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Original Article

Dynamics of the IBR-2M reactor at a power pulse repetition frequency of 10 Hz

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A R T I C L E I N F O

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A B S T R A C T

The results of the analysis of a mathematical modeling for the IBR-2M pulsed reactor dynamics for a transition from a power pulse repetition frequency of 5 Hz–10 Hz are presented. The change in the amplitude response of the reactor for variable pulse delayed neutron fraction was studied. We used a set of power feedback parameters determined experimentally in 2021 at an energy output of 1820 MW·day. At a pulse repetition frequency of 10 Hz, the amplitude of pulse energy oscillations significantly depends on the value of the delayed neutron fraction in pulse β_p. Depending on β_p both suppression and amplification of reactor power fluctuations in the frequency ranges of 0.05–0.20 and 1.25–5.00 Hz can be realized.

1. Introduction

During the operation of IBR-2 and IBR-2M pulsed batch reactors, power fluctuations occur at frequencies close to ~0.1 Hz, which are not good from the point of view of safety. There are a number of measures that can mitigate the development of instability. These measures do not require modifications to the reactor or its environment. They are available for use [1–3]. There is another possibility to attenuate power fluctuations by switching to a higher pulse repetition frequency, e.g. 10 Hz. Increasing the pulse frequency makes it possible to increase the value of the pulse fraction of delayed neutrons β_p and thereby reduce the reactor noise as a whole. But it is not known exactly how this will change the fluctuations. It is relevant to recall that once the 50 Hz and 25 Hz pulse repetition modes were studied on the IBR-2 reactor, but no special increase of β_p occurred. It is probably possible to create a reactivity modulator for the IBR-2M with increased β_p, but we should be aware that this would be a new reactor operating mode, in fact a new reactor, in which problems previously not considered may appear. At the same time, we cannot be 100% sure that this suggestion will allow to avoid power fluctuations. When switching to a higher pulse frequency, the reactor itself (the core and its immediate environment) will not change, but the dynamic properties of the reactor will change. This paper examines the dynamics of the IBR-2M in the 5 and 10 Hz modes, depending on the change of β_p. The core parameters, including the power feedback parameters, were taken as of the end of 2021. The design features of the reactivity modulator for change β_p were not considered, i.e., the value of β_p was considered a given.

2. Brief information about the IBR-2M reactor

The IBR-2 pulsed batch fast reactor is unique in its operating principle, design, and parameters [4]. The reactor generates narrow power pulses with a period of 0.2 s. The amplitude of the power pulse P_m is almost three orders of magnitude greater than the average power for the period $\overline{P}$ ($\overline{P} = 2$ MW, $P_m = 1850$ MW). Plutonium dioxide is used as fuel and liquid sodium is used as coolant.

The active zone has the shape of a vertical hexagonal prism. All but one of the prism faces are surrounded by stationary reflectors. The movable reflector (MR), which consists of two steel blades, runs past the free face (Fig. 1*a*). The blades rotate in opposite directions at different speeds in a helium-filled casing. The speed of the main moving reflector is 600 rpm, the additional one is 300 rpm.

When the blades pass the core at the same time, a reactivity pulse is created. In normal mode, the position of the controls is such that the reactor is in a supercritical state on prompt neutrons for

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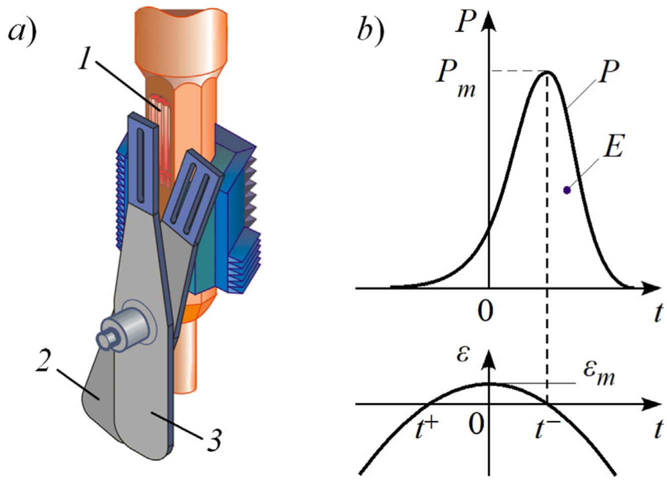

Fig. 1. *a*) Schematic view of the IBR-2 reactor: *1* – core, *2* and *3* – main and auxiliary movable reflectors, respectively. *b*) Power pulse (*P*) and an upper part of prompt neutron reactivity (ε): *E* – the energy of power pulse; *t* – the time; $t^+ - t^-$ - the super critical interval and ε_m – the maximum of the prompt neutron reactivity.

~450 μs. During this time there is a rapid increase in power. When the blades move away from the core, reactivity decreases sharply, and the reactor becomes deeply subcritical, the reactor power drops rapidly (Fig. 1*b*). The change in reactivity relative to the physical center of the core is symmetrical. At the same time, the power change is not symmetrical.

The efficiency of the moving reflector is large: $\Delta k_{MR} = 0.03$, i.e. 3%. Therefore, between power pulses, the reactor state is deeply subcritical. When only the main movable reflector passes the core, an incidental reactivity pulse of low amplitude is generated, which has no significant effect on reactor operation (the reactor remains deeply subcritical). As a result, the reactor generates narrow power pulses. The pulse width at half-height is ~200 μs, the pulse period is 0.2 s. The reactor power between pulses (background power) is an order of magnitude lower than the average power [4].

A pulsed reactor is subject to significant reactivity perturbations and is very sensitive to these perturbations. For steady-state and pulsed reactors, the change in average power or pulse energy Q/Q_0 following the instantaneous reactivity spike and the reactor riding up period on delayed neutrons T_S can be described by the same equations:

$$\frac{Q}{Q_0} = \frac{1}{1-P}, P = \sum_{i=1}^{6} \frac{\left(\frac{\beta_i}{\beta_{\text{eff}}}\right)}{1+\lambda_i T_S}.$$

At the same time, for stationary reactors $P = \Delta K/\beta_{\text{eff}}$, for pulsed reactors $P = \Delta K/\beta_{\text{p}}$. Since β_{p} is 14 times less than β_{eff} for the IBR-2M, the IBR-2M is seen to be more than an order of magnitude sensitive to changes in reactivity compared to the steady-state mode. Therefore, pulse amplitude fluctuations in the IBR-2M are large-45%. Emergency protection is triggered when the average power deviates by ± 20% and when the pulse amplitude deviates by +100 and −50% from the set values. When the emergency protection is triggered, the reactance decreases in 0.2 s so that the next power pulse does not occur. β_{p} is a mathematical term for the measurement of reactivity in a pulsed reactor. From the above, we can see that the value of β_p is important in the kinetics and dynamics, respectively, in the stability of the pulsed batch reactor. The evolution in the understanding of the meaning of β_p is given below.

3. Kinetics of IBR-2M as a dynamic system

The kinetic equations of the pulsed reactor can be represented as a system with dimensionless variables [5–8]:

$$\frac{\tau}{\beta}\frac{dP}{dt} = \frac{\varepsilon}{\beta}P + S, \tag{1}$$

$$S = \sum_i S_i, \tag{2}$$

$$\frac{1}{\lambda_i}\frac{dS_i}{dt} + S_i = \mu_i P. \tag{3}$$

Here $P = k_n n$ is the reactor power (k_n is the coefficient of proportionality between power and neutron density n); τ is the effective lifetime of prompt neutrons; β_i and β are the fraction of delayed neutrons of group i and total, respectively; $\varepsilon = \rho - \beta$ is the prompt neutrons reactivity, S_i, $S = \sum_i S_i$ are the normalized intensity of sources of delayed neutrons of group i and total, respectively. $\mu_i = \beta_i/\beta$ is the relative fraction of the delayed neutrons of the group i; t is the time.

The power in the intervals between pulses is small and does not change significantly:

$$P_b = \frac{\beta}{-\varepsilon_b}(S + S_c), \tag{4}$$

where ε_b is the background reactivity:

$$\varepsilon_b = \varepsilon_m - \Delta k_{MR}, \tag{5}$$

where ε_m is the maximum reactivity in the pulse; Δk_{MR} is the efficiency of the moving reflector. The background energy is

$$E_b = P_b T = \frac{\beta T}{\Delta k_{MR} - \varepsilon_m}(S + S_c), \tag{6}$$

where T is the period of power pulses, Δk_{MR} is much larger than ε_m^0, and ε_m^0 is significantly larger than the reactance deviation ε_m from the baseline value ε_m^0. Therefore, we can represent equation (6) in the form

$$E_b = P_b T = \frac{\beta T}{\Delta k_{MR} - \varepsilon_m^0}(S + S_c). \tag{6a}$$

The pulse energy is expressed by the equation [9].

$$E = M(S + S_c), \tag{7}$$

where M is the pulse transfer coefficient, $S + S_c$ is the total normalized intensity of neutron sources before reactivity pulse. S_i, S and S_c are expressed in the equations in the same units as the power P. Therefore M has the dimension of time and is expressed in seconds.

3.1. Calculation of the pulse transfer coefficient

To estimate β_p, it is important to correctly estimate the function M. This can be accomplished in different ways: for example, by direct calculation with known parameters determining the pulse transfer coefficient, or, more correctly, by solving a system of kinetics equations with experimentally determined course of modulating reactance. The coefficient M is calculated from equations (1)–(3) and (7) and is a nonlinear function of the maximum reactivity in the pulse ε_m. The moveable reflector reactivity range ε_{MR} and the variation of the maximum reactivity ε_m ($\varepsilon = \varepsilon_{MR} + \varepsilon_m$) were used as the total reactivity on prompt neutrons ε. The calculated value of the maximum prompt neutron reactivity in the equilibrium supercritical state of the IBR-2M reactor and the reactor power amplitude are $\varepsilon_m^0 = 1.1 \bullet 10^{-3}$ and 1.85 GW, respectively. In this case, the average power of the reactor is 2 MW. For the calculation we used the basic parameter values estimated earlier in separate experiments: $\Delta k_{MR}^0 = 0.03$, $\tau^0 = 65$ ns, $\beta^0 = 2.16 \bullet 10^{-3}$. The parameters of delayed neutrons in ^{239}Pu fission by fast neutrons were taken from G. R. Keepin [10]. The basic value of the pulse transfer coefficient M^0 (pulse equilibrium mode) is calculated from the identity

$$M^0 = \frac{E^0}{\left(S^0 + S_c\right)} = \frac{E^0 + E_b^0}{S^0} \frac{S^0}{\left(S^0 + S_c\right)} - \frac{E_b^0}{\left(S^0 + S_c\right)} \tag{8}$$

and equations (2), (3) and (6a)

$$M^0 = \frac{E^0}{\left(S^0 + S_c\right)} = \frac{1}{\left(1 + \frac{S_c}{S^0}\right) \sum_i \frac{\mu_i \lambda_i}{\exp(\lambda_i T) - 1}} - \frac{\beta T}{\Delta k_{MR} - \varepsilon_m^0}. \tag{9}$$

Fig. 2*a* shows the calculated pulse transfer coefficient M as a function of the maximum reactance ε_m. It also indicates its base value at equilibrium supercriticality.

3.2. *Calculated estimation of the impulse fraction of delayed neutrons β_p.*

When modeling regimes characterized by a wide range of reactivity changes, a nonlinear dependence of M on ε_m is used. In the study of normal regimes, various approximations of nonlinearity in the vicinity of the base values M^0 and ε_m^0 are possible. If the range of deviations E from E^0 is wide enough, it is acceptable to approximate the function $M = f(\varepsilon_m)$ by an exponent:

$$\frac{M}{M^0} = \exp\left(\frac{\Delta \varepsilon_m}{\beta_p}\right). \tag{10}$$

where $\Delta\varepsilon_m = \varepsilon_m - \varepsilon_m^0$ is the deviation of reactivity. The parameter β_p is equal to

$$\beta_p = \frac{1}{d \ln\left(\frac{M}{M^0}\right) / d\varepsilon_m \Big|_{\varepsilon_m^0}} = \frac{M^0}{dM / d\varepsilon_m |_{\varepsilon_m^0}}. \tag{11a}$$

From equation (10) it follows that

$$\frac{\Delta E}{E^0} = \left(\frac{\Delta S}{S^0} + 1\right) \exp\left(\frac{\Delta \varepsilon_m}{\beta_p}\right) - 1. \tag{12a}$$

For the stabilization regime, when the deviation of the pulse energy from the mean level is units of percent, a linear approximation of the $M = f(\varepsilon_m)$ function is possible. As a result, we get

$$\frac{\Delta E}{E^0} = \frac{\Delta S}{S^0} + \frac{\Delta \varepsilon_m}{\beta_p}. \tag{13a}$$

The equations do not include a constant neutron source, because it can already be neglected when the reactor power is six orders of magnitude lower than the rated power. Equations (12) and (13) show that the reactivity in fractions of β_p is related only to the relative deviations of the pulse and source energies. For IBR-2M $\beta_p = 1.54 \bullet 10^{-4}$.

Let us estimate the effect of neutron lifetime τ and the effective fraction of delayed neutrons β on the value of β_p. Fig. 2*b* shows the change in the pulse transmission coefficient with supercriticality when varying the parameters τ and β. In this case, as shown in Table 1, the value of β_p changes. Table 1 also shows three variants of variation: 1) the value β is constant ($\beta^0 = 2.16 \bullet 10^{-3}$) and only the value τ is changed by 10% ($\tau = \tau^0 \pm 10\%$); 2) the value τ is constant ($\tau^0 = 65$ ns) and only the value β is changed by 10% ($\beta = \beta^0 \pm 10\%$) and 3) both parameters τ and β are changed by 10% ($\beta = \beta^0 \pm 10\%$ and $\tau = \tau^0 \pm 10\%$). Table 1 shows that the greatest influence on the change of β_p has the third variant, which changes the values of both parameters τ and β (by 10%). In this case, the change of τ leads to a larger deviation of M from M^0 and change in β_p, than the change in β.

3.3. *Effective fraction of delayed neutrons of the IBR-2M*

The choice of the delayed-neutron system in the IBR-2M kinetics is of fundamental importance, and here is why. Fig. 3 shows the progress of reactivity changes near instantaneous criticality measured on the IBR-2M in two independent experiments: 1) in the subcritical state of the reactor in the continuous power mode (moving reflectors are inhibited and can only move slowly); 2) in the pulse mode from the solution of the inverse kinetics equation for the measured power pulse [11]. As can be seen from Fig. 3, a

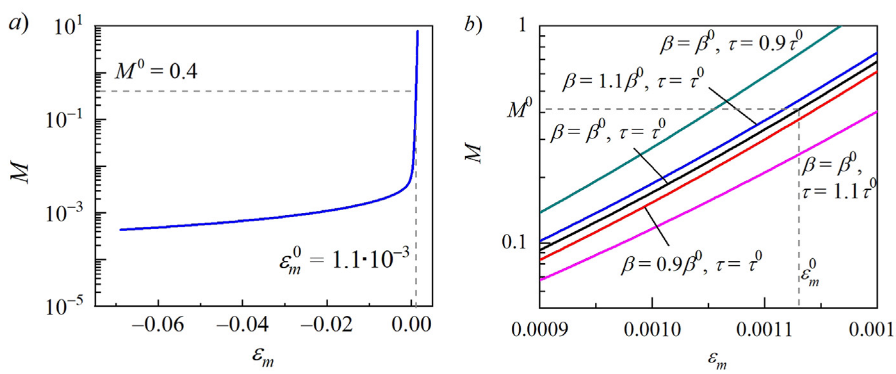

Fig. 2. *a*) Dependence of the pulse energy transfer coefficient M on the maximum reactivity ε_m: ε_m^0 and M^0 – the basic value of a maximum reactivity and a pulse energy transfer coefficient, respectively. *b*) Dependence of the pulse transfer coefficient on variation of parameters τ and β.

Table 1
The change of the pulse fraction of delayed neutrons when varying the parameters τ and β.

	Effective fraction of delayed neutrons	Effective lifetime of prompt neutrons, ns	Pulse fraction of delayed neutrons
Basic value	$\beta^0 = 2.16 \bullet 10^{-3}$	$\tau^0 = 65$	$\beta_p^0 = 1.54 \bullet 10^{-4}$
Variant 1	$\beta = \beta^0 = \text{const}$	$\tau = \tau^0 \pm 10\%$	$\beta_p = \beta_p^0 \pm 5.6\%$
Variant 2	$\beta = \beta^0 \pm 10\%$	$\tau = \tau^0 = \text{const}$	$\beta_p = \beta_p^0 \pm 1\%$
Variant 3	$\beta = \beta^0 \pm 10\%$	$\tau = \tau^0 \pm 10\%$	$\beta_p = \beta_p^0 \pm 6.2\%$

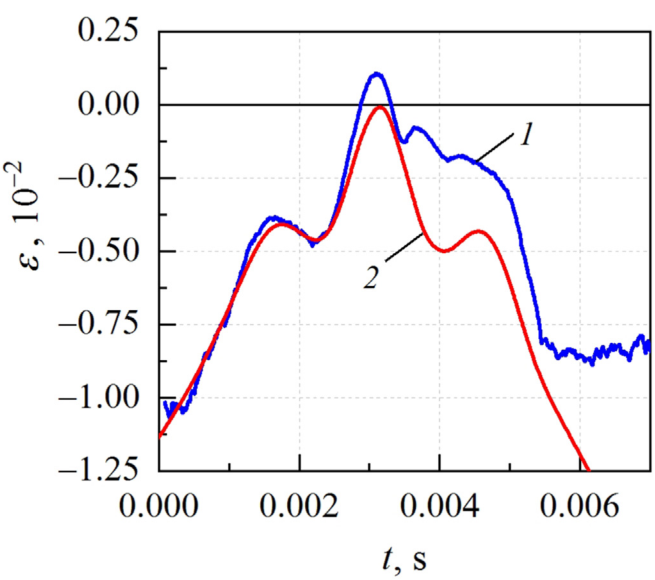

Fig. 3. Progress of reactivity changes near instantaneous criticality measured on the IBR-2M with movable reflector MR-3 (in abs. unit) during two independent experiments. *1, 2* – the reactivity at the power in critical and subcritical regime of the reactor, respectively.

different delayed-neutron system, not the one used to describe the kinetics of steady-state reactors, operates when describing the real pulse. The analysis showed that two more groups of so-called room neutrons must be added to the main group of delayed neutrons [12]. This also follows from Monte Carlo calculations for albedo neutrons, taking into account the real design of the IBR-2M core's immediate environment. What kind of multi-group delayed-neutron system could then be used on the IBR-2M? Two systems can be distinguished here. In order to have an accurate idea of the development of fast processes (within tenths of a second), for example, when describing the pulse itself, the development of emergencies, power dumping, etc., it is necessary to add room neutrons to the main group. When describing processes lasting more than a tenth of a second, room neutrons can be neglected. It is sufficient to use the Keepin 6-group division as the main group of delayed neutrons [10].

4. Power fluctuations of the IBR-2M. Dynamics model and fast feedback

The power instability of the IBR-2 and IBR-2M is associated with the appearance of quite strong oscillations at low frequencies: 0.05–0.2 Hz. These fluctuations arise and intensify with increasing average power and energy output. There are no such fluctuations in a reactor with fresh (unirradiated) fuel. Fig. 4 shows an example of the appearance of fluctuations on the IBR-2M reactor at the beginning of power reduction.

A detailed study of fluctuations is associated with the creation of a model of the dynamics of pulsed batch reactors [1,2]. Model and experimental studies have shown that the development of power fluctuations in pulsed reactors is associated with changes in the parameters of fast power feedback (PF). Change of PF parameters depends on many factors: average power, energy output, coolant flow rate, position of control and protection system, etc. The PF of IBR-2 and IBR-2M can described by linear equations and represented as a sum of three parallel aperiodic links [5,6,13]:

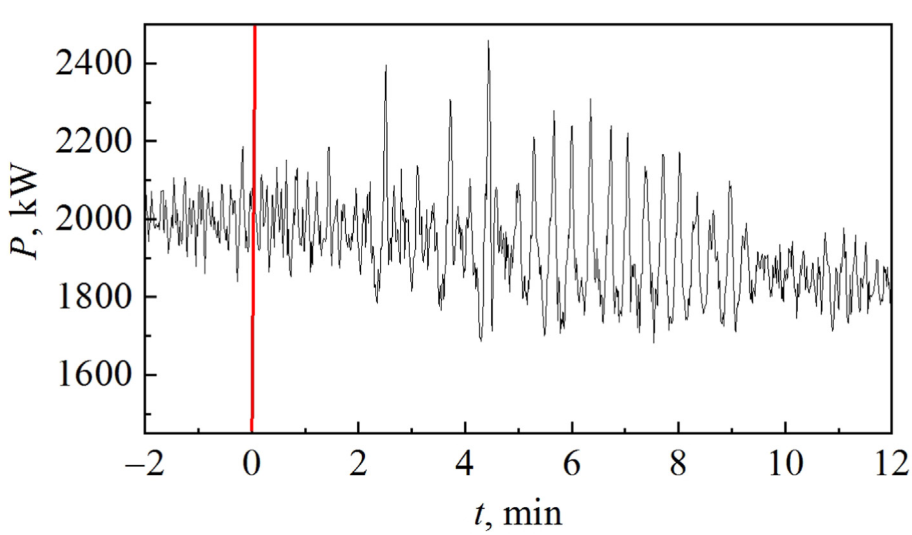

Fig. 4. An example of the appearance of fluctuations on the IBR-2M reactor at the beginning of power reduction from 2 to 1.8 MW (2017). Vertically red line is marking a moment of beginning of power reduction. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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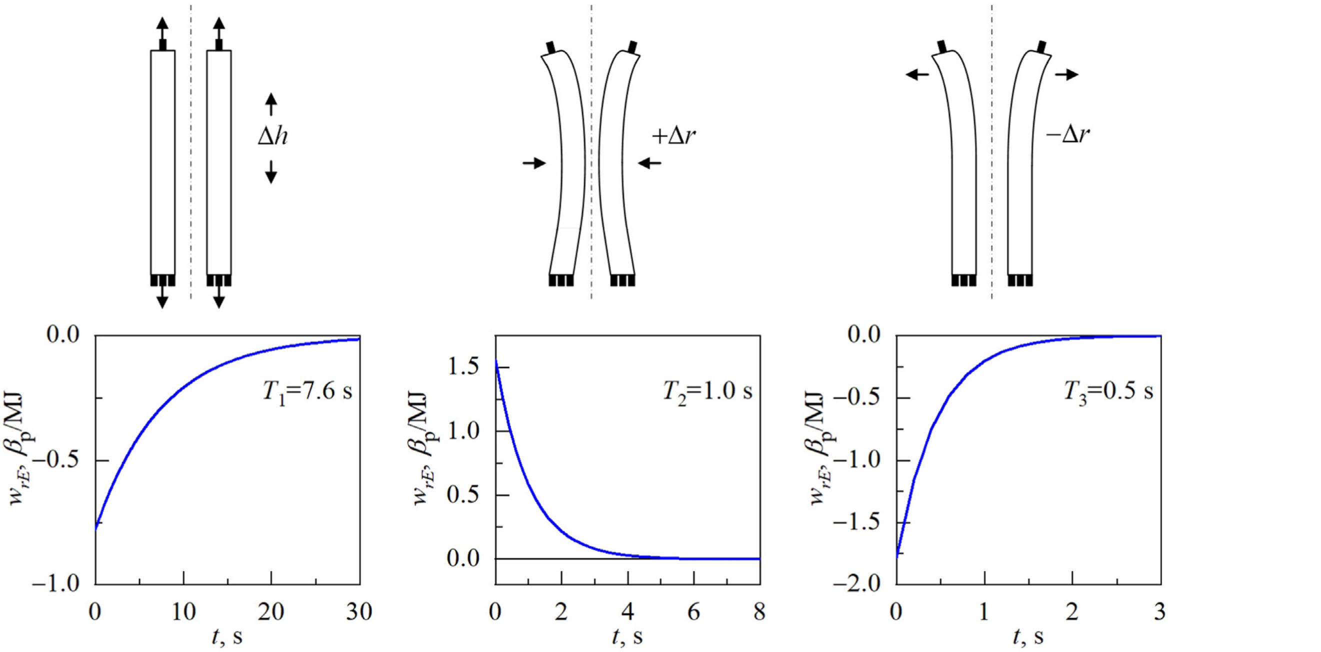

Fig. 5. An example of the effect of individual components of the IBR-2M power feedback: *1* – the axial fuel expansion, *2* – the bending of fuel assemblies towards the center of the core, *3* – the bending of fuel assembly's periphery of the core. Below – the corresponding pulse responses of the power feedback components with time constants.

$$\Delta r_{Tn} = \sum_{j=1}^{3} \Delta r_{Tjn}, \tag{11b}$$

$$\Delta r_{Tjn} = \left(\Delta r_{Tjn-1} + \Delta E_{n-1}\frac{k_{Tj}}{T_{Tj}}\right)\exp\left(-\frac{T_p}{T_{Tj}}\right), \tag{12b}$$

where Δr_{Tn} and Δr_{Tjn} are the total reactivity of the PF and its j-th components corresponding to the n-th power pulse in fractions ($\beta_p = 1.57\text{-}10^{-4}$); k_{Tj}, T_{Tj} are the transfer coefficient in β_p/MW and the time constant in seconds of the *j*-th PF component ($j = 1, 2, 3$), respectively; ΔE_n– is the deviation of total energy during the *n*-th power pulse from the base value; T_p is the power pulse period ($T_p = 0.2$ s).

The impulse characteristic of the IBR-2 and IBR-2M PF, i.e. the change of reactivity of the PF under the influence of a single power pulse, can be described by three terms as follows:

$$w_{rE} = \sum_{j=1}^{3} \frac{k_{Tj}}{T_{Tj}}\exp\left(-\frac{t}{T_{Tj}}\right), \beta_p \Big/ \text{MJ}, \tag{13b}$$

where *t* is the time, s.

In our opinion, the scenario for the action of the individual components of the PF is as follows. When exposed to a power pulse, the fuel heats up momentarily by 18 °C, followed by a decrease in temperature between pulses to the equilibrium temperature. In this case, various relaxation processes act, bringing the reactor to some quasi-stable equilibrium state. The slowest component of the PF ($T_{T1} \approx 8$–10 s) is due to the axial expansion of the fuel as it heats up during the impulse. The other two links with smaller time constants reflect the bending of the fuel cells: one bend is toward the center of the core with positive reactance input, the other is negative away from the core with some expansion of the baseplate, to which the cells are connected. Note that the cells at the top are free. The first bend toward the center of the core is due to the temperature gradient along the radius of the core. Note that for the energy-stressed zone, which is the core of the IBR-2M with a small volume of ~20 l, the fuel cells when the reactor is running are already bent toward the center of the core due to the quasi-stationary temperature gradient. Heating the fuel over the pulse further enhances this bend. The second bend toward the periphery of the core is related to the heating of the sodium from the instantaneous gamma rays and pulse neutrons. Heating is small at ~0.1 °C, but causes a noticeable push of the cells toward the periphery. It is possible that other physical processes are also involved in the formation of the PF, but the above are the most likely. Fig. 5 shows the behavior of the individual PF components for

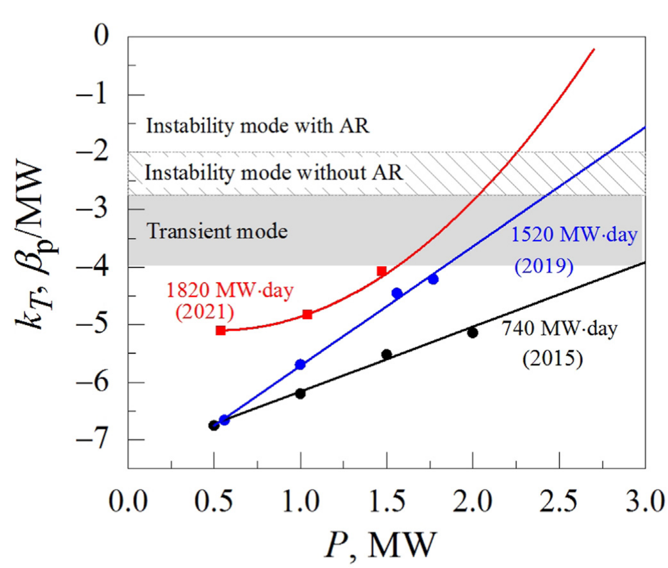

Fig. 6. Stability boundary for the IBR-2M and depending of the transfer coefficient of power feedback on the reactor power and energy for some energy output values.

Table 2
Measured data of the IBR-2M fast power feedback parameters at energy output of 1820 MW·day and coolant flow rate through the core of 100 m^3/h (2021).

P^0, MW	Parameter	j			$k_T = \sum k_{Tj}$, β_p/MW
		1	2	3	
0.54	k_{Tj}, β_p/MW	−5.1	–	–	−5.1
	T_{Tj}, s	6.65	–	–	
1.04	k_{Tj}, β_p/MW	−4.82	–	–	−4.82
	T_{Tj}, s	7.6	–	–	
1.47	k_{Tj}, β_p/MW	−4.54	0.74	−0.28	−4.07
	T_{Tj}, s	9.44	1.31	0.29	

Table 3
Calculated values of transfer coefficients of the IBR-2M power feedback at different values of β_p with a pulse frequency of $f_p = 10$ Hz and an average power of 2 MW. Energy output of 1820 MW·day and coolant flow rate through the core of 100 m^3/h.

β_p, 10^{-4}	k_{T1}, β_p/MW	k_{T2}, β_p/MW	k_{T3}, β_p/MW	$k_T = \sum k_{Tj}$, β_p/MW
1.00	−8.01	0.78	−0.31	−7.54
1.54	−5.10	0.50	−0.20	−4.80
2.00	−4.00	0.39	−0.16	−3.76
2.50	−3.20	0.31	−0.13	−3.01
3.00	−2.67	0.26	−0.10	−2.51
3.50	−2.29	0.22	−0.09	−2.15
4.00	−2.00	0.20	−0.08	−1.88

clarification. In fact, the bends of fuel rods and assemblies are very complex in shape and very small in size. For our article, this is a simplified illustration for a fundamental understanding of the bending of assemblies to the center.

The main criterion for the effectiveness of a particular fluctuation reduction measure is the increase in the absolute value of the total transfer coefficient $k_T = \sum_{j=1}^{3} k_{Tj}$ of the PF. It has been experimentally shown that the change in the PF coefficient during operation of the IBR-2M reactor has a complex structure [1,2,6,13]. The main part of this structure is the cumulative component, which increases with energy output and reactor power [1,2]. The dynamics of the IBR-2M at a pulse repetition frequency of 10 Hz is considered within the action of this cumulative component of instability.

5. Results of simulation of IBR-2M dynamics at 5 and 10 Hz

The first thing to know when switching to a different reactor frequency is to answer the question: what will change in the basic (initial) reactor parameters? First, at equal average power the value of the pulse energy will change, and second, the value of the critical Nyquist frequency will change (it will increase twice: from 2.5 to 5 Hz when switching to a frequency of 10 Hz). The value of the impulse fraction of delayed neutrons will change in the kinetics block. This value also determines the values of the PF coefficients in the feedback and automatic power control blocks [6,14]. The PF transfer coefficients are expressed in terms of β_p/MW. In addition, it is necessary to recalculate the PF coefficients according to the average power and energy output. This type of recalculation is performed directly within the reactor dynamics model for each reactor component in accordance with the physical concept of the PF adopted in this paper. The time constants of the action of the individual components of the PF are preserved during the transition to an increased frequency (the core itself does not change). All the initial experimental data on the PF parameters for the IBR-2M reactor measured through September 2021 with an energy production rate of up to 1820 MW·day are presented in Fig. 6 and Table 2. Table 3 shows the calculated values of PF coefficients for the IBR-2M at a power of 2 MW and a frequency of 10 Hz for different values of the pulse fraction of delayed neutrons. The following time constants of the three PF components were used: $T_{T1} = 7.6$ s, $T_{T2} = 1.3$ s, and $T_{T3} = 0.3$ s.

The feedback coefficient and the path of the IBR-2M impulse characteristic, as stated above, significantly depend on the power output and the average power level [1,6,13]. Fig. 7 shows the calculated pulse characteristics of the IBR-2M PF at some values of β_p at a frequency of 5 Hz and a power of 1.5 MW (*a*), and at a frequency of 10 Hz and a power of 2 MW (*b*). As can be seen from Fig. 7, the pulse characteristics depend significantly on the pulse repetition rate. You can also see that the amount of feedback in the 10 Hz mode is much greater than in the 5 Hz mode, which means that the reactor at 10 Hz has a more negative feedback and should be more stable.

The type of the amplitude-frequency response (AFR) of the reactor, as well as the value of its resonance peaks depending on the value of β_p. can serve as another, more obvious indicator of stability or instability of the reactor. Thus, Fig. 8 shows the AFR of the IBR-2M at a pulse frequency of $f_p = 10$ Hz and a power of 2 MW in the automatic power control mode (*a*) and the peak of the AFR (*b*) at different values of β_p. The ordinate axis in Fig. 8 shows the values of the relative change in the amplitude of pulse energy fluctuations when subjected to fluctuations of unit amplitude reactance at frequencies up to the critical Nyquist frequency, equal to 5 Hz. In this representation, AFR values above one can serve as a measure of fluctuations or, in other words, as a measure of the magnitude of the resonance peak.

Under the same conditions, but in 5 Hz mode and at a power of

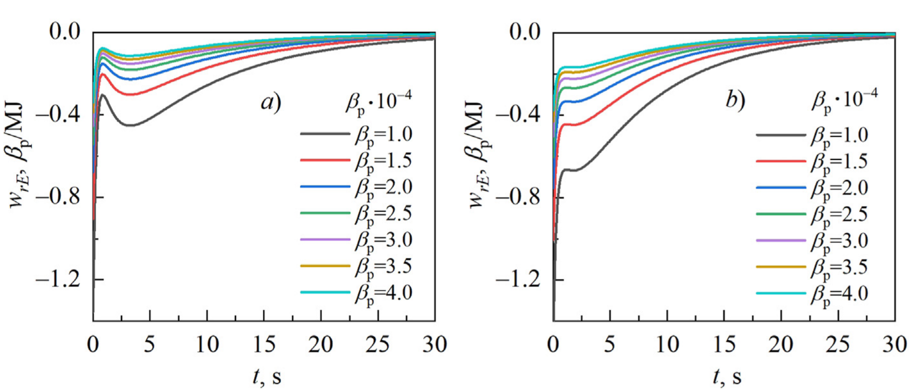

Fig. 7. Pulse response of the IBR-2M power feedback at energy output of 1820 MW·day for some values of β_p and power pulse frequency of 5 (*a*) and 10 Hz (*b*). Red curve corresponds to value of $\beta_p = 1{,}54 \cdot 10^{-4}$ for IBR-2M. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

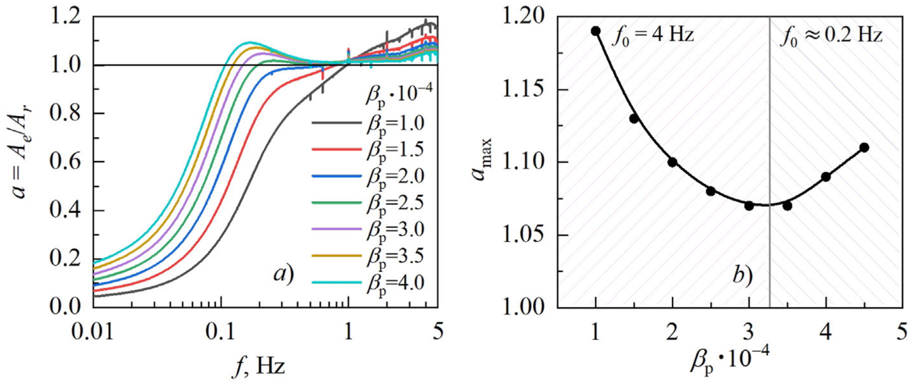

Fig. 8. Amplitude frequency response (AFR) of IBR-2M at power pulse frequency of 10 Hz and average power of 2 MW in regime with automatic regulator of power (*a*) and peak of the AFR (*b*) for some values of β_p. Energy output of 1820 MW·day (2021). Red curve corresponds to value of $\beta_p = 1{,}54 \cdot 10^{-4}$ for IBR-2M, f_0 – the resonant frequency. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

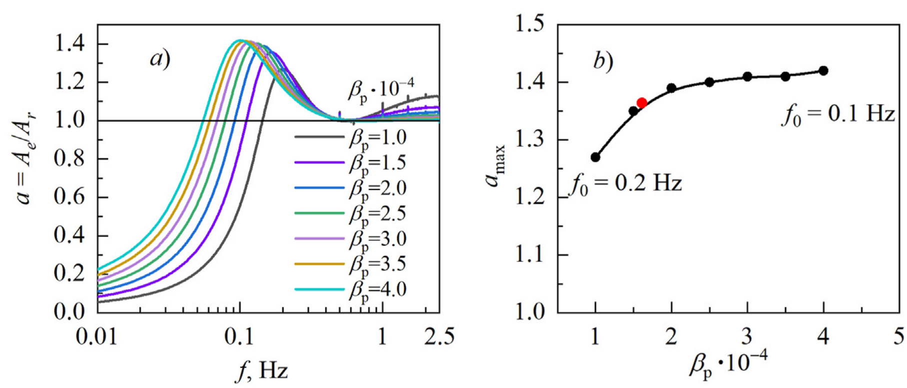

Fig. 9. AFR of the IBR-2M at power pulse frequency of 5 Hz and average power of 1.5 MW in regime with automatic regulator of power (*a*) and peak of the AFR (*b*) for some values of β_p. Energy output of 1820 MW·day (2021). Red point corresponds to value of $\beta_p = 1{,}54 \cdot 10^{-4}$ for IBR-2M, f_0 – the resonant frequency. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

1.5 MW (more is meaningless for reasons of reactor stability), increasing β_p, as can be seen from Fig. 9, only increases the fluctuations, although not by much. Thus, it does not make sense to increase β_p to increase the stability of the reactor in the 5 Hz mode.

Fig. 10 shows the AFR mapping as a function of the pulse energy and the value of the pulse fraction of delayed neutrons at pulse repetition rates of 5 and 10 Hz. Fig. 10 clearly illustrates that in the frequency interval of pulse energy fluctuations of 0.05–0.25 Hz the peak of the AFR at a pulse repetition frequency of 10 Hz is much lower than at 5 Hz (more than 30%). We should also note that a new range of resonant frequencies appears when β_p changes in pulse energy fluctuations: for a pulse repetition rate of 5 Hz in the region of 1.2–2.5 Hz, and for 10 Hz in the region of 1.2–5 Hz.

For a more accurate understanding of the kinetics of the IBR-2M pulsed reactor, additional computational studies using the Monte Carlo method are needed, as presented in Refs. [15,16].

6. Conclusions

The results of mathematical modeling of the dynamics of the IBR-2M reactor at the repetition rate of power pulses of 5 and 10 Hz have been obtained. The simulations studied the change in the

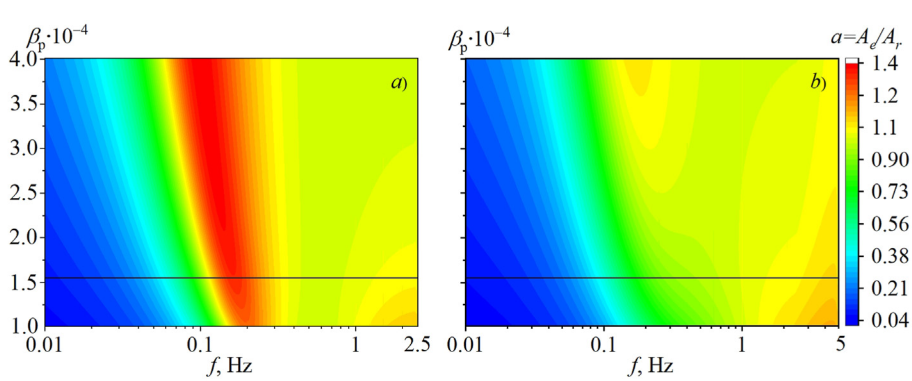

Fig. 10. Colormap of AFR in regime with automatic regulator of power: *a* – frequency of 5 Hz and average power of 1.5 MW and *b* – frequency of 10 Hz and average power of 2 MW.

reactor AFR with changes in the pulse fraction of delayed neutrons. A set of PF parameters measured at the IBR-2M reactor in 2021 at a power generation rate of 1820 MW·day was used. As a result, it is shown that the frequency characteristics of the reactor and the amplitude of fluctuations (resonances) of the pulse energy depend significantly on the value of the pulse fraction of delayed neutrons. At the same time, depending on the pulse repetition frequency, both growth and decrease of reactor power fluctuations in the frequency range of 0.05–0.20 Hz and at frequencies close to the critical Nyquist frequency can be realized. When switching the reactor from 5 Hz mode to 10 Hz regime, the frequency response of the reactor improves, and we can hope to attenuate fluctuations in this regime.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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