UDC 531:535

Dr. Sci. Tech. **Mokritskij V.A.** (ONPU)
Dr. Sci. Tech. **Maslov O.V.** (ONPU)
Dr. Sci. Tech. **Banzak O.V.** (OSATRQ)

METHODS AND MEANS FOR CONTROL OF NUCLEAR MATERIALS STATE OF PROTECTIVE BARRIERS AT NUCLEAR POWER PLANTS

The key problem of nuclear power - radiation safety - is solved by ensuring the reliability of protective barriers main objects technological process of nuclear power plants (NPP) operation: fuel rods, fuel assemblies (fuel assemblies), coolant transfer circuits, etc.

Radiation sensors of new generation created in this work and measuring systems based on them open previously unknown possibilities in solving problems of analyzing nuclear fuel, increasing the accuracy and efficiency of monitoring technological parameters and the state of protective barriers in nuclear power plants.

When analyzing existing radiation sensors, it was found that, due to their iterative nature, they have several disadvantages: their rate of convergence is low (moreover, their convergence in the general case has not been proven at all), respectively, counting time can be so great that the algorithm can be inapplicable in real time when performing regular technological operations; all algorithms use empirical starting parameters of the iterative process, on which convergence also strongly depends; in some cases, an unsuccessful choice of the parameter iterative process may increase counting time to values that are unacceptable in practice, and may cause a divergence of iterative process. However, main disadvantage of such algorithms should be considered as unsuitability for solving tomography problem in the case of a large number conditionality matrix weights of fuel elements.

The use of algebraic reconstructive passive tomography (ART) methods for reconstructing the image internal structure of fuel assemblies was proposed for the first time. For this purpose, a new algorithm for passive tomography of nuclear fuel has been developed using the example of the WWPR-1000, which uses the angular projection method of the fuel assembly's own radiation. Computer experiments on the tomography of this object showed that measuring the radiation intensity at 360 points of detector location relative to fuel assembly axis for two or more energy values of the gamma radiation references ^{134}***Cs isotope is optimal. In this case, the proposed ART method allows identifying defective fuel elements with a leakage level of more than 30% on reconstructed tomograms, as well as the absence of fuel elements in the fuel assembly. It has been proposed to replace ionization sensors with CdZnTe-detectors in a modern coolant flow control system.***

Keywords: algebraic reconstructive passive tomography, CdZnTe-detectors, radiation sensors, protective barriers.

Introduction. The development of modern detection units designed to monitor the state of protective barriers by measuring the gamma-radiation dose rate in the air as part of the NPP radiation monitoring systems is an important and urgent task. The detection units of the RSME-03 system currently in operation have exhausted their resources (RSME – radiation safety monitoring equipment). The system itself, developed more than 20 years ago, has not only developed its resource, but is also morally obsolete. Obviously, new detection units should have higher metrological and operational indicators. A significant improvement in the metrological and operational characteristics of the detectors, as shown above, can only be obtained through the use of new materials, in particular, wide-gap semiconductors such as CdZnTe.

Formulation of the problem. The aim of this work is to develop new improved methods and means of controlling nuclear materials and the state protective barriers at nuclear power plants. Creation of new generation radiation sensors and measuring systems based on them.

Analysis of recent research. Methods for tomographic analysis objects of different physical nature, i.e. the restoration of the physical structure an object from physical fields measured outside the object, as a rule, on a closed surface, originated in the 70s of the 20th century. in connection with the construction of x-ray tomographic images of human organs [1]. In the 80s tomographic methods were widely used in industry for flaw detection [2, 3]. 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 transmitted 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 the registration of its own gamma radiation from fission products (FP) NF, followed by determination of their activity inside the studied fuel assembly.

A rather limited number of papers are devoted to the actual tasks passive emission tomography of nuclear fuel. All of them are made at Uppsala University (Department of Radiation Sciences, Uppsala, Sweden). In particular, in the most thorough pioneering work, as in the subsequent works of Swedish researchers, task was to substantiate theoretically passive emission tomography of the BWR fuel assembly produced by ABB Atom, Sweden of a square form containing 8x8 = 64 round fuel rods [4]. The goal of this work was to establish the absence of one or more fuel rods in the fuel assembly, since the task of nuclear fuel imaging was solved within the framework program for ensuring the non-proliferation of nuclear materials.

The analysis of state questions led to the following conclusions:

– there is a fundamental possibility of using emission gamma tomography of nuclear fuel in order to restore the distribution of fission products by the example of a fuel assembly of a BWR reactor with 64 fuel rods;

– for a fuel assembly of WWPR-1000 reactor containing much more structural elements, development of a new, more efficient tomography algorithm is required;

– from point view of real-time tomography implementation when performing routine operations with nuclear fuel, in particular, overloading, is required sufficiently high computational efficiency of the algorithm.

Main part. The implementation of the developed algorithm NF WWPR-1000 computed tomography requires a modern high-resolution CdZnTe-detector or a set of spatially distributed detectors, a digital gamma-spectrometric tract and an average-performance computer for processing and interpreting the tomography results. For the formation of spatial projections self-radiation field of a fuel assembly, several methods are possible: discrete angular displacement of a controlled fuel assembly around its own axis, placement of a sufficiently large number detectors around a controlled fuel assembly, placement of gamma-radiation detectors at several angular positions around the fuel assemblies. Regardless of the method implementing computed tomography, it is very difficult, from a constructive point of view, to radially move a gamma detector or a controlled fuel assembly. Therefore, further computed tomography of nuclear fuel is investigated only for the angular projections of self-radiation of fuel assemblies [5].

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

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

where A_{mi} – is the activity of *i-th* isotope for *m-th* fuel element, taking into account its real state; k_{i_j} – gamma line output with number *j* for *i-th* isotope; w_{mn} – contribution factor of *m-th* fuel element to the radiation intensity of *i-th* isotope with energy, taking into account the effects of attenuation during propagation of gamma-radiation beam from *m-th* fuel rod to the *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 rods in the fuel assembly.

The method of calculating the contribution coefficients of individual fuel elements is described below [6, 7].

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

$$I_n = \sum_m A_m w_{mn} \; . \qquad (2)$$

The principle of the tomographic study fuel assemblies consists in making *n* measurements of the intensity γ-radiation for different mutual arrangements of the detector and fuel assembly, 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 the system of projections in algebraic reconstructive tomography, in this case angular.

The task of algebraic reconstructive tomography is the restoration *m* values of activity A_m fuel rods inside fuel assemblies for the selected reference isotope by solving the resulting system of equations. In this formulation, in this paper (as opposed to [8, 9]), we formulate problem of tomography on the principle of "one tvel – one pixel of the reconstructed tomogram". A more detailed tomography is possible – by dividing the cross-sectional area of a fuel element by several pixels in accordance with a particular fuel assembly geometry. However, the simulation results below show that there is no practical need.

When solving the problem, computer experiments were carried out on the tomography process of fuel assemblies the WWPR-1000. Below are some data for the WWPR-1000 FA, which is generally valid.

To form the system of equations (2), measured intensities were calculated at 360 detector location points for a constant distance "FA detector axis" (i.e. FA rotate pitch in the pickup bar of reloading machine was taken to be 1 degree). For 331 elements of fuel assemblies, activity reference isotopes was set: for all 312 fuel rods single, for 19 core holes – zero. Thus, a system of equations of field projections was formed:

$$WA = I, \qquad (3)$$

where W – is matrix of contributions (weights) of fuel rods dimension (360x331); A – column vector of reconstructed fuel rod activities of dimension (331x1); I – column vector of measured intensities dimension (360x1).

To simulate the noise accompanying field measurements, generated vector components were superimposed with normal noise with a dispersion equal to 5-10% of the value maximum vector component [10, 11, 12]:.

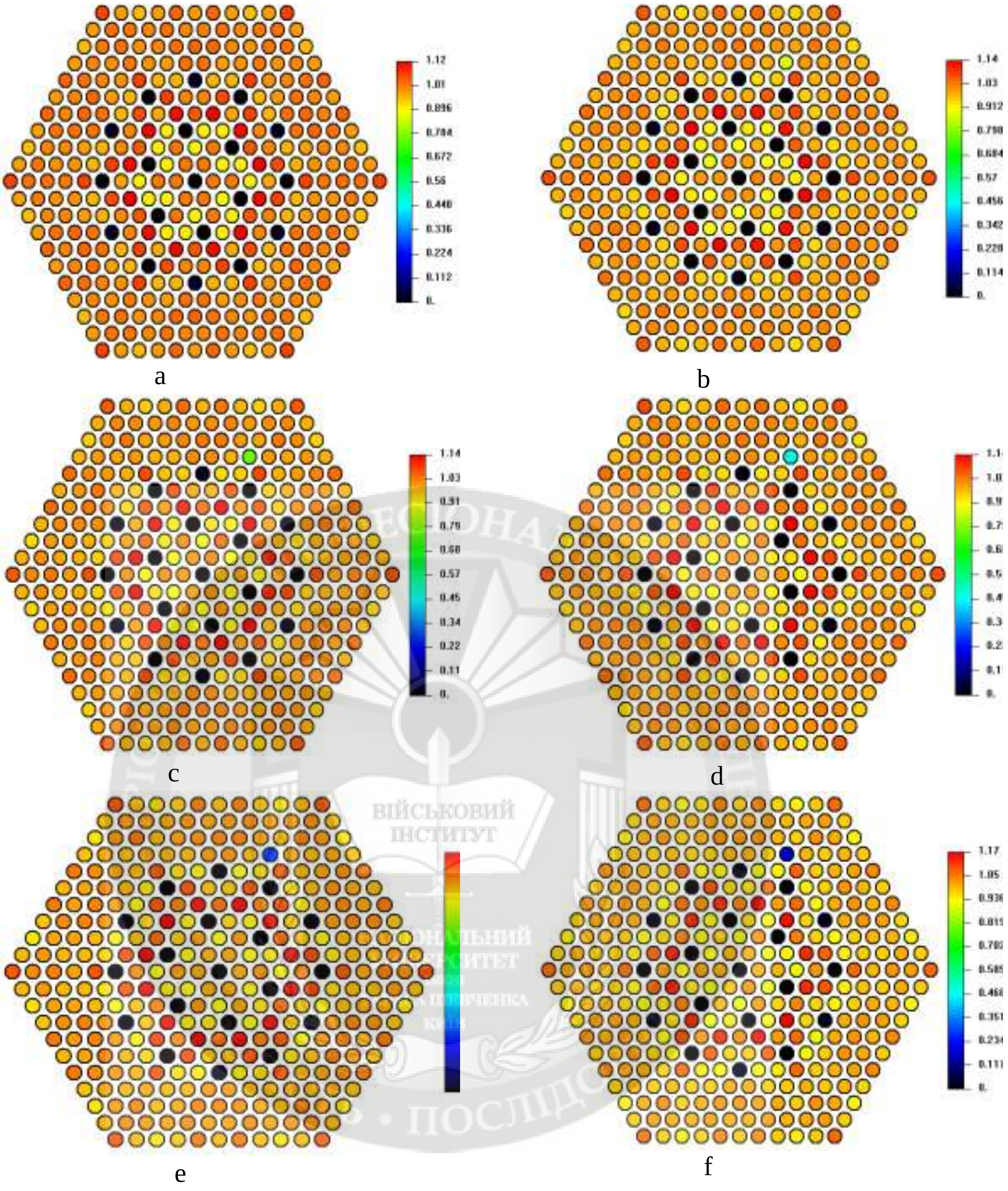
$$A = W^{\#} I. \qquad (4)$$

The pseudo-inverse matrix $W^{\#}$ corresponding to (*mxn*) matrix *W* is uniquely determined by the components of the decomposition of the matrix W by singular numbers according to the procedure of the SVD-decomposition. A detailed algorithm for the formation of a pseudo-inverse matrix is described below.

Figure 1 shows the reconstructed tomograms of FA for gamma radiation ^{134}Cs (1365 keV) for well-identified in the spectra of its own gamma radiation SNF with a short exposure time of the line ^{134}Cs (sum of lines with energies 795.8 keV and 801.8 keV). Analysis of reconstructed tomograms shows that for energy of the order of 800 keV with a dispersion recovery of the order of 0.024, only two external rows of fuel elements are restored. In this case, almost all core holes are restored.

The distribution of fission products can be used to control the integrity of cladding fuel elements, since in the case of depressurization fuel elements, the distributions of lightly moving and slow-moving fission products will differ. An increase in the average burnup of nuclear fuel in the zone up to 60-70 GW day / t leads to significant values of local burnout. This allows you to more confidently identify leaking fuel rods.

Figure 2 shows reconstructed tomograms of a fuel assembly containing one unpressurized fuel element with a microdefect. Tomography was performed for the ^{154}Eu line (1274 keV). On color scale of the restoration error, it is clearly seen that assessment of the violation tightness of a fuel rod significantly exceeds calculation error.

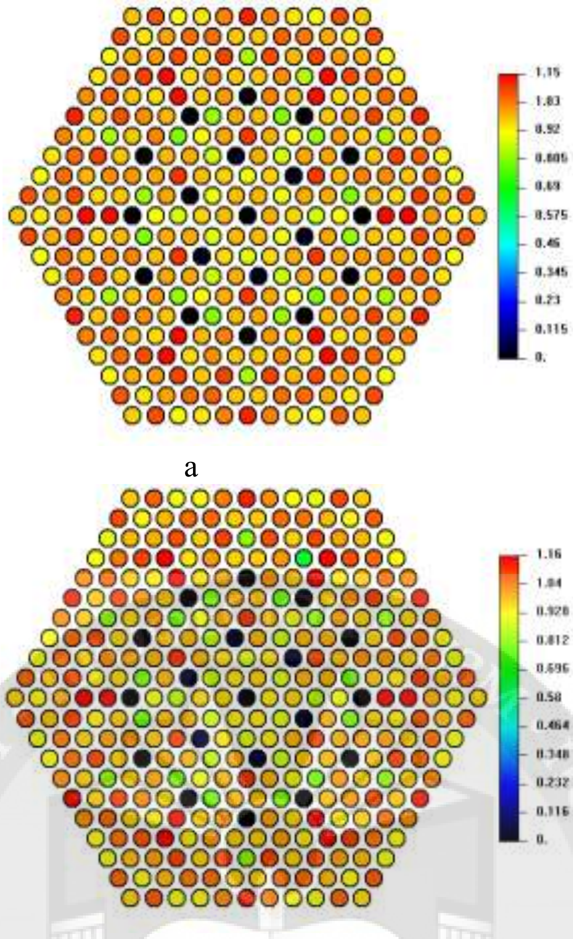


a b c d e f

Fig. 1. FA tomograms recovered from ^{134}Cs (1365 keV) and ^{134}Cs radiation (sum of lines with energies of 795.8 keV and 801.8 keV):

a – with intact fuel elements. With a decrease in activity in a single fuel element on a site up to 20 cm high: b – by 10%; c – by 20%; d – by 50%; e – 70%; f – by 80%

Questions of the practical implementation of gamma-emission tomography in real time during the fuel overload required an estimate of the time spent on calculations. It has been established that the time spent on tomogram restoration increases with an increase in the condition number of the matrix (or with a decrease in the energy of reference isotope).



a

b

Fig. 2. Restored tomograms of TA with a defective tvel: a – with 10%; b – 30% loss of activity due to leakage (defective tvel number 45)

A rough estimate of the estimated time to restore a tomogram on a computer gives a value from 31.4 s for ^{134}Cs (1365 keV) (the matrix condition number is – $4{,}2 \cdot 10^6$) to 49.9 s (condition number is 4.2 4106). Such time costs are quite acceptable and do not violate the real-time performance of the routine technological operations [10].

Conclusions. The use of algebraic reconstructive passive tomography (ART) methods for reconstructing the image of the internal structure of fuel assemblies was proposed for the first time. For this purpose, a new algorithm for passive tomography of nuclear fuel has been developed using the example of the WWPR-1000, which uses the angular projection method of the fuel assembly's own radiation. Computer experiments on the tomography of this object showed that measuring the radiation intensity at 360 points of detector location relative to fuel assembly axis for two or more energy values of the gamma radiation of the reference ^{134}Cs isotope is optimal. In this case, the proposed ART method allows identifying defective fuel elements with a leakage level of more than 30% on reconstructed tomograms, as well as the absence of fuel elements in the fuel assembly.

Under these conditions, the time spent on computerized tomogram recovery does not exceed 50 s. Similar results are provided by using detectors based on CdZnTe-detectors, created in this work, for solving these problems.

It has been proposed to replace ionization sensors with CdZnTe-detectors in a modern coolant flow control system. Due to this benefits:

- the sensor can be placed at any point of control circulations coolant;
- simplifies the design of protection device from the environment;
- it remains possible to use the existing method of correlation measurement coolant flow rate by isotope activity, allowing for an accuracy of control at least 2%.

REFERENCTS:

1. Vavilov V.S. Effect of radiation on semiconductors / V.S. Vavilov, N.P. Kekelidze, L.S. Smirnov. - M .: Science, 1988. - 192 p.

2. Lenkov S.V. Physico-technical basis of radiation technology semiconductors / S.V. Lenkov, V.A. Mokritsky, D.A. Peregudov, G.T. Tarielashvili. - Monograph. - Odessa: Astroprint, 2002. - 297 p.

3. Garkavenko A.C. Radiation modification of the physical properties of wide-gap semiconductors and the creation of high-power lasers on their basis / Lviv: ZUKTS, 2012. - 258 p.

4. Bansak O.V. Semiconductor detectors of new generation for radiation monitoring and dosimetry of ionizing radiation / OV Banzak, O.V. Maslov, V.A. Mokritsky: Ed. V.A. Mokritskogo, O.V. Maslova. - Monograph. - Odessa, 2013. - Publishing House "WWII". - 220 s.

5. Bouchet J.M. PWR primary flow masurements by correlation analysis of nitrogen-16 fluctuations / J.M. Bouchet, et al. – Progress in Nuclear Energy. – 1982. – Vol. 9.

6. Awadalla S.A. Characterization of detector-grade CdZnTe crystals grown by traveling heater method (THM) / S.A. Awadalla, J. Mackenzie, H. Chen, eds. // Journal of Crystal Growth. – Vol. 312, issue 4. – 2010. – 507-513c.

7. Grybos P. Front-end Electronics for Multichannel Semiconductor Detector Systems; EuCARD Editorial Series on Accelerator Science and Technology, Vol.08 / Institute of Electronic Systems Warsaw University of Technology . – Warsaw: 2010. – 201 p.

8. Dumitrescu A. Comparison of a digital and an analogical gamma spectrometer at low count rates / A. Dumitrescu // U.P.B. Sci. Bull., Series A. – Vol. 73. – Iss. 4, 2011. – P. 127-138.

9. Maslov O. Passive Computer Gamma- Tomography of Nuclear Fuel / O. Maslov, V. Mokritsky, O. Banzak, // ANIMMA. Third International Conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications – Marseille, June 23-27, 2013. – Book of Abstracts – P. 51.

10. Maslov O.V. The Improved CdZnTe Dose Rate Probe / O.V. Maslov, M.V. Maksimov, L.L. Kalnev // 2008 IEEE Nuclear Science Symposium, Medical Imaging Conference and 16th Room Temperature Semiconductor Detector Workshop – Dresden: 19–25 Oct. 2008. – P. 12-87.

11. Masuruk K. Dopant incorporation during liquid phase epitaxy / K. Masuruk, T.Bryskewicz // J. Appl. Phys., 1981. – V. 52. – N3. – part 1. – P. 1347–1350.

12. Maslov O. Multiple energies passive computer tomography of nuclear fuel / O. Maslov // Proceedings of the International Ukrainian-Japanese Conference on Scientific and Industrial Cooperation – Odesa 24 – 25 October 2013. – P. 114-116.

д.т.н., проф. Мокрицький В.А., д.т.н., доц. Маслов О.В., д.т.н., доц. Банзак О.В.

МЕТОДИ ТА ЗАСОБИ КОНТРОЛЮ ЯДЕРНИХ МАТЕРІАЛІВ І СТАНУ ЗАХИСНИХ БАР'ЄРІВ НА АЕС

Ключова проблема ядерної енергетики - радіаційна безпека - вирішується шляхом забезпечення надійності захисних бар'єрів основних об'єктів технологічного процесу функціонування АЕС: твелів, тепловиділяючих збірок (ТВЗ), контурів передачі теплоносія та ін.

Створені в даній роботі радіаційні датчики нового покоління і вимірювальні системи на їх основі відкривають раніше невідомі можливості в рішенні задач аналізу ядерного палива, збільшення точності і ефективності контролю технологічних параметрів і стану захисних бар'єрів в АЕС.

При аналізі існуючих радіаційних датчиків було встановлено, що, у зв'язку з їх ітеративним характером, вони мають ряд недоліків: швидкість збіжності їх невисока (більш того, збіжність їх в загальному випадку взагалі не доведена), відповідно час рахунку може бути великим настільки, що алгоритм може бути непридатний в реальному масштабі часу при здійсненні штатних технологічних операцій; всі алгоритми використовують емпіричні стартові параметри ітераційного процесу, від яких також сильно залежить збіжність; в окремих випадках невдалий вибір параметра ітераційного процесу може збільшити час рахунку до неприпустимих на практиці значень, а може викликати розбіжність ітераційного процесу. Однак головним недоліком таких алгоритмів слід вважати непридатність для вирішення завдання томографії в разі великого числа обумовленості матриці вагових коефіцієнтів твелів.

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 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 гамма-випромінювання реперного ізотопу ^{134}Cs. В цьому випадку запропонований метод АРТ дозволяє ідентифікувати на відновлених томограммах дефектні твели з рівнем протікання більше 30%, а також відсутність твелів в ТВЗ. Запропоновано в сучасній системі контролю витрат теплоносія замінити іонізаційні датчики на CdZnTe-детектори.

Ключові слова: алгебраїчна реконструктивна пасивна томографія, CdZnTe-детектори, радіаційні датчики, захисні бар'єри

д.т.н., проф. Мокрицкий В.А., д.т.н., доц. Маслов О.В., д.т.н., доц. Банзак О.В.

МЕТОДЫ И СРЕДСТВА КОНТРОЛЯ ЯДЕРНЫХ МАТЕРИАЛОВ И СОСТОЯНИЯ ЗАЩИТНЫХ БАРЬЕРОВ НА АЭС

Ключевая проблема ядерной энергетики – радиационная безопасность – решается путем обеспечения надежности защитных барьеров основных объектов технологического процесса функционирования АЭС: твэлов, тепловыделяющих сборок (ТВС), контуров передачи теплоносителя и др.

Созданные в данной работе радиационные датчики нового поколения и измерительные системы на их основе открывают ранее неизвестные возможности в решении задач анализа ядерного топлива, увеличения точности и эффективности контроля технологических параметров и состояния защитных барьеров в АЭС.

При анализе существующих радиационных датчиков было установлено, что, в связи с их итеративным характером, они обладают рядом недостатков:

скорость сходимости их невысока (более того, сходимость их в общем случае вообще не доказана), соответственно время счета может быть велико настолько, что алгоритм может быть неприменим в реальном масштабе времени при осуществлении штатных технологических операций; все алгоритмы используют эмпирические стартовые параметры итерационного процесса, от которых также сильно зависит сходимость; в отдельных случаях неудачный выбор параметра итерационного процесса может увеличить время счета до недопустимых на практике значений, а может вызвать расходимость итерационного процесса. Однако главным недостатком таких алгоритмов следует считать непригодность для решения задачи томографии в случае большого числа обусловленности матрицы весовых коэффициентов твэлов.

Впервые предложено использование методов алгебраической реконструктивной пассивной томографии (АРТ) для восстановления изображения внутренней структуры тепловыделяющих сборок. С этой целью разработан новый алгоритм пассивной томографии ядерного топлива на примере ВВЭР-1000, который использует способ угловых проекций собственного излучения ТВС. Компьютерные эксперименты томографии данного объекта показали, что оптимальными являются измерения интенсивности излучения в 360 точках расположения детектора относительно оси ТВС для двух и более значений энергии гамма-излучения реперного изотопа ^{134}Cs. В этом случае предложенный метод АРТ позволяет идентифицировать на восстановленных томограммах дефектные твэлы с уровнем протечки более 30 %, а также отсутствие твэлов в ТВС. Предложено в современной системе контроля расхода теплоносителя заменить ионизационные датчики на CdZnTe-детекторы.

Ключевые слова: алгебраическая реконструктивная пассивная томография, CdZnTe-детекторы, радиационные датчики, защитные барьеры.