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METHODOLOGICAL ASPECTS OF THE METROLOGICAL SUPPORT FOR THE DETERMINATION OF THE COMBUSTION OF THE PROCESSED NUCLEAR FUEL IN THE PROCESS OF OVERLOADING

The article deals with the issues of metrological support of methodology for controlling burn-out of spent nuclear fuel in real time during congestion. The peculiarity of the technique is that for calculating the burnout, no preliminary knowledge of the initial enrichment and holding time is required. The sources of error, the stages of information processing, which can lead to the appearance of an additional error are determined. The analysis made allowed estimating the errors of determination of burn-up and suggest ways of reducing the error. On the basis of the results obtained, a technique for controlling the burn up of spent nuclear fuel in real time during maintenance service is proposed. The peculiarity of the technique is that for calculating the burnout, no preliminary knowledge of the initial enrichment and holding time is required.

Keywords: error sources, information processing steps, burnout control methods, nuclear fuel.

Statement of a problem. In accordance with safety rules, a conservative approach to justify nuclear safety in storage and transportation of nuclear fuel at nuclear power plants can be removed if there is control over the burnout of irradiated nuclear fuel [1].

The use of the burnout control system for irradiated nuclear fuel makes it possible to really monitor the state of nuclear safety while storing and transporting nuclear fuel, and to reduce financial costs when handling fulfilled nuclear fuel (FNF). At the same time, the decrease in financial costs is due to an increase in the loading of irradiated nuclear fuel into the existing equipment (container for FNF, transport containers) or design of new equipment for FNF without taking a conservative approach to justify nuclear safety.

Combination of burnout control of fulfilled assembly allocating warmly (FAAW) in real time with transport and technological operations will allow to increase the operational efficiency of the nuclear power plant, by increasing the utilization factor of the installed capacity [2]. Currently, there are no such systems for monitoring the burn-up of spent nuclear fuel in real time during transportation and technological operations at nuclear power plants. Taking into account the above, it can be concluded that there is a need to create a system for controlling the burnout of irradiated nuclear fuel, which allows reducing the measurement time, increasing the safety and efficiency of operating the nuclear power plant.

The basic part. To solve this problem, we proposed to use measurements of the gamma radiation of AAW [3]. The justification of radiation methods for monitoring the state of nuclear fuel in real time during congestion is given in [4]. A description of the system that realizes the measurements during the conduction of the overload and its main elements is given in [5 - 7], and the results of measurements carried out at the Zaporozhye nuclear power plant using the prototype system are given in [8]. The system contains several measuring channels, including a detector and a multichannel amplitude analyzer with accompanying electronics [9].

On the basis of the results obtained, a technique for controlling the burnup of spent nuclear fuel in real time during maintenance service [10, 11] is proposed. The peculiarity of the technique is that for calculating the burnout, no preliminary knowledge of the initial enrichment and holding time is required.

However, in presentation of methodology and in other publications devoted to the solution of the problem controlling the burnout of spent nuclear fuel in real time, the issues of metrological support and analysis of the results obtained remained on the sidelines. The purpose of this article is to eliminate this gap.

For further consideration, we briefly outline essence of the methodology. The procedure consists of a sequence of operations to measure and process the results below:

- determination of the holding time using ratio of measured gamma radiation intensity of 137Cs to integrated intensity of gamma radiation;

- estimated burnup calculation (BU) of controlled FAAW on 137Cs, determination of the error ΔBU of the obtained burn-out value;

- determination of ratio intensities gamma radiation of isotopes 134Cs, 137Cs by the time reactor is shut down based on the obtained time of exposure;

- estimation of initial enrichment of AAW, based on the estimated burnup calculation of the controlled FAAW and the value of ratio gamma radiation intensity of the isotopes 134Cs, 137Cs (I (134Cs) / I (137Cs)) at moment shutdown of the reactor;

- determination of the burnout controlled AAW using the ratio of gamma radiation intensity of the isotopes 134Cs, 1137Cs and the initial enrichment value;

- determination of the error ΔBU of the obtained burnout value of the controlled AAW.

The analysis of the technique makes it possible to determine the sources of error, the stages of processing information, which can lead to the appearance of an additional error. Such an analysis makes it possible to estimate the errors in determining the burn-up and take steps to reduce them.

In practice, all known methods, including those described for determining burn-up, use empirical dependencies obtained on the basis of measurements at nuclear power plants, while a part of fuel assemblies is taken as exemplary. And for calculating the calibration dependence, calculated data on the burnup depth are used. Calculation of burnout can be carried out with the use of more complex software, which in the practice of operating nuclear power plants are not used. The measurement procedure for constructing the calibration curves corresponds to the standard procedure for measuring fuel assemblies.

Thus, the following main dependencies used in the control of burnup AAW in real time were obtained [1]:

- dependence of the ratio measured intensity of gamma radiation 137Cs to the integrated intensity of gamma radiation and the time of exposure to fuel assemblies (Fig. 1);

- set of the same dependencies of the ratio intensity of gamma radiation isotopes 134Cs, 137Cs (I (134Cs) / I (1137Cs)) at the moment of shutdown of the reactor from burnup for each initial enrichment value (2, 3, 4%) (тable 1);

- dependence of the gamma radiation intensity of the 137Cs isotope at the moment of reactor shutdown from burnup for all enrichment values (fig. 2).

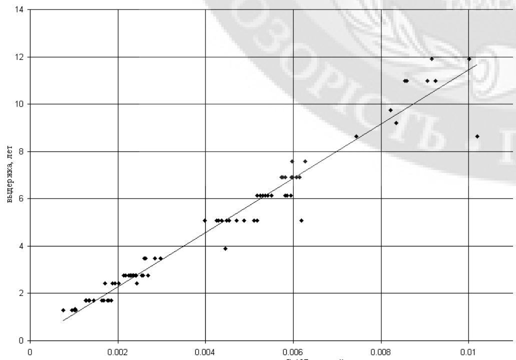

Fig. 1. Dependence of the ratio measured intensity of gamma radiation 137Cs to the integrated intensity of gamma radiation and the time of exposure to fuel assemblies

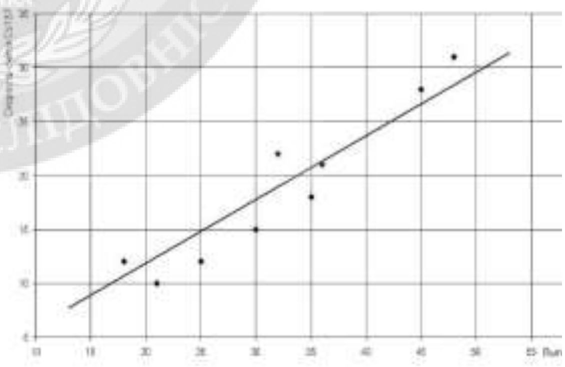

Fig. 2. Dependence of the gamma radiation intensity of the 137Cs isotope at the moment of reactor shutdown from burnup for all enrichment values

With this approach, the error in determining the burnup depth is determined from the set of error estimates performed during calibration of the system in the laboratory, statistical error of the measurements and errors of calibration dependences (an estimate of the aging time and enrichment and determination burning dependence on the intensity of intrinsic gamma radiation of 137Cs and the ratio of the intensity of gamma radiation isotopes of gamma radiation I (134Cs) / I (137Cs)).

Table 1

Relations describing dependence of measured intensity gamma radiation isotope or ratio of gamma-radiation intensities isotopes from burnout

Isotope	Expression
137Cs	$I_{mes} = (2{,}0917 \pm 0{,}167)\ BU$
134Cs/137Cs, enrichment 1,6%, 2%	$I_{mes}(^{134}Cs)/I_{mes}(^{137}Cs) = (0{,}0608 \pm 0{,}0116) BU$
134Cs/137Cs, enrichment 3%, 3,23%, 3,3%	$I_{mes}(^{134}Cs)/I_{mes}(^{137}Cs) = (0{,}0479 \pm 0{,}002) BU$
134Cs/137Cs, enrichment 4,23%, 4,4%	$I_{mes}(^{134}Cs)/I_{mes}(^{137}Cs) = (0{,}0410 \pm 0{,}001) BU$

The error of calibration dependences is determined by systematic error of burnout data used as control AAW and the error due to statistical measurement errors during calibration.

The error in calibration of spectrometer is mainly determined by the error in determining the recording efficiency at peak of total absorption in real measurement geometry and in the case under consideration will be determined by the statistical error for a particular energy point on the calibration curve and error in determining coefficients of equation.

The total statistical error in determining the registration efficiency determined by GOST 26874 is 7.75% with an error in determining activity of a reference source of 5% (this is a conservative estimate, because the maximum value allowed by standard documents for a reference source is 3%), 1%, a statistical error of repeated measurements of peak area of 2.0%. Then the error of graduation - dependence of registration efficiency will be 8.7%.

In this case, the total error (statistical, calibration) of determination of intensity in real conditions of measurements at nuclear power plants was:

- for line 661 keV 137Cs at best - 8.78%, in the worst case it is equal to 17.3%, in most cases the error is equal to 9.2%.
- for 604 keV line, 134Cs is at best 10.6%, at the worst 36%, it is usually 11.8%.
- for sum of the 796 and 802 keV lines 134Cs at best - 9.2%, at the worst 36%, it is usually equal to 10.6%.

The total error in the ratio of the intensity of cesium isotopes without taking into account the reduction in error due to a decrease in the effect of the error in the efficiency of registration is:

- at best it will be 13.24%,
- in the worst case, 29.0%
- the main value is 14.5%.

The total error in ratio of intensity of cesium isotopes with allowance for the decrease in error due to a decrease in effect of rror in the registration efficiency (the inaccuracies in determining the activity of the source and time are compensated):

- at best, it will be 7.94%,
- in the worst case, 29.0%
- the main value is 9.91%.

However, the results obtained from our point of view do not meet the needs of the system. Because simple deviations are very small and this creates a false impression of very accurate results. But if you analyze variance variances, you can get useful information about the main sources of errors.

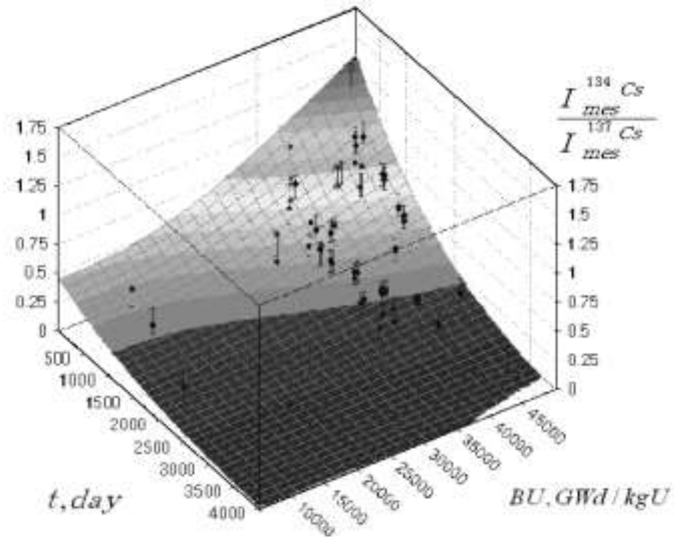

Fig. 3. Dependence of the ratio of activities 134Cs and 137Cs on time of aging and burning out. Surface - calculated values obtained during simulation simulation; points on the surface - experimentally obtained values; Vertical segments are the standard deviation of experimental values from calculated values

Such an analysis shows that the mean deviation of the time definition is very small, but a very large variance in the distribution of errors. This leads to the fact that there is an increase in the error of determination burnout on basis of ratios, since at a typical aging time of several years the error of several percent in the determination of the exposure leads to a large error for 134Cs with a small half-life. But at the same time this is less reflected in 137Cs.

The analysis of the obtained empirical gauge dependences for the ratios (I (134Cs) / I (137Cs)) showed that they practically coincide with the theoretical values considered in [4] and [10, 11] on the basis of [14] (see Fig. 3).

It should be taken into account that these dependences are the basis for calculating the burnout. This allows us to make an assumption about another version of the analysis and interpretation of the results. An approach was proposed that is based on the application of information theory, for example, for numerical evaluation of the results of chemical analytical studies, evaluation of simulation results in the analysis of complex systems [15, 16].

On the basis of the results presented in [16] for statistical evaluation of hypothesis that the collection of experimental data differs slightly from that which, under some theoretical law, a test for compliance can be made using the parameter $\chi2$. In the method $\chi2$, as a measure of the deviation of the experimental points from the expected values, the sum of squares of deviations from the assumed dependence is assumed.

The procedure for using $\chi2$ is as follows:

1. The assumption about the dependence connecting burning out and the relation of activities for each enrichment is put forward.

2. The value of $\chi2$ is determined for each sample (enrichment, statistical error, number of experimental points). When calculating $\chi2$, the difference between the expected theoretical burn-up value and the real

3. The obtained value of $\chi2$ is compared with the normalized tabular value for a given confidence probability. Usually take 0.95.

If the obtained value of $\chi2$ is less than the norm, then we can say that at a given level of confidence, the hypothesis accepted for the quality of the hypothesis describes the experimental data

4. The procedure can be repeated after removing the "misses" (obvious errors).

The value of parameter $\chi 2$ is determined for different enrichment values and statistical error of measurement.

The typical error should be no worse than 10% (see above - 9.91%), therefore this value is used as the main one. The achievable error is 8%. Therefore, the verification is carried out for this value. It is more correct to carry out a calculation with the substitution of an individual experimental value for each observation. But it is very cumbersome - it's very simple to make a mistake. If you need to do this, it will take two days. But usually when testing hypotheses take any one value, usually specified in the regulatory documentation.

To calculate $\chi 2$, we use the formula from [16]:

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{y_{i_{экс}} - y_{i_{теор}}}{\sigma_i^2} \right)^2 . \quad (1)$$

In our case, it is difficult to determine what the current value, experimental and theoretical is. In the calculation, the difference between the declared burn-out value (passport) and calculated on the basis of the dependencies obtained was used - the difference between the experimental points and the surface in Fig. 3. This approach is good because, in principle, one generally does not need to talk about the empirical relationships given in Table 1. When can be argued that burnout calculations use theoretical dependencies on the ratio of isotope activities.

For 4.4% theory and experiment practically coincided, therefore these results do not need further consideration. For 3%, the first four rows in the table are shown on the basis of theoretical calculations (surface in fig. 3), and then for empirical dependencies obtained experimentally (table 1). The time is then used, and indicated in the passport and obtained on the basis of data on the measurement results, the ratio of the intensity of gamma radiation 137Cs to the total intensity of gamma radiation. It can be seen that with a statistical error of 10%, the theoretical dependence for 3% enrichment can be used to determine the burnout after removing deliberately erroneous results. For 8% of the error, confidence probability is 0.9.

For experimental points, result of test always gives a positive result. This is most likely due to the fact that in the calculation of time and in calculating the burnout, the statistical errors of each other mutually compensate.

For the initial enrichment of 4% due to the increase in statistics, the effect of individual emissions is no longer compensated and must be eliminated. However, after removing errors, the results are better than for 3% of initial enrichment.

Therefore, we can safely say that with a confidence probability of 0.95, burnout can be calculated using experimental data on the ratio of gamma radiation intensities of cesium isotopes, and the error does not exceed 10%.

A similar approach is used to estimate the time delay errors. It can be seen that, without exception of errors, the dependence for determining the exposure time should be applied with caution. It should be noted that the small value of the average error (less than 5%).

Conclusions. Thus, it can be concluded that there is a rather high probability (about 25%) of single emissions. This was confirmed by calculating the burn-up using time using the relationship of Fig. 1. The error values shown in tables are confidence intervals. This, according to Shannon, is an estimate of the parameters of the aggregate to which the response variable belongs. For example, if we have an estimate of the true mean, we usually want to determine the upper and the boundaries, so that the probability of the true average falling into the interval enclosed between these boundaries is equal to the given value. " In order to determine the value of the confidence interval, the difference between the "theoretical" burn-out value and the burn-out value determined on the basis of experimental measurements was used (each individual measurement has its own error).

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Без рецензії.

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МЕТОДИЧНІ АСПЕКТИ МЕТРОЛОГІЧНОГО ЗАБЕЗПЕЧЕННЯ ВИЗНАЧЕННЯ ВИГОРЯННЯ ВІДПРАЦЬОВАНОГО ЯДЕРНОГО ПАЛИВА У ПРОЦЕСІ ПЕРЕВАНТАЖЕННЯ

У даній роботі розглядаються питання метрологічного забезпечення методики контролю вигоряння відпрацьованого ядерного палива у реальному часі при проведенні перевантаження. Особливість методики полягає в тому, що для розрахунку вигоряння не потрібно попереднього

знання початкового збагачення і часу витримки. Визначено джерела похибки, етапи обробки інформації, що можуть приводити до появи додаткової похибки. Проведений аналіз дозволив оцінити похибки визначення вигоряння і запропонувати способи їх зниження. На підсьаві отриманих результатів запропонована методика контролю вигоряння відпрацьованого ядерного палива в реальному часі при проведенні технічного обслуговування. Особливість методики полягає в тому, що для розрахунку вигоряння не потрібно попереднього знання початкового збагачення та часу витримки.

Ключові слова: джерела похибки, етапи обробки інформації, методики контролю вигоряння, ядерне паливо.

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МЕТОДИЧЕСКИЕ АСПЕКТЫ МЕТРОЛОГИЧЕСКОГО ОБЕСПЕЧЕНИЯ ОПРЕДЕЛЕНИЯ ВЫГОРАНИЯ ОБРАБОТАВШЕГО ЯДЕРНОГО ТОПЛИВА В ПРОЦЕССЕ ПЕРЕГРУЗКИ

В статье рассматриваются вопросы метрологического обеспечения методики контроля выгорания отработавшего ядерного топлива в реальном времени при проведении перегрузки. Особенность методики состоит в том, что для расчета выгорания не требуется предварительного знания начального обогащения и времени выдержки. Определены источники погрешности, этапы обработки информации, которые могут приводить к появлению дополнительной погрешности. Проведенный анализ позволил оценить погрешности определения выгорания и предложить способы снижения погрешности. На основании полученных результатов предложена методика контроля выгорания отработавшего ядерного топлива в реальном времени при проведении технического обслуживания. Особенность методики состоит в том, что для расчета выгорания не требуется предварительного знания начального обогащения и времени выдержки.

Ключевые слова: источники погрешности, этапы обработки информации, методики контроля выгорания, ядерное топливо.