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MONITORING OF LOCAL PERTURBATIONS OF THE MULTIPLICATION FACTOR ON OVERLOADS IN THE CORE OF A SHUT-DOWN REACTOR

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A method of revealing the fact of existence (absence) of a local region in the reactor core with an anomalous value of the multiplication factor, detection of this region, and on-line monitoring of its "movement" throughout the volume of the core of a shut-down reactor during the entire period of overloading is proposed.

The problem of monitoring of the distribution of the multiplication (breeding) properties throughout the volume of the core of a physically large heterogeneous reactor considered as an object of control with spatially distributed physical characteristics becomes particularly important and pressing in overloading of assemblies of dissipative fuel elements in a shut-down reactor when monitoring of the neutron power is made difficult by the low density of the thermal-neutron flux and the high γ-ray background. When an assembly of dissipative fuel elements is removed, such a reactor is characterized by the formation of a peak of the neutron flux localized on the finite group of working assemblies surrounding the removed assembly (see Fig. 1).

If, as a result of a mistake of the technical personnel, the removal of another assembly (formation of an interfering double neutron trap) is begun near such a local inhomogeneity of the neutron field (neutron trap), then under certain unfavorable conditions in the reactor there can arise a zone with anomalously high multiplication properties (increased energy release) – a local "boiler" with a neutron-multiplication factor $K_{\infty} > 1$. It should be noted that the mistake can be "hidden" from the operating personnel of the reactor, i.e., they can be unaware of the fact that the absorption properties of the dissipative fuel elements of the assembly that is loaded into the reactor-core cell differ, for any reason, from the properties indicated in the loading cartogram.

Despite the continued work on monitoring traps in the core of a shut-down "R" reactor, the problem of monitoring of the overloads of absorbers (of the type of central assemblies and rods of the monitoring and safety system) and determination of the coordinate of the potentially dangerous trap remained unsolved because of the absence of standard intracore neutron detectors and low-sensitivity side measuring channels (SMC). The solution of the problem was significantly simplified when the subcriticality monitoring system (SMS) (developed at the Research and Design Institute of Power Equipment) was brought into service.

The system includes six subcore measuring channels (SCMCs) for monitoring of the neutron flux plus a channel for monitoring of the intrinsic function of the neutron source (gamma-converter) and four side channels (SCs). The suspensions of the subcore measuring channels are positioned in the sleeves of the energy release monitoring system, in cells 11–26, 11–42, 17–20, 19–50, 27–26, and 27–42, while the gamma-converter is positioned in cell 16–41 (see Fig. 2). There is a post for control of the suspension drives that provides a means for automated alternate displacement of the neutron fission chambers with a solid radiator

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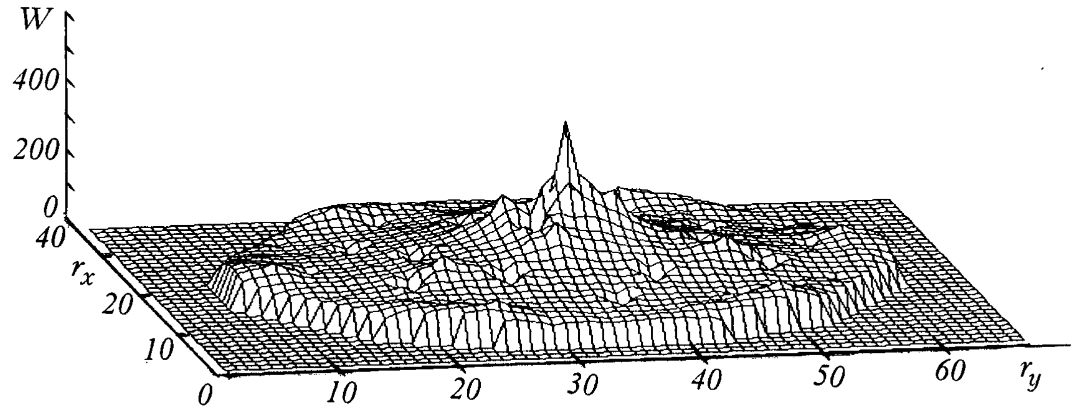

Fig. 1. Isometric representation of the field of energy release W obtained using the program STAT-42 for an "R" reactor in the shut-down state (modeling of a trap in cell 20–35). W, rel. units; r_x and r_y, step of the FA grid.

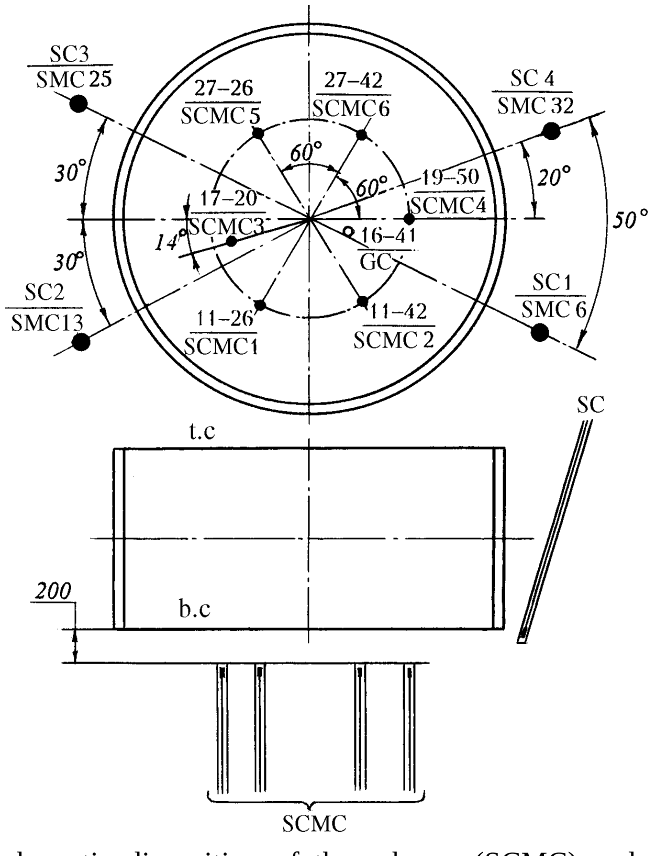

Fig. 2. Schematic disposition of the subcore (SCMC) and side (SC) measuring channels of the subcriticality monitoring system (t.c and b.c are the top and the bottom of the reactor core, respectively).

of the type KNT-31-1 of the subcore measuring channels down from the extreme upper position (~ 200 mm from the lower plane of the core) for a distance of ~ 600 mm with a step of 4 mm, and the chambers can be stopped at any intermediate mark chosen by the operator. The chambers of the side channels of the subcriticality monitoring system move in the sleeves of the side measuring control channels in much the same way as the chambers of the subcore channels down from the extreme upper position (upper plane of the core) for

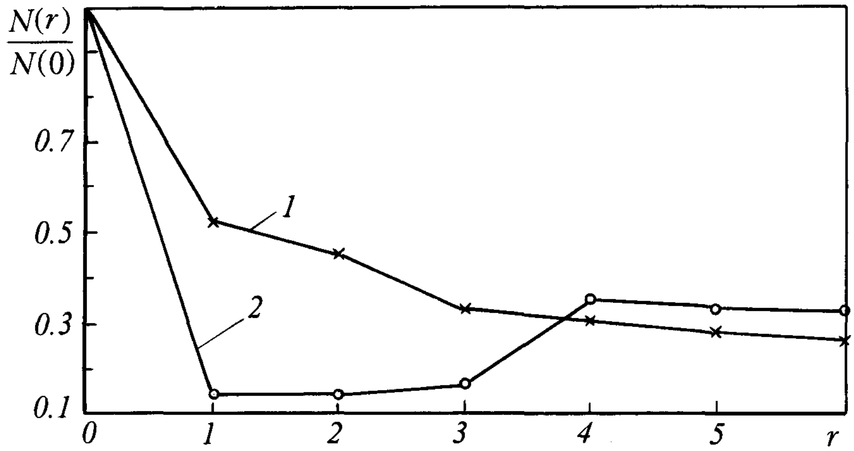

Fig. 3. Calculational dependences of the change in the relative indication of the counting rate of the subcore NS (cell 27–26) on the distance to the center of the local perturbation "moving" in the direction of the center of the core (cell 20–33) in the projection on the horizontal plane: 1) homogeneous loading in the perturbation zone; 2) inhomogeneous loading in the perturbation zone. $N(r)/N(0)$, rel. units; r, step of the FA grid.

a distance of ~1000 mm (along the length of the suspension). The information-measuring communication lines (of length ~110 m) of each group of measuring channels (subcore and side) are connected independently of each other to the corresponding posts of collection and primary processing of data. Each of the posts is connected to a personal computer through an individual interface. The neutron-physical calculation proper of the subcriticality and the reactivity effects is carried out by a computer program in the "ON LINE" regime. The software presented by the development engineer contained programs in three versions: programs for work only with subcore sensors, programs for work with side sensors, and programs for combined work of subcore and side sensors.

The calculational modeling of the reactivity effects for the case where absorbers are removed performed by the authors using the two-group software complex STAT-42 (the author of the complex is S. N. Barkov, Institute of Nuclear Reactors of the "Kurchatov Institute" Russian Scientific Center), in which diffusion equations for planar geometry are solved, has shown that the indications of the subcore measuring channels can be used for monitoring of the occurrence of traps. Comparative analysis of the calculated "indications" of the hypothetical intracore chambers demonstrates that the relative change in the energy release (proportional to the "indications" of the hypothetical intracore chambers) in the cells of the reactor core is sufficiently informative to be used for determination of the coordinate of a local perturbation of the density of the thermal-neutron flux. Moreover, in mathematical modeling of the construction of the functional dependence of the relative change in the indications of the subcore measuring channels on the distance to the center of the perturbation of the neutron flux, it has been established that the form of this dependence is largely determined by the inhomogeneity of the core loading (see Fig. 3).

The experimental investigations of the sensitivity of the system to local perturbations (standard overloads of the central assemblies), which were carried out during the scheduled shutdowns in 1997–1999, have shown that:

a) the sensitivity of the subcore fission chambers of the subcriticality monitoring system decreases with increase in the depth of the subcriticality;

b) for subcriticalities of ~$1.6–2.0\beta_{ef}$ and a stop time of ~300 h of the subcriticality monitoring system, the localized perturbations positioned in the zone of the core plateau are reliably recorded by a group of subcore measuring channels.

c) six subcore fission chambers make it possible to record the overloading of the "R" reactor throughout the volume of its core over the time interval from the moment of shutdown to the moment of exit from the "iodine hole" ($4\beta_{ef} \le \rho_{subcr} \le 10\beta_{ef}$);

d) for the subcriticality $4\beta_{ef} \le \rho_{subcr} \le 10\beta_{ef}$ and the perturbation effect $\Delta\rho \approx 0.1\beta_{ef}$, the radius of the sensitivity zone of a subcore sensor is ≈ 2–3 steps of the grid of the fuel assemblies (FAs);

c) for reliable monitoring of the overloading of products throughout the volume of the reactor core of a subcritical "R" reactor, it is necessary to have ~20 subcore measuring channels positioned at the nodes of a triangular grid with a step R equal to ≈ 6 steps of the fuel-assembly grid;

f) the form of the distribution of the interval counting rates of neutrons (CRN) of the subcore measuring channels of the subcriticality monitoring system of a shut-down "R" reactor does not change within ~4000 h of its step; the distribution was classified as flattened unimodal, representing the composition of exponential and uniform distributions, and close to the normal distribution, which allows one to use the "rule of three sigmas" as a significance criterion of the change in the counting rate of a subcore channel in the case where a trap appears in the zone of its sensitivity.

Analysis of the base of experimental data revealed a functional dependence of the relative change in the counting rate of neutrons of a subcore channel on the distance r to the perturbation center in the subcritical reactor for any type of product of the core and the levels of subcriticality $\rho_{subc} < 4\beta_{ef}$. We proposed that this dependence have the form $\dfrac{N\uparrow - \overline{N}_{buf}}{\sigma_{buf}}(r) = \mathrm{A}r^{-B}$, where A and B are constants. The form of the regression was chosen from the 12 most frequently used functional dependences by the maximum correlation factor.

The regression curves obtained were used for the development of the method of detecting local perturbations of the multiplication factor in the core of a subcritical reactor and determination of its probable coordinate based on the indications of the system of neutron sensors (NSs).

The method implies that the rod-absorbers (assemblies of dissipative fuel elements and other sources of perturbation of the multiplication properties) are moved successively and equally in the reactor core and the response of the neutron field to these displacements is determined from the signals of the neutron sensors. A special feature of this method is that the efficiency of a rod-absorber is not measured. It is implied that the system of neutron sensors ("grid") is positioned in one plane perpendicular to the longitudinal axis of the reactor core and it can be both intracore and extracore. In the latter case, the above-mentioned plane should be positioned at such a distance that the fact of existence of a local perturbation at any point of the reactor core be recorded by at least two neutron sensors. Moreover, the number of neutron sensors (it is determined by the ratio of the area of the core to the area of the zone of minimum sensitivity of neutron sensors to a local perturbation) is chosen on the assumption that the zones of minimum sensitivity of neutron sensors to a local perturbation are partially overlapped. By the zone of sensitivity of a neutron sensor to a local perturbation (which is determined experimentally) we mean the circle of radius r_s equal to the distance from the neutron sensor to the center of the local perturbation, at which the relative change in indications of the neutron sensor is still significant. The statistical criterion is used as the significance criterion and for determination of the fact of existence of a local inhomogeneity of the density of the thermal-neutron flux (a local perturbation (LP) of the multiplication factor in the core) as applied to the interval values of the counting rate of neutrons of a neutron sensor. To decrease the dispersion of the analyzed signal from a neutron sensor, we took for this signal not the running value of the counting rate but its value averaged over the m-point interval, i.e., the interval value of the counting rate. The most probable coordinate of a local perturbation (extremum of the neutron field) is determined using a regression dependence of the relative change in the indications of the neutron sensor on the distance to the perturbation center that is constructed in advance from the results of experimental investigation of an equal displacement of preassigned absorbers with identical absorption properties in the direction of a decrease in the subcriticality. The sought coordinate of the local per-

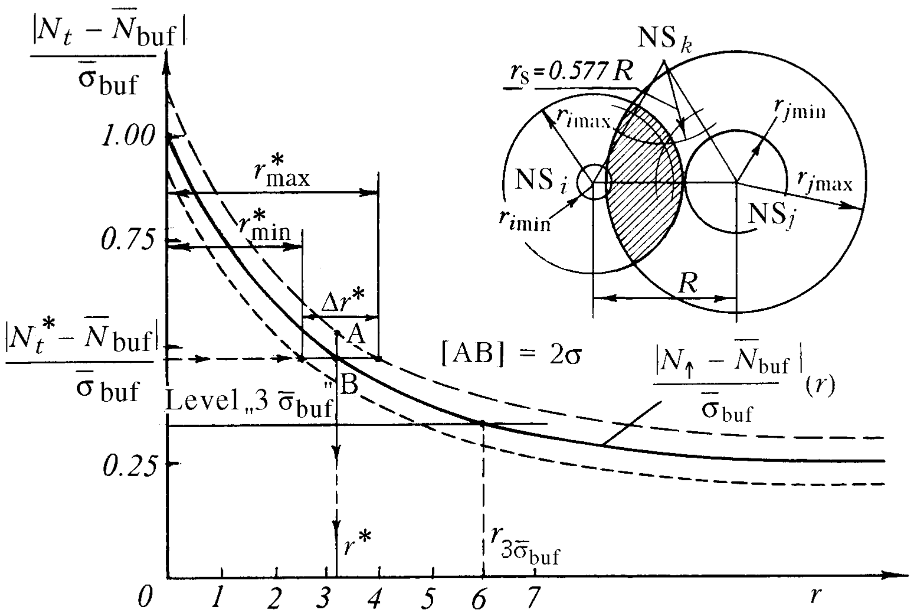

Fig. 4. Regression curve. $(N_t - \overline{N}_{\text{buf}})/\overline{\sigma}_{\text{buf}}$, rel. units; r, step of the FA grid.

turbation is determined from the measured running value of the relative change in the indications of the neutron sensor.

A distinctive feature of the method proposed is that it does not require that the reactor be converted to a nuclear-hazardous critical state and the efficiencies of the absorbers (both single absorbers and their groups) be calculated within the framework of the adopted physical models operating only conventionally. Moreover, monitoring of a local perturbation of the multiplication factor is performed throughout the volume of the core on the basis of only the initial information, i.e., individual changes in the counting rates of neutrons of neutron sensors averaged over the same time interval. The above-mentioned parameter can be monitored by hand or using a personal computer, continuously and in real time, throughout the period of shutdown of the reactor.

The method is illustrated in Fig. 4. It is realized in the following order.

1. In the initial stationary subcritical state (displacement of the rods of the control and safety system or of the assemblies of dissipative fuel elements is absent and there is no trap in the reactor core), the interval values (averaged over the interval Δt) of the counting rates (N_i) of each neutron sensor, their standard deviations (σ_i), and their values ($\overline{N}_{\text{buf}}$, $\overline{\sigma}_{\text{buf}}$) averaged over n intervals (the time of "rest" is $t_{\text{r}} = n\Delta t$) are calculated:

$$\overline{N}_{\text{buf}} = \frac{\sum_{i=1}^{n} N_i}{n}, \quad \overline{\sigma}_{\text{buf}} = \frac{\sum_{i=1}^{n} \sigma_i}{n}, \tag{1}$$

where $N_{\text{buf}} = \{N_1; N_2; \ldots N_n\}$ and $\sigma_{\text{buf}} = \{\sigma_1; \sigma_2; \ldots \sigma_n\}$ are respectively the buffer of interval values of the counting rates of neutrons and the buffer of standard deviations for each neutron sensor; Δt = const is half the minimum time within which a trap is found in the reactor core and which is determined as an interval of the average time from the beginning of removal of an assembly of dissipative fuel elements from the core to the return of them to the core (lifetime of the local perturbation); n = const is the number of intervals (the buffer capacity).

The interval of averaging Δt is chosen from the following considerations:

a) to decrease the dispersion of the analyzed signal (interval counting rate of neutrons), it is necessary to have a maximum number of readings m of the running counting rate in the interval Δt;

b) the upper limit is imposed by the nuclear safety requirements, and the period within which the subcriticality is determined in overloading must not exceed $\Delta t_{\max}$:

$$\Delta t_{\max} = \frac{\rho_n - \rho_{\min}}{V_\rho^{\max}} . \tag{2}$$

2. A successive displacement (removal and return to the initial position or another equal displacement in the direction of a decrease in the subcriticality) of sources (equal in absorption properties) of perturbation of the multiplication properties of the same type (rods of the control and safety system and assemblies of dissipative fuel elements) is performed in the cells of the reactor core that are chosen in advance, and the obtained values of the relative change in the signals of the neutron sensor are used for construction of a regression dependence on the distance to the source of perturbation (see Fig. 4):

$$\Delta_{\text{buf}} = \frac{N_{\uparrow} - \overline{N}_{\text{buf}}}{\overline{\sigma}_{\text{buf}}} (r) . \tag{3}$$

3. During the overloading, the fact of the presence of a local perturbation in the reactor core is determined from the change in the average (interval) values of the counting rate of neutrons of the neutron sensor in accordance with the following criterion of the boundary value of the counting rate N_b:

$$N_b = t_b \, \overline{\sigma}_{\text{buf}} , \tag{4}$$

according to which, when the running interval value of the counting rate $N_t = N_t^*$ of any neutron channel exceeds the average buffer value of this channel $\overline{N}_{\text{buf}}$ by $t_b \overline{\sigma}_{\text{buf}}$ (i.e., $N_t^* - \overline{N}_{\text{buf}} \geq N_b$), a positive conclusion of the significance of the perturbation, i.e., of the presence of a local perturbation in the reactor core, is drawn. In the case where the perturbation is recognized to be insignificant ($N_t - \overline{N}_{\text{buf}} < N_b$), the running interval value of the counting rate N_t is entered in the buffer with a shift to the left and removal of the first buffer element (interval value of the counting rate of neutrons) by the principle "last in – last out," by which a constant renewal of the buffer is attained. Then the drift of the values of $\overline{N}_{\text{buf}}$ and $\overline{\sigma}_{\text{buf}}$ is corrected by formula (1). The procedure described is required in order that the variation in the neutron flux due to the drift of the physical properties of the reactor core be taken into account.

4. In the case where the perturbation is significant ($N_t = N_t^*$), the coordinate of the local perturbation, which is considered as the most probable radius r^* separating the local perturbation from the neutron sensor, is determined by the regression dependence using the measured value of N_t^* and the running value of the relative change in the indications of the neutron sensor $(N_t^* - \overline{N}_{\text{buf}})/\overline{\sigma}_{\text{buf}}$, calculated from the measured value of N_t^* (see Fig. 4). The most probable zone of perturbation localization is a ring bounded by the radii $r^*_{\min}$ and $r^*_{\max}$. If the number of neutron sensors determining the running change in the counting rate as significant is two or more, the probable zone of perturbation localization can be marked on the videogram of the core as a region of intersection of several circles (shaded region in Fig. 4). Figure 4 also shows the level "$3\overline{\sigma}_{\text{buf}}$" (for the normal distribution of interval counting rates, $t_b = 3$ [1]), the distance $r_{3\overline{\sigma}_{\text{buf}}}$ from a neutron sensor to the local perturbation (radius of the circle with a center at the point of location) that corresponds to the level $3\overline{\sigma}_{\text{buf}}$ and at which the neutron sensor can still record the perturbation as significant, and a fragment of the regular triangular grid of the neutron sensor.

The method proposed makes it possible to increase the reliability of monitoring of changes in the multiplication properties throughout the physical volume of the reactor core in the real-time mode during overloading using an optimum finite number of neutron sensors and to make this monitoring continuous (on-line).

NOTATION

K_∞, neutron-multiplication factor; t, time; β_{ef}, effective fraction of delayed neutrons; ρ_{subcr}, depth of subcriticality; ρ_n, minimum value of the "normal" subcriticality; ρ_{min}, minimum value of the subcriticality which is considered as safe in the state with a local perturbation; R, step of the grid of the neutron sensor (triangular in this case) such that $R < r_{3\bar{\sigma}_{buf}}$; $\bar{N}_\uparrow$, value of the counting rate of neutrons of the neutron sensor averaged over the interval Δt in the perturbed state (with a trap); N_{buf}, interval value of the counting rate of neutrons of the neutron sensor found in the buffer; $\bar{N}_{buf}$, value of the counting rate of neutrons averaged over the buffer of interval values of the counting rate of neutrons (without a trap); N_b, boundary value of the counting rate of neutrons; σ, standard deviation; σ_{buf}, standard deviation of the running interval N_t values of the buffer; $\bar{\sigma}_{buf}$, value of the standard deviation averaged over the buffer of interval values of the standard deviations (without a trap); r^*, most probable radius of the circle containing a trap with a center at the point of location of the neutron sensor; Δr^*, interval of uncertainty in the coordinate r^* that is due to the heterogeneity of the reactor-core loading; r_x and r_y, axes of the Cartesian coordinate system; t_b, boundary value of the quantile factor of the significance boundary for the distribution of the interval values of the counting rate of neutrons that depends on the form of the distribution and the volume of sampling of the analyzed data [2]; V_ρ^{max}, maximum rate of the reactivity change (decrease in ρ_{subcr} as a result of the perturbation-removal of an absorber); W, energy release. Subscripts and superscripts: max, maximum; min, minimum; t, observed at the instant t (running); ρ, reactive; b, boundary; buf, buffer; $\uparrow$, perturbed (removed); n, normal; r, rest; subcr, subcritical; s, sensitive; ef, effective.

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