EXPERIENCE OF COMMISSIONING OF THE SECTORAL MONITORING TIGHTNESS SYSTEM OF FUEL ELEMENTS CLADDINGS (SSKGO) OF RF BN-600, RF BN-800

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Introduction

The sectoral system of monitoring tightness of fuel elements claddings (SSKGO) is a system important for reactor facility (RF) safety. It is designed for operative control of the state of fuel claddings, arising and development of such type faults as “fuel-coolant contact”. Designers of the system are JSC “SSC-RF-IPPE” and JSC “OKBM Afrikantov”.

In 2014-2015 the renewed system SSKGO of RF BN-600 (safety class is 3H) and system SSKGO of RF BN-800 (safety class is 3НУ) were implemented in pilot operation at Beloyarsk NPP in cooperation with Beloyarsk NPP specialists. Renovation of system SSKGO in RF BN-600 is based on replacement of boron neutron counters SNM-14 by suspensions with ionization fission chamber, use of new design in detecting units (DU) of BN-800, application of up-to-date measuring and computing facilities. The suspensions with ionization fission chambers are used in SSKGO of RF BN-800 as well. The performed renew resulted in over 40 % increase in sensitivity of measuring channels to neutron flux density and considerable reduction in the level of background indications caused by neutrons of the core of RF BN-800.

Optimization of technical solutions of RF BN-800 SSKGO

While operating the reactor at power, the main sources of background neutron radiation in the SSKGO detecting units are as follows:

- neutron radiation caused by the reactor core;
- photoneutron radiation caused by polyethylene of detecting units and concrete of the reactor shaft;
- neutron radiation caused by delayed neutron precursors from fuel contaminated surfaces of fuel elements.

The principle of operation of SSKGO used at RF BN-600 and RF BN-800 is based on the opportunity to monitor the component of neutron radiation caused by delayed neutron precursors from depressurized fuel elements at the total background level of neutron radiation caused by other sources.

The detecting unit is designed for the following:

- collimation of delayed neutron flux from the controlled volume of sodium in the area of intermediate heat-exchanger (IHE);
- reduction of background neutron flux to the suspensions of ionization chambers (SIC);
- thermal energy moderation of delayed neutrons.
- The designs of detecting units applied in SSKGO of RF BN-800 and that of RF BN-600 are different, namely:

- mass-dimension characteristics are increased;
- the number of installed suspensions of ionization chambers (SIC) in each detecting unit is extended (three ones instead of two);
- the background effect on SICs is reduced.

In an event of fuel element depressurization to the state of "fuel-coolant contact", the extra source of neutron radiation is arising that is caused by penetration of short-lived fission products – delayed neutron precursors – into the primary circuit coolant. The SSKGO efficiency is determined by the opportunity to monitor neutron radiation caused by delayed neutron precursors from the fault in the fuel element cladding with a minimal area of the free fuel surface contacting with sodium in the primary circuit. The less is the free fuel surface, the higher is the system efficiency.

To assess the efficiency of SSKGO, a statistical error of single measuring is used. It is determined by an expression:

$$\sigma = \frac{\sqrt{N_{\text{фон}} \cdot \delta t}}{N_{\text{фон}} \cdot \delta t} \tag{1}$$

where $N_{\text{фон}}$ is a background velocity of SIC counting, s^{-1};

δt is an exposure time, s.

The minimal area of the fuel surface is determined using a background counting velocity and counting velocity resulting from a minimal area of the fuel surface caused by delayed neutron precursors from faulty fuel elements, in line with an expression:

$$S_{min} = \sigma \cdot \frac{N_{\text{фон}}}{N_{\text{з.н.}}} \tag{2}$$

where $N_{\text{з.н.}}$ is a SIC counting velocity determined by delayed neutrons, which precursors penetrate into coolant from 1 cm^2 of free fuel, s^{-1}.

Resulting from the presented data upon the same exposure time, while increasing the value of $N_{\text{фон}}$, the efficiency is reducing in proportion to $\sqrt{N_{\text{фон}}}$, while reducing the value of $N_{\text{з.н.}}$, the efficiency is increasing in proportion to $N_{\text{з.н.}}$. Therefore, the criterion of SSKGO efficiency is a following coefficient:

$$K = \frac{N_{\text{з.н.}}}{\sqrt{N_{\text{фон}}}} \tag{3}$$

The higher is the value of that coefficient, the higher is the efficiency i.e. the much earlier is the time of identification of arising the fault.

Mainly, the aim of optimization in the design of SSKGO detecting units of RF BN-800 was to reduce background neutron radiation to SICs.

The efficiency of SIC at RF BN-800 compared with that at RF BN-600 increased approximately twice.

Performance of physical measurements on certification of neutron flux density in the SSKGO detecting units using certified neutron sources and determination of errors

For the DU design the physical mock-up of the SSKGO DU identical to the standard SSKGO DU of RF BN-800 was manufactured in JSC "SSC-RF-IPPE". In 2013–2014 in JSC "SSC-RF-IPPE" the IPPE specialists in cooperation with those of FSUE "VNIIFTRI" performed certification of neutron flux density at the SSKGO DU mock-ups that made possible reduce considerably the scope of works and time of performance of measurements at the reactor upon certification of neutron flux density from neutron sources in the standard DUs. With account of the results of certification, the effect of neutron spectrum shape on sensitivity of measuring channels is investigated and strategy-programs of periodical calibration from the standard source of neutrons are developed.

In the process of mock-up experiments, the JSC “SSC-RF-IPPE” specialists in cooperation with those of FSUE “VNIIFTRI” have solved the following tasks:

1. By activation of detectors with uranium-235 with different values of exposure time in DU chambers, the time needed for exposure of tracking detectors based on uranium-235, which were used for certification with required accuracy of neutron fields in the SSKGO DU at Beloyarsk NPP using the certified radionuclide source of neutrons (RSN), was determined.

2. Assessment of the disturbance of neutron flux density in the SSKGO SIC DU is performed, which has revealed the design of the presented DU is optimal and excludes virtually the disturbance of neutron fields in the inner DU chamber due to existence of the SSKGO SIC.

3. Assessment of non-uniformity of neutron flux density in the inner DU chamber where SSKGO SICs are mounted is realized by in turn re-installation of SSKGO SICs in the standard points of their installation in the DU. The analysis of the measurement results has revealed that the values of maximal distinctions of neutron flux density realized in the inner DU chamber in the points of installation of SSKGO SICs do not exceed 3 %.

4. Assessment of the effect of RSN location in the DU on the rate of counting in the SSKGO measuring channel (MC) (disturbance of neutron fields in the inner DU chamber upon a random change of RSN location) is performed. It was realized by multiple RSN re-installation in the DU. The experiment has revealed that upon keeping the location of the source, the rate of counting in SSKGO SICs (and therefore, neutron fields in the inner DU chamber) is invariable.

5. The neutron flux density in the DU that is caused by a RSN used in the experiments performed at the metrological facility (MSPIK) [5] is measured. It was realized by activation of tracking detectors with uranium-235.

The activation data were processed by FSUE “VNIIFTRI” specialists in line with a strategy of GSSSD MR182-2011 (Certificate No. 182 dated on 03.05.2011) with application of complex code KASKAD allowing to obtain energy distributions of neutron flux densities and their errors by use of the experimental data. The energy format of the code is 176 groups at the range of 10^{-10} – 18 MeV formed from 620 groups of ENDF format. The data, which indicate the conformity of energy neutron spectra realized in the SSKGO DU of RF BN-800 with neutron spectra realized in the SSKGO DU of RF BN-600 (cadmium ratio is 20.4 and 21.7 correspondingly), have been obtained.

In the SSKGO DU of RF BN-800 the neutron flux density is calculated by a formula:

$$\varphi_{\text{БД}} = \varphi_0 \cdot \varphi \tag{4}$$

where φ_0 is a unit neutron flux density in the SSKGO DU mock-up of RF BN-800; φ is a ^{238}Pu(α, n) flux – a source of neutrons.

The results on determination of neutron flux density in the SSKGO DU of RF BN-800 have been obtained with an error of 4 % for the confidence coefficient of 0.95.

The data on certification of neutron flux densities obtained in JSC “SSC-RF-IPPE” for the physical mock-up of SSKGO DU of RF BN-800 could be used for performance of calibration of SSKGO MCs of RF BN-800, considering them as reasonable for use directly at Beloyarsk NPP.

At RF BN-600 and RF BN-800 the investigations in stability of technical and metrological characteristics of SSKGO measuring channels based on ionization fission chambers were performed. While operating at different power levels, dependence of background indications on reactor power was determined. Testing of the SSKGO upon putting it in operation at RF BN-600 and RF BN-800 have revealed high reliability and noise-immunity of the systems.

Sensitivity of the renewed SSKGO system

Renew is consisting in replacement of measuring channels with boron neutron counters SNM-14 by channels with SIC suspensions based on ionization fission chamber and electronic equipment and commutation lines for the new hardware complex (HWC).

In the renewed sectoral KGO system the primary converter of neutron flux density is a fission chamber installed in the tight SIC.

The additional source of current pulses in the chamber is alpha particles generated in the process of uranium alpha decay. Power generated by alpha particles and, consequently, current pulses are by a factor of 10-15 less than pulses from fission fragments. Therefore, they could be discriminated by an amplitude.

Setting of the discrimination threshold as well as primary calibration was performed at the MSPIK facility in JSC “SSC-RF-IPPE” [5]. The MSPIK facility is a reactor purity graphite assembly of 2600x2200x1200 mm in dimensions with a neutron source in the center. Radionuclide sources of neutrons ^{238}Pu (α,n) Be are used as sources at the facility. The FSUE “VNIIFTRI” specialists certified neutron flux densities in three channels of the MSPIK facility (F6, E6, D6) with an error of 4 % for the confidence coefficient of 0.95. RSN-1 with neutron flux of $(2.28 \pm 0.09) \cdot 10^6$ 1/s and RSN-2 with neutron flux of $(1.20 \pm 0.08) \cdot 10^8$ 1/s were used.

After setting of the discrimination threshold, sensitivity of detectors was determined in a following way. By knowing the density of neutron flux falling on the detector and counting velocity of pulses in the detector, the detector sensitivity is determined by a formula:

$$\varepsilon = \frac{N}{\varphi_{\text{т}}} \tag{5}$$

where N is a counting velocity of pulses, 1/s; $\varphi_{\text{т}}$ is a density of thermal neutron flux, 1/ $\text{cm}^2 \cdot \text{s}$; ε is a sensitivity to thermal neutron flux, cm^2.

In the result of measurements at the facility, functions of dependence of ε for fission chambers and SNM-14 on discrimination threshold V were obtained. The obtained dependences are presented in Fig. 1 – 3.

The working area of the discrimination parameter for the fission chamber is in the range of $\Delta V \approx (400\text{-}600)$ mV. In that area the measured values of sensitivity of the fission chamber are changed in the range of $\varepsilon \approx (1.1 - 0.94)$ cm^2 (see Fig. 1, Fig. 2).

At the same value of discrimination threshold (for example, V=500 mV), the measured values of ε are changed in a random way that is caused by errors in measurements. In that case an average value of sensitivity is $\varepsilon_{\text{кнт}} = (1.025 \pm 0.025)$ cm^2.

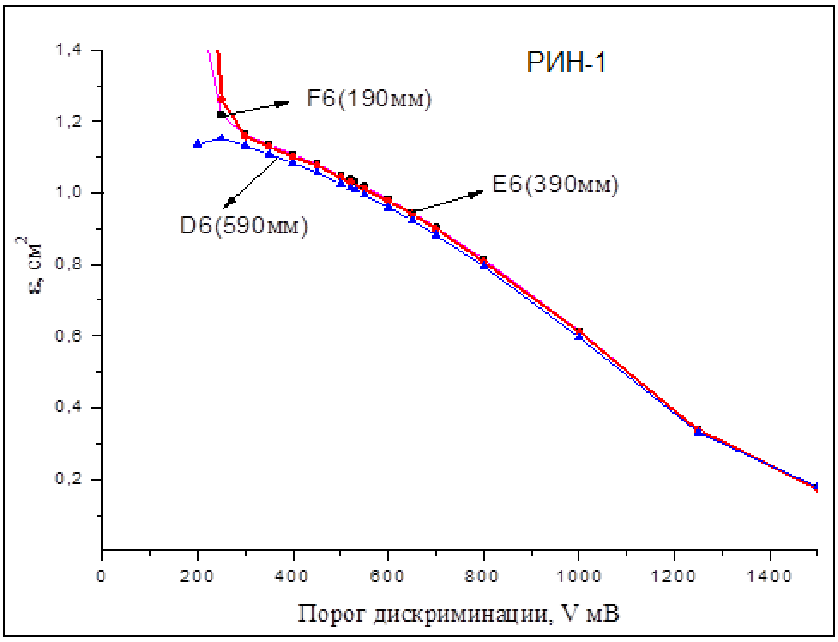

Fig. 1 – Dependence of sensitivity of the fission chamber on a value of discrimination threshold. Measurements are performed at the metrological facility with neutron source RSN-1 in cells F6, E6, D6

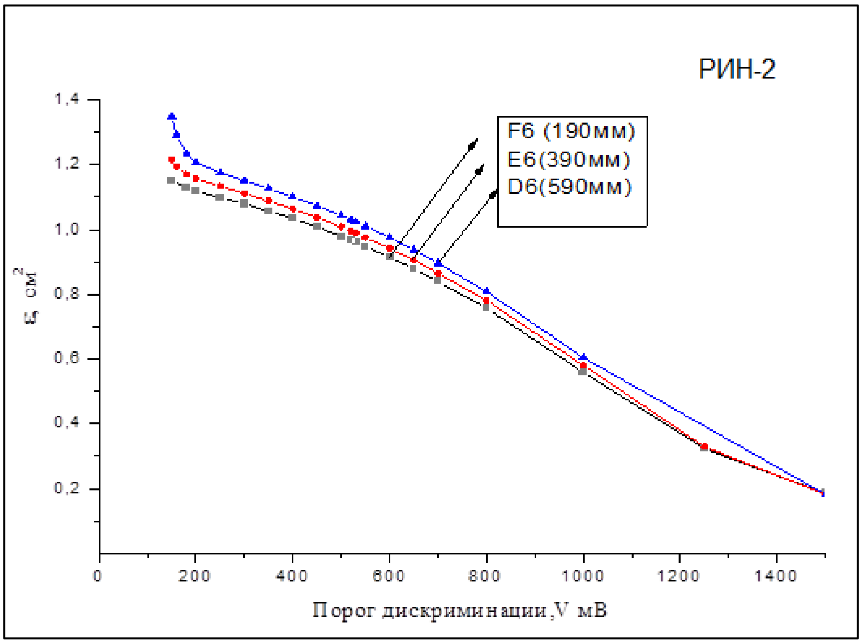

Fig. 2 – Dependence of sensitivity of the fission chamber on a value of discrimination threshold. Measurements are performed at the metrological facility with neutron source RSN-2 in cells F6, E6, D6

Dependence of sensitivity of counter SNM-14 on a value of discrimination threshold is presented in Fig. 3. The following conclusion could be made as a result of the analysis of the presented data:

– the working area of the discrimination parameter for counter SNM-14 is in the range of ΔV≈(500-700) mV.

– at V=600 mV, an average value of sensitivity of counter SNM-14 is $\varepsilon_{\text{снм}}$ = (0.726±0.064) cm^2. That value virtually agrees with a passport one.

– sensitivity of the fission chamber is exceeding that of counter SNM-14 approximately by a factor of 1.4 (1.025/0.726).

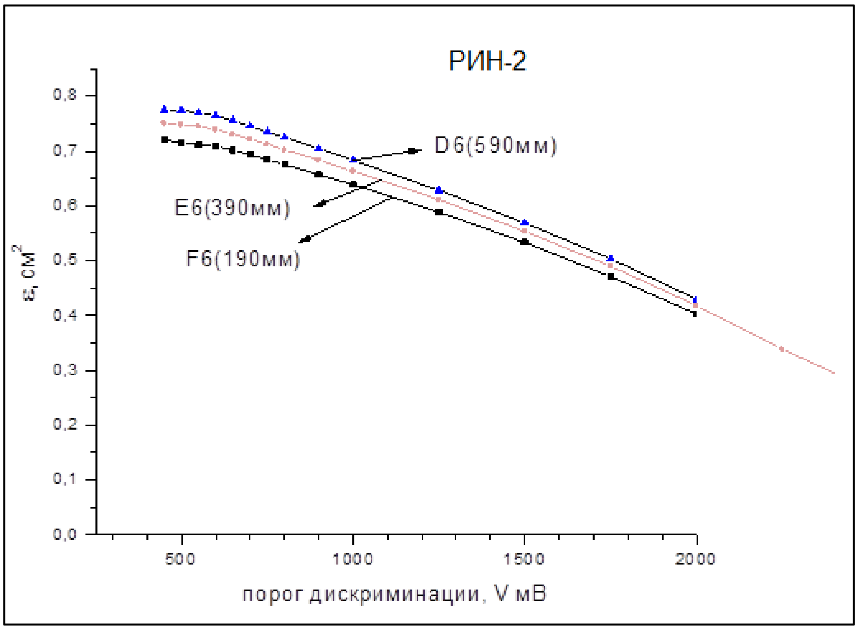

Fig. 3 – Dependence of sensitivity of counter SNM-14 on a value of discrimination threshold. Measurements are performed at the metrological facility with neutron source RSN-2 in cells F6, E6, D6

At the metrological facility for all fission chambers included in the renewed SSKGO system the sensitivity was set in the range of ε=(1.04 – 1.05) cm^2 by varying the value of discrimination threshold within a working area of discrimination parameters.

For fourteen fission chambers the average value of sensitivity is $\varepsilon_{\text{КНТ}}$=(1.047±0.0023) cm^2.

SSKGO indications for RF BN-800

The measurements of SSKGO neutron fluxes were performed at the stage of launching of RF BN-800:

1. The measurements on determination of neutron flux densities in working areas of the SSKGO DU using the certified source of neutrons in conditions of RF BN-800 at unit No. 4 of Beloyarsk NPP are performed. Measurements of the simulated reference neutron field in working chambers of the SSKGO detecting units of RF BN-800 are performed in line with FSUE “VNIIFTRI” strategies with application of tracking fission detectors. The analysis of the results have revealed the noticeable difference in indications of the SSKGO MC of RF BN-800 (mean value is 285.5 n/cm^2·s) from those obtained while determination of the simulated reference neutron field in the DU with use of FSUE “VNIIFTRI” strategies (161.0 n/cm^2·s). “Sensitivity” of the SSKGO SIC8 MC determined at facility MSPIK differs from that of the MC obtained while the measurements are performed at the SSKGO DU of RF BN-800. That difference is caused by difference in energy neutron spectra realized in different moderating media. The calculations have revealed the spectra formed at facility MSPIK are more corresponding to the spectrum of delayed neutrons.

2. The calculation assessments have revealed that in the performed experiments with source IBN-8-1 at RF BN-800, the measuring channel “sensitivity” is changing by a factor of 1.5 – 1.6 (dependent on the chosen margin for thermal neutrons) compared with measurements at facility MSPIK.

3. It should be highlighted the performance conditions for the experiment with source IBN-8-1 at RF BN-800, which are described in the present paper, differ from those for measurements at the operating reactor due to different spectra of thermal neutrons.

Primary processing of the information and data analysis

Experience of operating the SSKGO at RF BN-600 and RF BN-800 has revealed the separate tasks dealt with:

- determination of background values for correct calculation of the background excess value;
- updating of the process of calibration of the SSKGO MC;
- optimization of the process of primary processing of the information obtained from the SSKGO and next data analysis.

Determination of background values

In case of absence of untight fuel elements in the core, the SSKGO MC indications are determined by a background of core neutrons. The background values are strongly dependent on DU location in the reactor shaft and power-unit operating modes [1], [3].

At present the values of background indications of channels are inserted by the operational personnel by hand. Determination of background indications by calculation will make it possible to avoid errors while inputting, more accurately separate the signal component from delayed neutrons, provide more reliable forecasting of the time of achievement of the SSKGO emergency setpoints and accuracy in localization of faulty assemblies [2].

And so, the method of forecasting of background indications of the SSKGO MC depending on reactor power and DU temperature was developed and tested for the real indications at RF BN-600 and RF BN-800. The regression models are developed for each MC [3].

The general view of the model is as follows:

$$\frac{\left(N(t)-k_1\cdot t_{\text{эфф}}(t)\right)}{W(t)}=k(T(t),\,dT(t)) \tag{6}$$

$$k(T(t),\,dT(t))=k_1+k_2\cdot\left(T(t)-T_{\text{ср}}\right)+k_3\cdot dT(t) \tag{7}$$

where N – MC forecasting value, neutron flux density, n/cm^2·s;

k, k_1, k_2, k_3 – regression coefficients; $t_{\text{эфф}}$ – time of reactor operation, efficient days; W – reactor power, %N$_{\text{ном}}$; T – temperature in the DU, °C; $T_{\text{ср}}$ – average temperature in the DU, °C; $dT = T(t) - T(t-1)$ – temperature difference, °C; t – time moment.

To control the quality of the regression model, the following parameters were used: absolute residual function $D(t)$ (8) and relative residual function $\delta(t)$ (9), which were calculated using the data averaged over minutes.

$$D(t)=N_{\text{исх}}(t)-N(t) \tag{8}$$

$$\delta(t)=\frac{D(t)}{N_{\text{исх}}(t)} \tag{9}$$

where $N_{\text{исх}}(t)$ – MC initial indications, neutron flux density, n/cm^2·s; $N(t)$ – MC forecasting value in accordance with regression model (6), neutron flux density, n/cm^2·s.

The sample size includes 150000 values. The investigation results have revealed that maximal values of D and δ specify the MC with a low value of background. For the MC with a maximal value of background, the relative residual function does not exceed 2%.

There is also a necessity to provide “on-line” forecasting of SSKGO MC indications. Though the results of determination of MC indications in the initial micro-lifetime (ML) are positive, application of regression models to the data obtained in the next MLs has revealed the following problems:

- systematic disagreement in initial and forecasting indications;
- disagreement in the initial and forecasting SSKGO MC indications upon increasing power-production and corresponding rise of the current residual function.

That is why to provide “on-line” forecasting of SSKGO MC indications, the algorithm of adaptation of regression models coefficients to the conditions of the new ML has been developed, which, if necessary, assures their automatic correction (see Fig. 4).

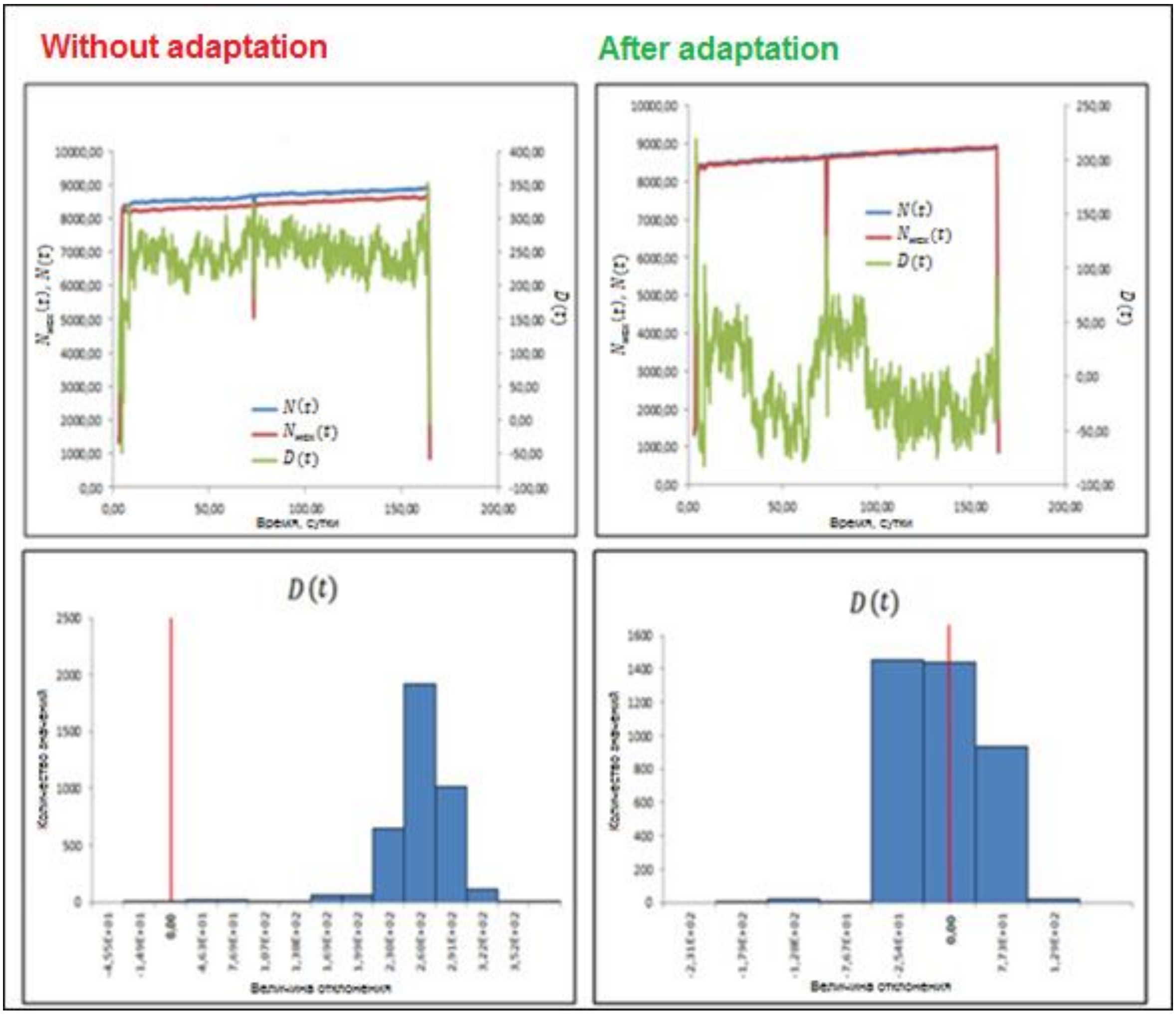

Fig. 4 – The result of application of the adaptation algorithm to the SSKGO MC

Calibration of the SSKGO MC

The methods of reliability control of indications (paired regression and median filtration) have been developed and tested for the real SSKGO indications at RF BN-800. The methods allow performance of control of SSKGO functioning in the inter-calibration period and, in future, to give up the radiation-hazardous procedure of SSKGO calibration using the neutron source.

Optimization of information primary processing

The information obtained from the KGO sub-systems needs in regular processing that is performance of calculations, analysis of the data and compiling of reporting protocols.

However, that process includes a sizeable scope of technical functions concerned with a necessity in reading and formatting of the initial data, plotting of diagrams and Tables, insertion of results in Word-files and compiling of reporting protocols. Realization of routine functions is taking much time, so the specialist must focus attention not only on finding the solution to the main task of the KGO, but on observance of the sequence of technical manipulations such as text highlighting and copying, making Tables and diagrams, and so on. To enhance the working efficiency of the KGO specialist, the computerized workstation (CWS) of the KGO is being designed [4].

The KGO CWS is functioning in the following processes:

- normal reactor operation;
- refueling of the fuel sub-assemblies (FSA) at the shutdown reactor;
- washing of the spent FSA after unloading

In the mode of KGO CWS standard functioning, performance of the following tasks is provided:

- the textual, graphic and Table information is displayed;
- maintenance of archives and compiling of protocols at the operator’s request;
- performance of calculation of parameters, which specify tightness of fuel elements in the core;
- determination of the location of untight FSA by joint analysis of the data received from the KGO systems and upper level of the TP ACS (technological processes automated control system).

The software of the KGO CWS is realized under OS Windows and includes a set of add-ins for MS Excel, which have been developed using Visual Basic for Applications (VBA) as a program language in MS Office. The proposed approach makes possible enhancement of working efficiency of the specialists by computerization of routine functions in conditions of traditional data processing.

Moreover, in the process of development the integrated approach on solving the KGO task is formed based on the used methods of regression analysis, pattern recognition, correlation and spectral analysis.

At present the SSKGO of RF BN-600 and that of RF BN-800 are in standard operation at Unit 3 and Unit 4 of Beloyarsk NPP.

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