ABSTRACT

Based on the method of neutron flux expansion by proper orthogonal functions for a homogenous stationary task, conditions of the VVER-1000 stability in radial-azimuthal and axial xenon power fluctuations have been studied in this work. It is shown that even under the great negative power reactivity coefficient, the increase in neutron flux at the end of the fuel cycle destabilizes the VVER-1000 core in xenon transients, and the reactor can be stabilized and xenon fluctuations can be suppressed only by the control rods movement. Results of VVER-1000 stability analytical assessment based upon the methods of mathematical physics absolutely comply with results of the straightforward numerical simulation of xenon transients with the three-dimensional dynamic computer code DYN3D [1,2].

INTRODUCTION

In thermal reactor with high level of the neutron flux there exists the possibility of appearing local fluctuations of power caused by periodical spatial-temporal redistribution of xenon concentration due to local disturbing of neutron flux. The period of such power fluctuations is close to that of I-135 half-life. If these fluctuations will be of damping, or continuous, nature depends upon the value of neutron flux inside reactor, magnitude and sign of the power reactivity coefficient, as well as upon a number of other factors.

1. Linearizing equations

Since xenon fluctuations occur inside the large thermal reactors, then one can accept that the one-group diffusion approximation is sufficient enough for describing transfer of neutrons. Also, we will assume that yield of Xe-35 is induced by $\beta$- decay of I-135 (it means, direct output of xenon due to fission of the fissile isotopes will be neglected) and, since xenon transients are slow ones, we will consider that prompt and delayed neutrons are emitted after fission simultaneously. To start with, let us consider the reactor with zero power reactivity coefficient. Then, the system of equations describing the spatial-temporal behaviour of the neutron flux taking the feedback of Xe-135 into account, can be written as:

$$\frac{1}{\Sigma,\nu} \frac{\partial \Phi}{\partial t} = M^{-1} \Delta \Phi + (K_0^{(r)}(r) - 1) \cdot \Phi (r,t) + \delta \cdot K_\infty (r,t) \cdot \Phi (r,t)$$

$$\frac{\partial X}{\partial t} = \lambda, I - \lambda, X - \sigma, X \cdot \Phi (r,t)$$

$$\frac{\partial I}{\partial t} = -\lambda, I + \gamma, \Sigma, \Phi (r,t)$$

(1)
\[ \delta K_\star (r,t) = \alpha_s (X (r,t) - X (r,0)) \]  

(1)

Here: \( \tau_\star \) - neutrons life time, \( \alpha_s = \frac{1}{K_\star} \frac{\partial K_\star}{\partial X} \), while the rest of designations are the conventional one.

After presenting the value of each function in its deviation from the relevant stationary condition as:

\[ \Phi (r,t) = \Phi (r,0) + \delta \Phi (r,t) = \Phi_\star + \delta \Phi, \]

\[ X (r,t) = X_\star + \delta X, \]

\[ I (r,t) = I_\star + \delta I. \]

the system of equations (1) can be written in the linearized form as follows:

\[ \frac{\partial \Phi}{\partial t} = \tau_\star \frac{\partial \Phi}{\partial t} - \tau_\star \Phi - \sigma_\star \Phi, \]

\[ \frac{dX}{dt} = \tau_\star \frac{\partial X}{\partial t} - \sigma_\star \Phi - \sigma_\star \Phi_\star, \]

\[ \frac{dI}{dt} = -\lambda_\star I + \lambda_\star \Phi. \]

\[ \delta K_\star = \sigma_\star \Phi. \]

Here: \( \Phi = \frac{\delta \Phi (r,t)}{\Phi_\star}, X = \frac{\delta X (r,t)}{X_\star}, I = \frac{\delta I (r,t)}{I_\star} \), where \( \Phi_\star, X_\star \), and \( I_\star \) - average values of neutron flux, xenon and iodine concentrations (invariant as to the coordinates);

\[ \tau_\star = \lambda_\star + \sigma_\star \Phi_\star (r) = \lambda_\star + \sigma_\star \Phi_\star \] - time constant by xenon;

\[ \sigma_\star = \sigma_\star \Phi_\star. \]

While deriving the linearized equations (3) the following correlations were used:

\[ M \cdot \Delta \Phi + (K_\star - 1) \cdot \Phi (r) = 0; \]

\[ \lambda_\star I_\star - \lambda_\star X_\star - \sigma_\star X_\star \Phi_\star (r) = 0; \]

\[ \delta K_\star \delta \Phi = \varepsilon \quad \text{and} \quad \sigma_\star \cdot \delta X \cdot \delta \Phi = \varepsilon \quad \text{are the values of the 2nd order of infinitesimal.} \]

Later on, the sign "\(-\)" is excluded from the designation of variables: \( \Phi, X, I \) in equations (3).

2. Study of stability against xenon fluctuations in radial-azimuth geometry.

To study the system of equations (3) as to stability, we will search for solution of the task:

\[ \frac{\partial \Phi}{\partial t} = L \Phi \]  

as the series:

\[ \Phi (r,t) = \sum \Phi (r) \Phi (r,t). \]

(4)

where \( \Phi (r) \) are the eigen-functions of the homogeneous stationary task:

\[ \nabla^2 \Phi (r) + B^2 \Phi (r) = 0 \]

(5)
Then, \( \Phi (r, \varphi) \) can be presented in cylindrical geometry (\( r, \varphi \)) as the following series:

\[
\Phi (r, \varphi) = \sum_{m} A_{m} J_{m} \left( \frac{\xi_{m, l}}{R_{\text{ext}}} r \right) \cdot \left( C_{m} \cos m \varphi + S_{m} \sin m \varphi \right),
\]

where \( J_{m} \left( \frac{\xi_{m, l}}{R_{\text{ext}}} r \right) \) - the \( m \)th kind Bessel function of the order \( m \), and \( \xi_{m, l} \) - \( l \)th root of this function, \( R_{\text{ext}} \) is the extrapolated boundary of the core at which the function \( J_{m} (\chi) \) shall become zero.

Then, we will search for the solution of this spatial-temporal task as follows:

\[
\Phi (r, \varphi, t) = \sum_{m} J_{m} \left( \frac{\xi_{m, l}}{R_{\text{ext}}} r \right) \left\{ T_{m}^{1}(t) \cos m \varphi + T_{m}^{1}(t) \sin m \varphi \right\},
\]

Since iodine and xenon concentrations are governed by the neutron flux, then their values can be searched of the similar manner, namely:

\[
\begin{align*}
I(r, \varphi, t) &= \sum_{m} J_{m} \left( \frac{\xi_{m, l}}{R_{\text{ext}}} r \right) \left\{ T_{m}^{1}(t) \cos m \varphi + T_{m}^{1}(t) \sin m \varphi \right\}, \\
X(r, \varphi, t) &= \sum_{m} J_{m} \left( \frac{\xi_{m, l}}{R_{\text{ext}}} r \right) \left\{ X_{m}^{1}(t) \cos m \varphi + X_{m}^{1}(t) \sin m \varphi \right\}.
\end{align*}
\]

2.1 Let us address the first equation of the system (3).

We will substitute expansion (7) into this equation, multiply each its term by:

\( \frac{J_{1} \left( \frac{\xi_{1, l}}{R_{\text{ext}}} r \right)}{R_{\text{ext}}} \cdot \cos \varphi \)

and integrate across the surface of the core cross-section.

2.1.1 Then, the first term of this equation can be presented as follows:

\[
\frac{\partial}{\partial t} \int_{r} r \frac{\partial \Phi}{\partial \varphi} J_{1} \left( \frac{\xi_{1, l}}{R_{\text{ext}}} r \right) \cdot \cos \varphi \ r \, dr \, dp = \pi \frac{\partial T_{1}^{1}(t)}{\partial t} \int_{r} J_{1} \left( \frac{\xi_{1, l}}{R_{\text{ext}}} r \right) \ r \, dr
\]

where:

\[
J_{1} = \int_{r} J_{1} \left( \frac{\xi_{1, l}}{R_{\text{ext}}} r \right) J_{1} \left( \frac{\xi_{1, l}}{R_{\text{ext}}} r \right) \ r \, dr.
\]

Doing so, the following properties of the adjoint functions were used:

\[
\begin{align*}
\int_{r} J_{m} \left( \frac{\xi_{m, l}}{R_{\text{ext}}} r \right) J_{n} \left( \frac{\xi_{n, l}}{R_{\text{ext}}} r \right) \ r \, dr &= 0, \quad \text{if } l \neq n \\
\int_{0}^{\pi} \cos m \varphi \cdot \cos \varphi \ d\varphi &= \frac{\pi}{2} \quad \text{if } m = 1 \\
\int_{0}^{\pi} \sin m \varphi \cdot \cos \varphi \ d\varphi &= 0, \quad \text{always}
\end{align*}
\]

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2.1.2 The second term of the first equation of the system (3) after completing the similar procedure can be presented, if we replace $\nabla \cdot \sum_{\ell} \Phi_{\ell} (r)$ with $-\sum_{m,l} B_{m,l}^2 \Phi_{m,l}(r)$ using the wave equation (5):

$$
\int \int J_{m,l}^m \nabla \Phi (r) J_{m,l}(\frac{\xi_{m,l}^l}{R_{\text{exp}}} \cdot r) \cdot \cos \varphi \; r dr d\varphi = -\pi M^2 B_{m,l}^2 T_c^{l,l}(t) J_{m,l}^{l,l}.
$$

2.1.3 Let us consider the third term of the first equation in the system (3).

On substituting expansion for the flux (7), after integration taking into account the correlations (9) and $B_i', = \frac{K_*^l - 1}{M}$ for the stationary task, we will obtain:

$$
\int \int (K_*^l - 1) \Phi (r,t) J_{m,l}(\frac{\xi_{m,l}^l}{R_{\text{exp}}} \cdot r) \cos \varphi \; r dr d\varphi = -\pi M^2 B_{m,l}^2 T_c^{l,l}(t) J_{m,l}^{l,l}.
$$

2.1.4 Let us address the 4th term of the 1st equation in the system (3). Following the similar procedure on integration with substituting expansion of (7) for the flux, the next expression is obtained:

$$
\int \int \delta K_{\alpha}(r,t) \Phi_0 J_{m,l}(\frac{\xi_{m,l}^l}{R_{\text{exp}}} \cdot r) \cos \varphi \; r dr d\varphi = -\pi M^2 B_{m,l}^2 T_c^{l,l}(t) J_{m,l}^{l,l}.
$$

Finally, after the transformation the 1-st equation of the system (3) can be written as follows:

$$
\frac{\partial T_c^{l,l}(t)}{\partial t} = M^2 T_c^{l,l}(t) \cdot (B_{3,3}^l - B_{1,1}^l) + \alpha_x \Phi_x X_c^{l,l}.
$$

2.2 Let us consider the 2nd and 3rd equations of the system (3). After completing the similar procedure as described in Section 2.1, one can obtain the following equations:

$$
\frac{\partial X_c^{l,l}(t)}{\partial t} = \gamma_x \cdot (I_c^{l,l}(t) - X_c^{l,l}(t)) - \sigma_x T_c^{l,l}(t)
$$

$$
\frac{\partial I_c^{l,l}(t)}{\partial t} = \lambda_x \cdot (T_c^{l,l}(t) - I_c^{l,l}(t)).
$$

2.3 The system of equations (14) and (15) allows to obtain the solution for the amplitude factor of neutron flux density as to the first radial-azimuth harmonic.

The solutions will be searched as follows:

$$
T_c^{l,l}(t) = T_c^{l,l} e^{\omega t}; \quad X_c^{l,l}(t) = X_c^{l,l} e^{\omega t}; \quad I_c^{l,l}(t) = I_c^{l,l} e^{\omega t}.
$$

After substituting them into the systems (14), (15), and performing simple transformations, the following characteristic equation can be obtained to find $\omega$:

$$
M^2 (B_{3,3}^l - B_{1,1}^l) = -\omega \tau_x + \alpha_x \frac{\tau_x \lambda_x - \sigma_x (\omega + \lambda_x)}{(\omega + \lambda_x)^2} \Phi_x.
$$

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Taking the accepted designations (see equation (3)) into account, the equation (16) can be eventually written as follows:

$$M'(B_{i} - B_{o}) = -\omega_{r} \cdot \alpha \cdot \alpha \cdot \Phi_{s}(r, \theta) \cdot \Phi_{s} \cdot \left[ \lambda_{s} \lambda_{s} \Phi_{s} \cdot \Phi_{s} \cdot \sigma_{s} \right].$$

(17)

It can be shown that after substituting expansion (7) into the equations of system (3), multiplying them by: $J_{1,l,} \cos \varphi = J_{1}(\frac{m \varphi}{R_{wv}})$, and performing integration across the surface of the core cross section, in the event of weak dependence of $\Phi_{s}(r)$ from $r$, the characteristic equation for determining $\omega$ of each radial-azimuth harmonic will be of the same type as (17). In general, the characteristic equation from which one can determine $\omega$ for the different radial-azimuth harmonics can be written as follows:

$$M'[\left(\frac{\xi_{m,l}}{R} \right)^{2} - \left(\frac{\xi_{n,1}}{R} \right)^{2}] = -\omega_{r} \cdot \alpha \cdot \alpha \cdot \Phi_{s}(r, \theta) \cdot \Phi_{s} \cdot \left[ \lambda_{s} \lambda_{s} \Phi_{s} \cdot \Phi_{s} \cdot \sigma_{s} \right].$$

(18)

3. Studying stability to xenon oscillations of power in axial geometry.

If to write the equations of system (3) for flat reactor of height $H$, use expansion of the functions: $\Phi(h, t)$, $I(h, t)$, and $\chi(h, t)$ by the eigen-functions $\sin \frac{m \pi h}{H}$ of the uniform one-dimensional steady task: $\frac{\partial^{2} \Phi(h)}{\partial h^{2}} + B \cdot \Phi(h) = 0$, and use the formalism described in Section 2 namely:

multiplying the equations of system (3) by $\sin \frac{m \pi h}{H}$, and integrating along the height of core from 0 up to the $H$, taking the orthogonal property of eigen-functions into account such as follows:

$$\int_{0}^{H} \sin \frac{m \pi h}{H} \sin \frac{n \pi h}{H} \, dh = 0 \quad \text{if} \quad m \neq n,$$

$$= \frac{H}{2} \quad \text{if} \quad m = n,$$

then the characteristic equation to determine $\omega$ for different axial harmonics can be written similarly to (18):

$$M'[\left(\frac{\xi_{m,1}}{H} \right)^{2} - \left(\frac{\xi_{n,1}}{H} \right)^{2}] = -\omega_{r} \cdot \alpha \cdot \alpha \cdot \Phi_{s}(h, \theta) \cdot \Phi_{s} \cdot \left[ \lambda_{s} \lambda_{s} \Phi_{s} \cdot \Phi_{s} \cdot \sigma_{s} \right].$$

(19)

Equations (18), (19) are cubic concerning $\omega$, and they determine both the period of xenon power oscillations and their nature, namely: damped or undamped mode. Characteristic equations (18) and (19) can be substantially simplified, if to neglect the temporal derivative in the one-group diffusion equation (1), that is conventional in the studying xenon processes due to their slow progressing. In this case, (18) and (19) can be represented as follows:

$$M'[\left(\frac{\xi_{m,1}}{R} \right)^{2} - \left(\frac{\xi_{n,1}}{R} \right)^{2}] = \alpha \cdot \alpha \cdot \Phi_{s}(r, \theta) \cdot \Phi_{s} \cdot \left[ \lambda_{s} \lambda_{s} \Phi_{s} \cdot \Phi_{s} \cdot \sigma_{s} \right].$$

(20)

for radial-azimuth geometry, and

$$M'[\left(\frac{m \pi}{H} \right)^{2} - \left(\frac{n \pi}{H} \right)^{2}] = \alpha \cdot \alpha \cdot \Phi_{s}(h, \theta) \cdot \Phi_{s} \cdot \left[ \lambda_{s} \lambda_{s} \Phi_{s} \cdot \Phi_{s} \cdot \sigma_{s} \right].$$

(21)
for axial geometry.
If we consider the main harmonic, then the left parts of equations (20) and (21) are equal to zero. In this case, \( \omega \) for both radial-azimuth geometry and for axial one, are determined by the following expression:

\[
\omega = \frac{\lambda; \cdot \lambda_s}{\sigma_0 \cdot \Phi_0}.
\]  

(22)

Deriving expressions (20) and (21) we don't take into account feedback caused by negative power reactivity coefficient and direct yield of xenon due to fission. In this case, \( \omega \) is positive value for the main harmonic, and oscillations have the undamped nature.

4. Considering direct yield of Xe-135 due to fission.

If to write down the equation for xenon in the system (3) taking the direct yield of this isotope due to fission into account as:

\[
\frac{\partial X}{\partial t} = \lambda; I + \gamma, \Delta, \Phi(r, t) - \lambda; \gamma, \Delta, \Phi (r, t)
\]

(23)

then, with the use of the system (2), the system (3), after linearizing, can be presented as follows:

\[
M^2 \Delta \Phi + \left( \kappa^2_0(r) - 1 \right) \Phi + \alpha, \Delta, \Phi_0 = 0
\]

\[
\frac{\partial X}{\partial t} = \lambda; I + \gamma, \Delta, \Phi - \lambda; \gamma, \Delta, \Phi_0 \gamma, \Delta, \Phi
\]

\[
\frac{\partial \gamma}{\partial t} = \gamma, \Delta, \Phi - \lambda; \gamma, \Delta, \Phi
\]

(24)

Here, \( \Phi, X, I \), designate the deviations of the relevant values from their steady magnitudes, and, in contrary to (3), these are not normalized by their average values across the volume of core. Using the expansions for \( \Phi, X, I \) by the eigen-functions, one can obtain the following characteristic equation to determine \( \omega \):

\[
M \left( \frac{\xi_0}{R} \right)^2 - \lambda; \mu, \Delta, \Phi_0 \left[ \gamma, \Delta, \Phi \left( \mu, \Delta, \Phi \right) \right] = 0
\]

(25)

in radial-azimuth geometry

\[
M \left( \frac{\mu}{H} \right)^2 - \left( \frac{\kappa^2_0(r)}{H} \right) = \alpha, \Phi_0 \left( \frac{\lambda; \mu, \Delta, \Phi_0 \gamma, \Delta, \Phi}{\gamma, \Delta, \Phi \left( \mu, \Delta, \Phi \right)} \right)
\]

(26)

in axial geometry.

From (25) and (26), \( \omega \) for the main harmonic is determined by the following expression:

\[
\omega = \frac{\lambda; \cdot \lambda_s \cdot / \gamma, \Delta, \Phi}{\sigma_0 \cdot \gamma, \Delta, \Phi_0}
\]

(27)

It is seen from (27) that, in contrary to (22), if the magnitude of flux \( \Phi_0 \leq 3.2 \times 10^{14} \), then \( \omega \) is negative, and perturbation by the main harmonic is of the undamped nature. If the flux magnitude \( \Phi_0 \geq 10^{15} \), then \( \omega \) , though, is positive, however, it becomes less than \( 1.8 \times 10^7 \).
5. Considering power reactivity coefficient.

In this case, the characteristic equations (25) and (26) become of the following type:

\[
M'\left[\frac{m\pi}{R}-\left(\frac{\pi}{R}\right)^2\right] = \alpha_r\Phi_0\left(\sigma_r+\sum_l\gamma_l\right) + \alpha_0\Phi_0 \quad (28)
\]

for radial-azimuth geometry, and

\[
M'\left[\frac{m\pi}{H}-\left(\frac{\pi}{H}\right)^2\right] = \alpha_0\Phi_0\left(\sigma_r+\sum_l\gamma_l\right) + \alpha_0\Phi_0 \quad (29)
\]

for axial one.

Here, \( \alpha_0 = \frac{1}{K_r} \frac{\partial K_r}{\partial P} \frac{\partial P}{\partial \Phi} \), and \( P \) is thermal reactor power.

If to designate \( M'\left[\frac{m\pi}{H}-\left(\frac{\pi}{H}\right)^2\right] \) or \( M'\left[\frac{m\pi}{R}-\left(\frac{\pi}{R}\right)^2\right] \) as \( \mu_m^2 \), then the equations (28) and (29) can be written as:

\[
\omega^2 + B\omega + C = 0 \quad (30)
\]

where

\[
B = \lambda_r+\lambda_s+\sigma_r\Phi_0\frac{\alpha_0\Phi_0}{\alpha_r\Phi_0-\mu_m^2}, \quad C = \lambda_0+\sigma_r\Phi_0+\frac{\alpha_0\Phi_0\sum_l\gamma_l}{\alpha_r\Phi_0-\mu_m^2}
\]

The threshold for oscillations of the \( m \)th harmonic of the neutrons flux density is being determined from the condition that \( \omega \) has purely imaginary values, i.e. if \( B = 0 \). Then, this condition can be written as follows:

\[
\mu_m^2 = \alpha_r\Phi_0\left(\sigma_r+\sum_l\gamma_l\right) \quad (31)
\]

If \( B < 0 \), then the real component of \( \omega \) is positive, and the oscillations will be of undamped nature. Imaginary part of \( \omega \) determines the period of xenon oscillations that for the threshold of oscillations is being determined as: \( \frac{2\pi}{\sqrt{-C}} \).

If to take into account that \( \alpha_r = \frac{\sigma_r}{\sum_l\gamma_l} = \frac{\sigma_r}{\Sigma_l} \), then (30) can be written as follows:

\[
\mu_m^2 = \alpha_0\Phi_0\left(1+\frac{\alpha_r}{\sum_l\gamma_l}\right) \quad (32)
\]

For the main harmonic (\( m = 1 \) in axial geometry) \( \mu_m = 0 \), and the oscillations threshold is reached, when:

\[
\alpha_0\Phi_0 = \frac{\alpha_0\Phi_0}{\sigma_r+\Phi_0} \quad (33)
\]

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It is evident from (32), that under \( \gamma = 0.003 \), \( \sigma = 3.5 \cdot 10^{-11} \, \text{cm}^2 \), \( \gamma = 0.056 \) and \( \lambda = 2.1 \cdot 10^{-7} \, \text{cm}^2 \), the oscillations threshold under \( \alpha_0 = 0 \) is reached, if \( \Phi_0 = 3.2 \cdot 10^{11} \, \text{n/cm}^2 \cdot \text{s} \) (see Fig. 1). All points on Fig. 1 lying to the left from the threshold curve correspond to the unstable state for the fundamental solution of homogenous stationary reactor. It should be noted that the curve in Fig. 1 was obtained under the assumption that the higher harmonics were not "linked" and the expression (32) was obtained due to a number of simplifications of mathematical model of real system. Therefore, there is better to use this curve for the qualitative analysis of stability against xenon oscillations, while the credible estimates for the certain type of reactor shall be obtained from the numerical calculations with the use of the relevant computer codes. As Fig. 1 shows, under small values of the neutron flux, and flux \( > 10^{12} \, \text{n/cm}^2 \cdot \text{s} \), the reactor is stable as to xenon power oscillations. There is the area of instability for the fundamental solution of the one-dimensional homogenous reactor under the fluxes of \( 10^{13} \cdot 10^{14} \, \text{n/cm}^2 \cdot \text{s} \), and stability inside this range can be assured due to large negative power reactivity coefficient. For example, for VVER-1000, this coefficient \( \alpha_0 \) is ranged between \( -4.6 \cdot 10^4 \) and \( -9.7 \cdot 10^6 \) \text{MW}^{-1} \, \text{n/cm}^2 \cdot \text{s}^{-1} \), that corresponds [taking into account that \( \frac{\partial P}{\partial \Phi} \approx 2.6 \cdot 10^{11} \, \text{MW/(n/cm}^2 \cdot \text{s}) \)] to -

\[ \alpha_0 = -1 + 2.5 \cdot 10^{-16} \, \text{MW/(n/cm}^2 \cdot \text{s}) \]. Fig. 1 shows that under large neutron fluxes achievable in VVER-1000, the relevant power reactivity coefficient is not capable to provide the stability against axial xenon power oscillations.

stability threshold as to xenon power oscillations for main harmonic of homogenous stationary reactor

Fig. 1

Reactivity coefficient by neutron flux, \text{1/(n/cm}^2 \cdot \text{s})

Neutron flux, \text{1/cm}^2 \cdot \text{s}

Before to consider the results of numerical modeling of the xenon axial power oscillations in VVER-1000, let us address the results of testing of computer code DYN3D [1,2] used for xenon spatial kinetics calculation. For this purpose, the transient connected with reactor power increase during start up experiment at the beginning of 14 fuel cycle of Rovno-3 was calculated. Fig.3 and Fig.4 show position of 10-th control rod group and thermal reactor power change during transient. These values were taken as input data into DIN3D. At the beginning of the transient xenon concentration is equal zero. Fig.4 shows the comparison of calculated and experimental values of boron acid concentration, as well. One can note the satisfactory coincidence of the relevant calculated and experimental values. For the end of this transient, (69 hrs 43 min.), the calculation was performed with the steady concentrations of xenon corresponding to reactor power level at the end of the transient (2320 MW). It is clear that in this case the calculated concentration of boron acid is substantially different from its experimental value (Fig.4). Figs. 5 and 6 show the comparison of calculated and measured values of axial power distribution for FA's numbered as 92 and 122 respectively, in the symmetry sector of 360°, while Fig. 7 - the integral relative FAs power distribution at the position of SPND at the end of the transient. By this moment, the state with equilibrium concentrations of xenon and samarium was not achieved yet.

Thus, the presented information allows to state that the DYN3D code simulates xenon transient quite adequately.
**Rovno NPP, Unit 3**

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### Experiment vs Calculation

- **Control rod position of 10-th group, %**
- **Time, hours**

**Fig. 3**

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### Equilibrium Xenon at Power 2320 MW

- **Thermal power (experiment)**
- **Thermal power (calculation)**
- **Boric acid concentration (experiment)**
- **Boric acid concentration (calculation)**

**Fig. 4**

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Fig. 5. Axial distribution of relative power

Fig. 6. Axial distribution of relative power
Let us consider the results of calculations to study VVER-1000 stability against axial xenon power oscillations. Figs. 8 and 9 present the free oscillations of axial offset (difference between the power from the lower and upper halves of reactor core, normalized by the total reactor power). These data were calculated by DYN3D code for different states of reactor core. Each state is described by different level of reactor power and different burnup of fuel (beginning and end of the 14th fuel cycle of Rivne-3). It was assumed in each calculation, that in steady state of reactor core the perturbation is introduced by withdrawal of working group of control rods. This reactivity as well as the reactivity induced by spatial-temporal changing of xenon concentration was compensated only by changing of boric acid concentration in coolant. As these figures show, if reactor power (neutron flux) is low, offset oscillations have the damped behaviour both for the beginning and the end of fuel cycle. In case of low neutron flux reactor is at the stable state. At the beginning of fuel cycle there is observed offset oscillations at nominal reactor power, however, they are damped. VVER-1000 instability against axial xenon oscillations of power can be observed only at the end of fuel cycle with high core burnup (Fig. 9). In this case, to achieve the rated reactor power level one should increase the neutron flux. Fig. 9 shows that at power level of 2200 MW axial xenon oscillations of power have undamped nature. If reactor power is greater than 2200 MW the power oscillations become unstable. It should be noted that at the end of fuel cycle, reactor power reactivity coefficient is more negative than at the beginning of cycle. However, this can not compensate the destabilizing role induced by increasing of thermal neutron flux.

The data presented here are completely consistent with the qualitative results concerning estimation of stability presented in Section 5.
Control rods movement of 10-th group from 220 cm to 325 cm

Initial reactor power 100 MWR
Initial reactor power 1000 MWR
Initial reactor power 3000 MWR

Fig. 8. Offset oscillations (at the beginning of fuel cycle)

Control rods movement of 10-th group from 290 cm to 330 cm

Initial reactor power 500 MWR
Initial reactor power 1500 MWR
Initial reactor power 2200 MWR
Initial reactor power 3000 MWR

Fig. 9. Offset oscillations (at the end of fuel cycle)
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References