion δ_i^* of the deviation of fuel element activities within the entire tomogram, relative dispersion of deviation fuel element activities within one row A_i^{max}, maximum deviation of the activity within one row and the histogram of the deviation of the fuel element activities. To calculate δ^* and δ_i^* dispersion of the fuel element activity original model and the dispersion of fuel element activity within the corresponding row were taken as reference point, respectively.

The analysis of reconstructed tomograms allowed us to draw an important conclusion: with an increase in the number of measurements, the quality of reconstructed tomograms improves insignificantly. An idea of determining the activity fuel elements by several energy values was proposed. From a computational point of view, there is no particular difference whether to reconstruct a tomogram by 720 detector readings or by 360 for two energy values. Therefore, a new series of tomograms was formed, reconstructed by (2...4) energy values.

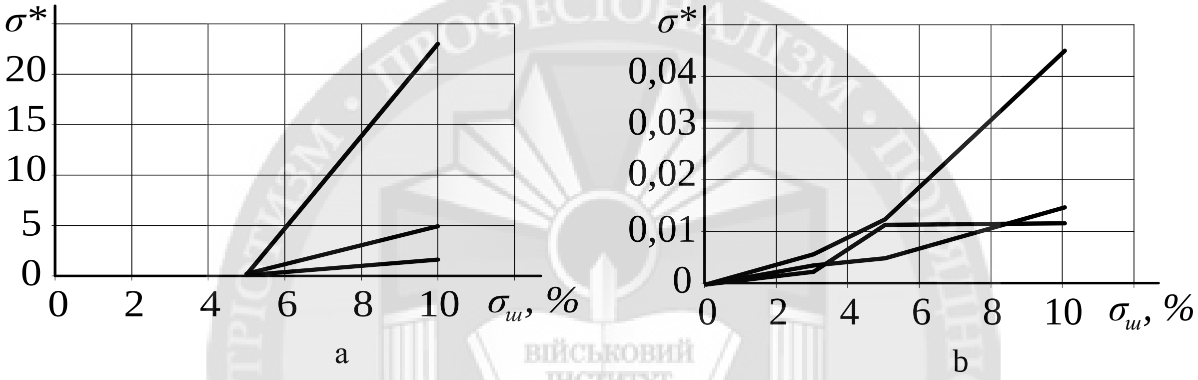
Further analysis confirmed the feasibility of proposed idea. Figure 2 shows the dependences of relative dispersion δ^* on the noise level for a different number of energy values used in reconstructing tomograms. The analysis of dependences allows us to draw following conclusions.

Firstly, with an increase in the noise level, for the case of one energy, the value of δ^* acquires a significant spread. In practice, this means that it is impossible to predict in advance the possibility of obtaining useful information from the reconstructed tomograms.

Secondly, the use of several energy values in the reconstruction process allows us to reduce the parameter δ^* by 2...3 orders of magnitude! This is clearly seen in figure 2. Although from a computational point of view these two cases are absolutely identical, using two energy values provides a significant gain in reducing the error.

Thirdly, increasing the number of measurements to n>360 does not seem appropriate. However, additional studies have also shown that reducing the number of measurements leads to a sharp decrease in quality. Thus, the number of measurements n=360 seems preferable.

Fourthly, from a computational point of view it is inappropriate to use more than three energy values in restoration, since in this case the ratio "gain in quality" / "expended resources" tends to zero.



a

b

Figure 2 – Dependences of the relative dispersion σ^*on the noise level $\sigma_ш$ for different numbers of energy values N_E and measurements *n*: a – N_E =1, n = 720; b – N_E =2, n = 360.
1 – first, second rows of fuel elements; 2 – third row of fuel elements;
3 – center of the fuel assembly behind the guide channels

The results of the analysis of the relative dispersion δ^* also allowed us to draw a conclusion about the accuracy of SVD- method as a whole. However, they do not allow us to answer the question of how to find a defective fuel element.

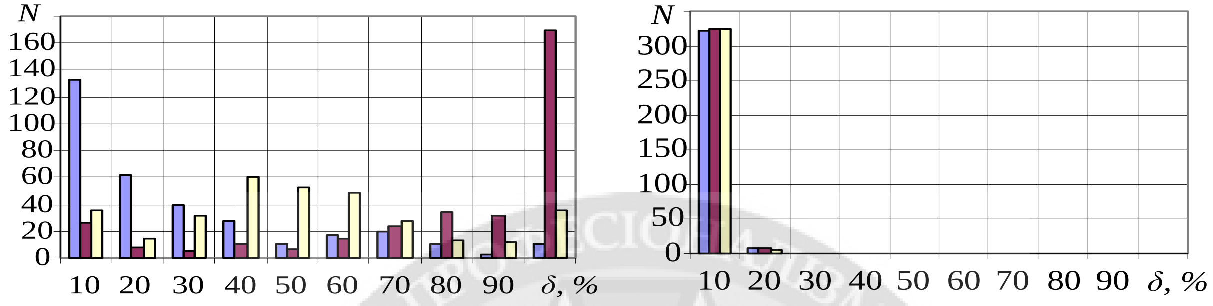
In the course of further research, the histograms presented in Figure 3 were obtained. The abscissa axis shows the deviation of fuel element activity from the true one in %. The ordinate axis shows the proportion of fuel elements falling within a given deviation range. All histograms correspond to a noise level of 10%. The color indicates different fuel burnup depth profiles by the volume of the fuel assembly.

Analysis of the presented histograms confirmed the usefulness of the idea using several gamma radiation energy values to determine the activity of fuel elements. In addition, analysis of the histograms for different energy values showed that when reconstructing a tomogram, it is advisable to use the gamma radiation energy values of one isotope, namely ^{134}Cs. The isotope distribution is the same, so this approach allows the best compensation for tomogram reconstruction defects. Thus, for ^{134}Cs, it was found that the deviation of the activity of the reconstructed fuel elements from the true values does not exceed 30%, total number of fuel elements with activity deviations of more than 10% from the true value does not exceed 8 ... 10 pieces.

The results obtained allowed us to assume that if the appropriate reference point is selected, defective fuel rods with a leakage level of more than 30% for fuel rods of inner rows can be identified on the reconstructed tomograms.

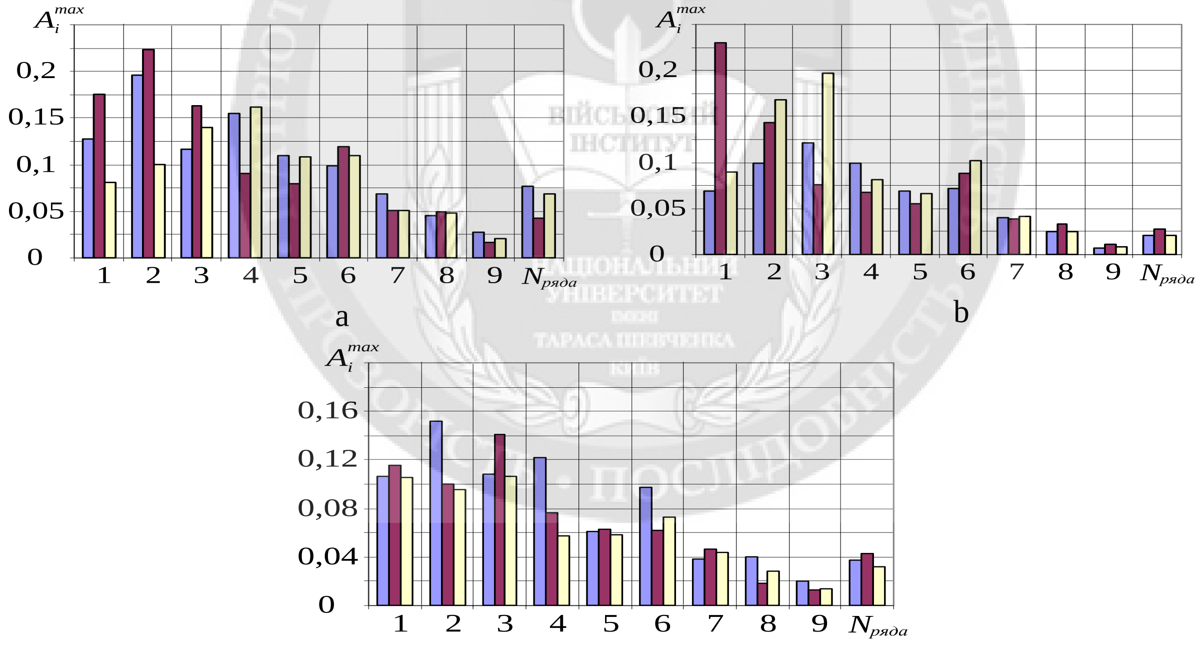
The final analysis of the experimental data involved constructing dependencies for the relative dispersion of fuel δ_i^* rod activity deviation within one row and the maximum activity deviation within one row A_i^{max}. These dependencies are presented in figures 3 and 4, respectively.

The general conclusion that can be made based on the results of the analysis of there is that the greatest reconstruction error is observed in the center of the tomogram. In the extreme rows, which are the most unfavourable from the point of view of the probability of the appearance of a defective fuel element, the accuracy of the tomogram reconstruction is the highest (fig. 4).



a b

Figure 3 – Histograms of fuel rod activity deviation from the true value for different numbers of N_E energy values and n measurements:
a – N_E=1, n = 720; b – N_E>1, n = 360,720



a b

c

Figure 4 – Histograms of dependence maximum activity deviation A_i^{max} on the number of row $N_{ряда}$: a – N_E=2, n = 360; b – N_E=3, n = 360;
c – N_E=4, n = 360

Conclusions. The results of measurements with the help of this system when the reactor is operating at a power of ≈100% of the nominal power" are: IR signals themselves, signal power spectral density, cross-correlation function, correlation coefficient and coolant mass flow rate. In addition to regular measurements of coolant flow at the nominal power level, background measurements and measurements at reduced power levels were carried out.

After the installation of the secondary equipment, measurements of the noise level brought to the input were performed with the input of the amplifier open, i.e. unconnected ionization chamber. The obtained values were $\sim 2\cdot 10^{-12}$ and $\sim 4\cdot 10^{-12}$ A in the frequency range $f_{в}$=0...10 and $f_{в}$=0...30 Hz, respectively, i.e. approximately 0.01% of IR output current level. The noise level is determined by the presence of electromagnetic noise and signals from the technological equipment of the power unit in the circuits of the measuring channels, each of which includes a 200-meter coaxial cable of RK-75-4-16 type between the amplifier located near the wall of the hermetic volume and the main amplifier placed in laboratory premises.

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МЕТОДИ ТА ЗАСОБИ КОНТРОЛЮ ЯДЕРНИХ МАТЕРІАЛІВ І СТАН ЗАХИСНИХ БАР'ЄРІВ НА АЕС В УМОВАХ ВІЙСЬКОВОГО ЧАСУ

Рівень розвитку та застосування радіаційних технологій значною мірою визначається станом ядерного приладобудування. За порівняно невеликий період часу ця галузь пройшла кілька етапів розвитку і кожен із них був відзначений появою різних приладів, що реєструють та вимірюють параметри іонізуючого випромінювання ядерних матеріалів: газорозрядних лічильників, сцинтиляторів, напівпровідникових детекторів та інших.

Поява сучасних напівпровідникових радіаційних датчиків уперше пов'язала ядерне приладобудування та електроніку в єдиний комплекс – напівпровідниковий детектор. У ньому поєднуються взаємопов'язані за задачею, що розв'язується та параметрам напівпровідниковий первинний перетворювач іонізуючого випромінювання (датчик), вторинний перетворювач інформації від датчика (електроніка) та програмне забезпечення для обробки цієї інформації. Однак розвиток атомної енергетики, поширення ядерних технологій у різних галузях висунув нові вимоги до контролю та метрології іонізуючих випромінювань, які не можуть бути повною мірою задоволені сучасним рівнем ядерного приладобудування та прикладних ядерно-фізичних досліджень. Створені в цій роботі радіаційні датчики нового покоління та вимірювальні системи на їх основі відкривають раніше невідомі можливості у вирішенні завдань аналізу ядерного палива, збільшення точності та ефективності контролю технологічних параметрів та стану захисних бар'єрів в АЕС, створення засобів для інспекцій МАГАТЕ.

У роботі вперше запропоновано використання методів алгебраїчної реконструктивної пасивної томографії (АРТ) для відновлення зображення внутрішньої структури тепловиділяючих збірок. З цією метою розроблено новий алгоритм пасивної томографії ядерного палива на прикладі ВВЕР-1000, який використовує спосіб кутових проекцій власного випромінювання тепловиділяючих збірок (ТВЗ). Комп'ютерні експерименти томографії даного об'єкта показали, що оптимальними є вимірювання інтенсивності випромінювання в 360 точках розташування детектора щодо осі ТВЗ для двох і більше значень енергії гама-випромінювання ізотопу реперного ^{134}***Cs. У цьому випадку запропонований метод АРТ дозволяє ідентифікувати на відновлених томограмах дефектні твели з рівнем протікання понад 30%, а також відсутність твэлів у ТВЗ.***

Ключові слова: радіаційні датчики, іонізуюче випромінювання ядерних матеріалів, пасивна томографія, твели