NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 8(4): 267–273
DOI 10.3897/nucet.8.96566

Research Article

Investigation of algorithms for suppressing xenon oscillations in a VVER-1200 reactor*

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Academic editor: Yury Korovin ◆ **Received** 1 November 2021 ◆ **Accepted** 30 August 2022 ◆ **Published** 13 December 2022

Citation: Soloviev DA, Khachatryan AG, Chernov YeV, Al Malkawi RT (2022) Investigation of algorithms for suppressing xenon oscillations in a VVER-1200 reactor. Nuclear Energy and Technology 8(4): 267–273. https://doi.org/10.3897/nucet.8.96566

Abstract

This paper presents the results of numerical studies of various algorithms for suppression of xenon offset and power distribution oscillations in the core of a VVER-1200 reactor. The purpose of the research is to select an algorithm that minimizes the amount of liquid radioactive wastes during water exchange in the primary circuit of a nuclear power plant. For this, several algorithms for xenon oscillations suppression were considered. The first algorithm considered was an algorithm for suppression of xenon oscillations, which uses regulation due to AWP only, without utilization of any additional regulation.

The second algorithm considered was an algorithm based on the use both AWP and boron regulation. In this algorithm suppression of xenon oscillations was carried out with the help of accelerated initiation of the work of the AWP by changing the boric acid concentration with constant second circuit pressure of the NPP and by utilization of the second control rods group.

Last algorithm considered was algorithm based on the use of temperature control for accelerated initiation of the work of the AWP. In this algorithm, xenon oscillations suppression was carried out by changing coolant temperature at the reactor inlet caused by pressure change in the secondary circuit in the normal operation margins, and by involving the second group of control rods.

It was shown that the best way to suppress xenon offset and power distribution oscillations in terms of minimization of radioactive liquid wastes amount is the algorithm with accelerated initiation of the AWP due to temperature regulation, with elimination of temperature regulation after minimizing of current axial offset value deviation from the nominal one.

Keywords

VVER-1200, offset-phase diagram, axial offset (AO), automatic power controller (APC), suppression algorithm, xenon oscillations, water exchange

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* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2022, n. 2, pp. 37–48.

Operational tasks in suppression of local power xenon oscillations

The purpose of this paper is to investigate different algorithms for suppressing local power xenon oscillations within the core to occur potentially due to technological reasons in the process of the power unit operation, and to select, out of the algorithms under consideration, the one leading to the minimized amount of liquid waste during water exchange in the primary circuit to achieve all safe operation requirements for the core components. Minimizing the water exchange is highly important for reducing the amount of chemically treated water, specifically towards the end of the reactor life.

The thing is that the required water exchange consumption to make up for the fuel burnup increases significantly towards the end of the core life. In accordance with (Rashdan 2018, Vygovsky et al. 2018, 2019), there is a formula for the liquid waste calculation as follows:

$$\Delta M = -M_1 \ln(1 - \Delta C/(C^* - C)), \qquad (1)$$

where ΔM is the weight of the coolant to be introduced into the primary circuit to change the concentration of boric acid, C_{H3BO3}, from current value C to value $C + \Delta C$; M_1 is the primary coolant weight (about 280 t); C^* is the concentration of boric acid in the makeup fluid (40 g/kg for the concentrate; 0 g/kg for the distillate, that is, $C^* = 40$ g/kg with $\Delta C > 0$, $C^* = 0$ with $\Delta C < 0$, and $C^* = 0.1$ with $|\Delta C| < C/2$).

It follows from formula (1) that the amount of liquid waste increases greatly as the critical concentration of boric acid is reduced and distillate is introduced as acid is removed from water.

The paper presents the results of numerical studies for different algorithms to suppress xenon oscillations in the VVER-12000 reactor core. The purpose of the studies is to identify the algorithm to allow minimizing the quantity of liquid waste during water exchange in the NPP primary circuit. Several algorithms for the xenon oscillation suppression were considered to this end (Shimazu 2008, Averyanova and Filimonov 2009, Averyanova et al. 2013, Semenov and Volman 2015).

Apart from the water exchange economy, implementing a specific control algorithm for suppressing xenon oscillations calls for a number of requirements to be achieved concerned with the safety of operating the core components (Vygovsky et al. 2011, 2013). Normal operation of the core requires, primarily, the following conditions to be fulfilled:

1. $\max(T_{cl}) - (T_{st}(P\text{-}1\mathrm{K}) + 2) < 0$;
2. $\max(Q_{lfuel} - 0.95Q_{lfuel\ \mathrm{lim}}) < 0$ is the maximum difference between estimated/measured and limiting fuel linear thermal load values for all reference core points;
3. $\min(DNBR) < 1.35$ – for all reference core points.

In these inequalities, $T_{st}(P\text{-}1\mathrm{K})$ is the saturated water temperature at the primary coolant pressure; T_{cl} is the fuel cladding outside temperature, °C; Q_{lfuel} is the fuel element linear thermal load, W/cm; and $DNBR$ is the departure from nucleate boiling ratio for the fuel surface.

The key requirement for normal operation in conditions of local power oscillations is that condition 2, as listed above, is fulfilled.

Apart from the above requirements, the offset-power diagram and the offset-offset diagram for the current lifetime point are used to monitor the field local power limits in the core during cyclic thermal loads on the fuel element. The offset-power diagram defines the range of the permissible reactor power axial offset values during the power unit operation as a function of the power value (Filimonov 1992). The axial offset (AO) value is determined as follows:

$$AO = [(W_1 - W_2)/W_0]\cdot 100\%,$$

where W_0 is the reactor power; W_1 is the core upper half power; and W_2 is the core lower half power.

Using an offset-power phase diagram ensures meeting the design criteria for no hoop stresses in the fuel cladding being in excess of the permissible values as local power changes as a result of the axial power density distribution change.

The base source for the offset-power diagram is the field local power limits expected to be smaller than the permissible local power values across the core. Local power is understood as the linear thermal power, Q_l, the fuel element accounts for. The other condition is meeting the requirement for minimizing the deviations of the local power values in different core states from steady-state values during rated power, with which it is securely achieved that no local power values are exceeded through the core as shown by the in-core instrumentation system data. This condition fulfilled does not lead to fatigue damage accumulated in fuel elements during cyclic loads in the course of the local power oscillations as these are suppressed. The offset-power phase diagram method to control in-core power density distribution was developed by RSC Kurchatov Institute and VNIINM (Averyanova et al. 2002, 2016).

Description of control algorithms to suppress xenon oscillations using the APC

At the present time, the VVER reactor unit power is controlled using the (APC) and the turbine control system (TCS). Whatever its operation mode is, the APC initiates the travel of the CPS control rod assembly to maintain the specified reactor or turbine power. When power is reduced, the control rod assemblies travel down, and they travel up as power is increased, influencing so the neutron power axial offset. And the above travel of the assemblies and its influence on the axial offset is such that another critical control function is involved as well, namely the reactor stability is improved against the local power axial oscillations while no integral power changes (Averyanova et al. 2011).

In the event of power oscillations induced by the xenon processes in the core, the control rod assembly travels in an antiphase with the offset change, this suppressing the oscillations (Averyanova et al. 2008).

The APC-based self-regulation of the axial offset is valid only with the control rod assemblies withdrawn from the core to more than 50%. With the control rod assembly inserted to over 50%, the neutron field shifts upwards, and the axial offset value is increased, this leading to a positive feedback between the integral power value and the power axial offset value.

Due to scheduled limits, the reactor operation without control actions (in a natural oscillation mode) is possible only in a relatively small power and offset range. With the rated power level, in particular, its value shall be maintained with an error of ±2%, this being achieved due to the control rod assembly being controlled by the APC. In the event of oscillations with an amplitude greater than ±2%, with the axial offset values being outside the permissible region, as defined by the offset-power diagram, it is required to actuate the APC operation in an accelerated mode. The APC operation can be initiated through boron regulation and/or temperature regulation. Boron regulation is ensured by introducing boron concentrate introduction when it is necessary to withdraw the control rod assembly, or distillate if it is required to insert the assembly. The APC operation can be initiated by temperature regulation using the pressure variation in the secondary circuit. Temperature regulation is ensured through a pressure increase in the secondary circuit if the control rod assembly requires to be withdrawn, or by reducing the pressure if the assembly requires to be inserted.

Let us formulate the key features of the control algorithm using the APC to suppress the local power xenon oscillations. With the specified power, the axial offset value on the optimum offset trajectory is determined as part of the offset-power phase diagram for the considered life point. This defines the permissible interval of deviations from the optimum value equal to ±1.5%. The monitored values are axial offset, neutron power and its time derivative. The actions to actuate the APC are based on monitoring the offset derivative and its value and sign. With the derivative and its value modulo being positive to over 1%/h, the offset deviations from the optimum value modulo being more than 2%, positive reactivity needs to be introduced, that is, the concentration of boron in water to be reduced by 0.003 g/kg to 0.01 g/kg and/or the core inlet coolant temperature reduced by 0.3 °C to 1.0 °C with the control rod assembly not used by the APC to be further withdrawn if possible. The travel range of the other control rod assembly is equal to between 90% withdrawn and 100% withdrawn, that is, the position of the second control rod assembly is limited to a 10% insertion (not more). With the derivative and its value modulo being positive to over 2%/h, negative reactivity needs to be introduced, that is, the concentration of boron in water to be increased by 0.003 g/kg to 0.01 g/kg and/or the core inlet coolant temperature increased by 0.3 °C to 1.0 °C, with the control rod assembly not used by the APC to be further inserted if possible.

The described scheduled actions to initiate the APC operation in the desired direction lead to different water-exchange consumptions. If only boron regulation is used for the entire control scope, such oscillation suppression algorithm will lead to large amounts of liquid waste accumulated, specifically at the end of life when the critical concentration of boric acid is low, and, in accordance with (1), much pure water needs to be consumed to achieve the required dilution. The most practicable algorithm is therefore that using temperature regulation and involving the second control rod assembly, potentially with no water exchange consumption.

The PROSTOR code with VVER-1200 models (Vygovsky et al. 2003, 2004) is used for investigating numerically the control algorithms described. This code is a multifunction analyzer of modes in the VVER-1200 reactor of the AES-2006 design and represents an integrated software and hardware package for problem solving in engineering support for operation of the core components.

Description of numerical studies for the xenon oscillation suppression algorithms

The reactor operation for several days was simulated using only the reactor model with the specified dependence of the core coolant inlet temperature on the integral reactor power and the secondary circuit pressure in accordance with operating data:

$$T_{in} = 297 + 0.12(N - N_0) + 9(P - P_0), \tag{2}$$

where T_{in} is the core inlet coolant temperature; N is the current reactor power, %; N_0 is the rated reactor power, %; P is the current secondary circuit pressure, MPa; and $P_0 = 6.8$ MPa.

In accordance with (2), the temperature regulation limits, with the rated power value being 90%, are defined by a range of 294 °C to 297.6 °C

The initial oscillation excitation method is not essential for investigating the oscillation suppression algorithms. The following method was used. With the preset 90% reactor power, control rod assembly 12 was 20% inserted (70%–90%) while power was kept constant through boron regulation; the assembly remained in this position for two hours and traveled back to the initial position (90% of the withdrawal height). This led to axial offset xenon oscillations.

To investigate different suppression algorithms, the initial fuel load for the Novovoronezh NPP's unit 6 was considered as of the life end (after 320 effective days), since the reactor is not stable, in terms of xenon oscillations, for the given load and lifetime point, and the oscillations are diverging. An offset-power diagram was plotted for the given lifetime point (Fig. 1).

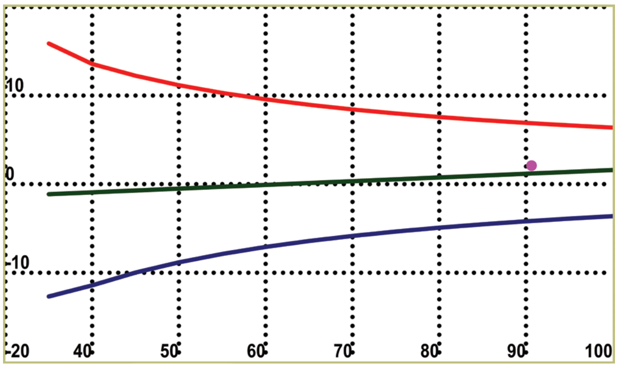

Figure 1. Offset-power phase diagram.

For the given initial reactor state after natural xenon oscillations are excited, physical processes in the core were simulated without using any oscillation suppression method (option 1) and using the above control algorithms:

- using only the APC operation (option 2);
- using the APC, boron regulation and manual control by the second CPS control rod assembly (option 3.1);
- using the APC, boron regulation and manual control by the second CPS control rod assembly and keeping the control rod assembly in the scheduled limits (70%–90%) in the closing oscillation suppression phase (option 3.2);
- using the APC, temperature regulation and manual control by the second CPS control rod assembly (option 4.1);
- using the APC, temperature regulation and manual control by the second CPS control rod assembly and keeping the control rod assembly in the scheduled limits in the closing oscillation suppression phase (option 4.2);

The APC operation took place when changing from the control rod assembly traveling mode with the travel interception (TI) to a mode using only one CP rod control assembly (No. 12), and the second control rod assembly was assembly No. 11, which was used for manual control.

For option 3 and 4, following the stabilization of the axial offset behavior in time, two control methods (3.2 and 4.2) were considered additionally. These two methods are as follows. For the first method, temperature and boron regulation served exclusively to keep the axial offset near the equilibrium value with monitoring the control rod assembly position. In this case, the assembly could travel beyond the scheduled limits, in terms of the height of withdrawal from the core. For the second method, temperature and boron regulation served not just to keep the axial offset near the equilibrium value but also to retain the control rod assembly position in the scheduled limits. Simulation was undertaken for not less than 160 hours (Filimonov et al. 1998, Averyanova et al. 2010).

Right after oscillations are excited using the above method, the reactor's lower core starts to be depoisoned and the offset starts to increase, so, to change the growth trend, we reduce the core inlet coolant temperature or the boric acid concentration in the coolant (Braslavsky et al. 2018, Kazansky and Slekenichs 2018). Positive reactivity is introduced into the reactor, and power starts to grow, so, to keep its value constant, the APC inserts the control rod assembly and reduces the offset growth. These actions are repeated until the core inlet coolant temperature reaches the minimum permissible value of 294 °C (the minimum value during boron regulation is the boric acid amount equal to 0.02 g/kg), following which the offset growth is suppressed by assembly 11 inserted to 90% of the withdrawal height. As soon as in 8 to 9 hours, the offset is at the permissible boundary, and, after 12 to 13 hours, the offset trend changes and the offset value starts to decrease; actions are now required to prevent the offset reduction. To this end, the core inlet coolant temperature or the boric acid concentration is increased, which reduces the reactivity and power, and the APC lifts the control rod assembly.

Where such control actions are taken, one needs to monitor the neutron power axial offset derivative in time. If the offset derivative is negative, and its value modulo is great, the second control rod assembly needs to be gradually withdrawn to the upper limit switch positions. The coolant temperature value can be increased to 297 °C. In both algorithms, as in the case of temperature regulation, regulation is of a high priority, using which the APC operation is initiated in an accelerated manner and the axial oscillations start to be suppressed much earlier. Another method, after the offset value is stabilized for the given algorithms, is to use different types of regulation so that the APC could bring the control assembly back to the scheduled position of 90% and keep it in this position.

Figs 2–5 present the simulation results showing the behavior of the monitored parameters in the core as a function of time.

Fig. 2 shows the behavior of the neutron power axial offset for all considered simulation options. It can be seen from the figure (option 2) that the oscillation suppression algorithm using exclusively the APC, with no extra control actions involved, does not make it possible to achieve all safe operation requirements, that is, the axial offset value fails to be retained within the offset-power diagram boundaries for three days. The algorithm of APC-based control, in combination with boron or temperature regulation, allows this retention throughout the time interval, excluding the initial portion with primary excitation.

Fig. 3 shows the behavior of the value of the margin for the linear thermal load on the fuel element, $\max(Q_{lfuel} - 0.95Q_{lfuel\lim})$and the amount of liquid waste during water exchange as a function of time for all simulation options considered.

As to the water exchange consumption, the amount of liquid waste for the boron regulation option reaches

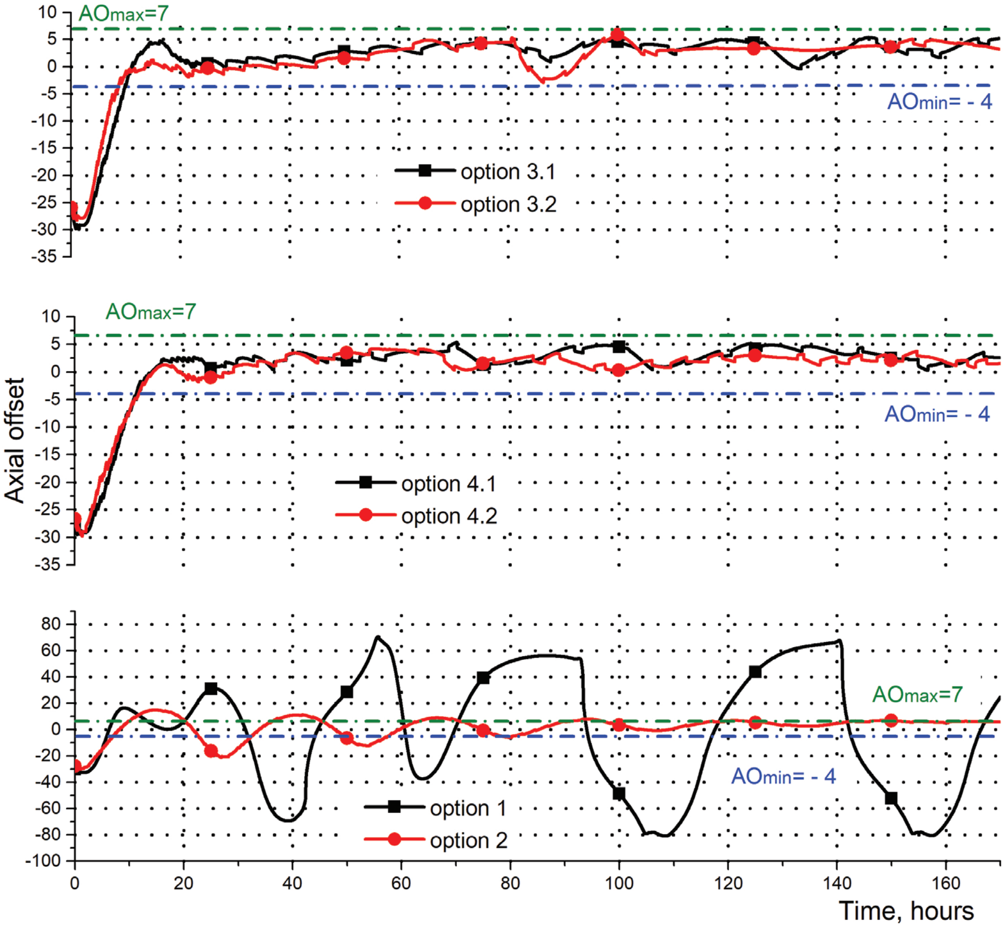

Figure 2. Neutron power axial offset as a function of time with no suppression of oscillations and with different suppression techniques.

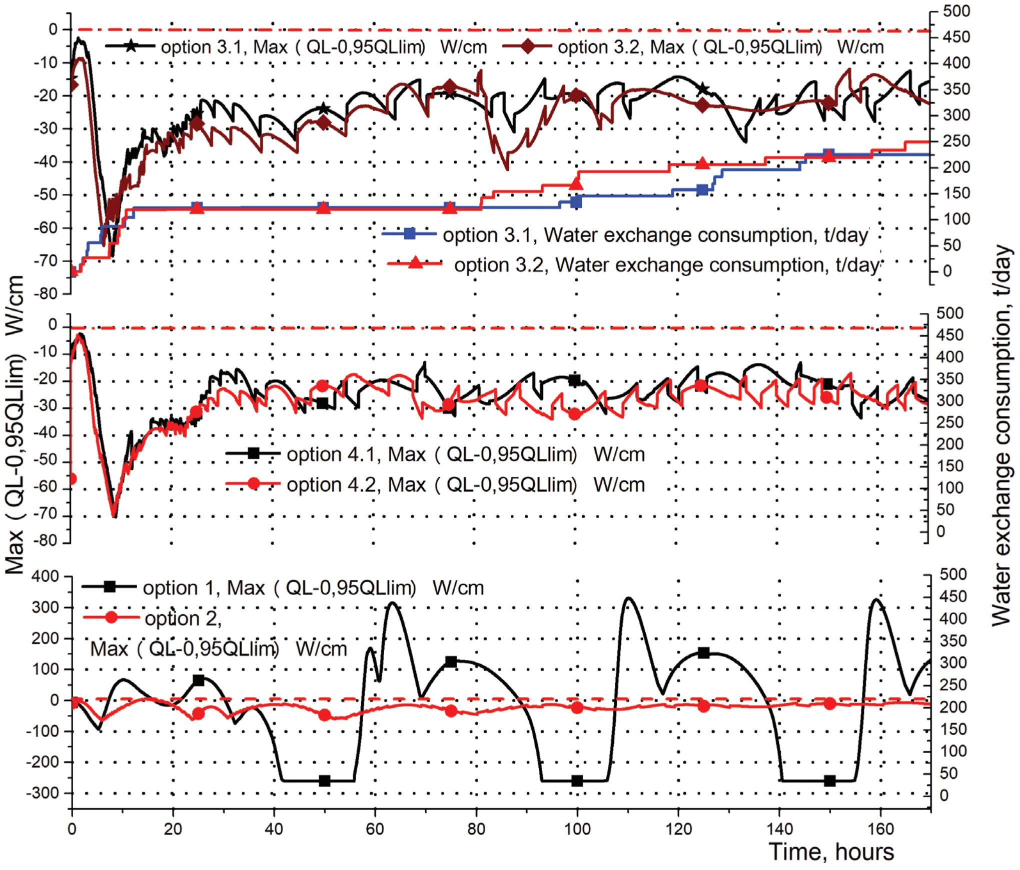

Figure 3. Behavior of the linear thermal load margin value for a fuel element as a function of time.

a substantial value of 250 t/day. The additional water exchange consumption for the other options is equal to zero.

Fig. 4 present the positions of the control rod assemblies and the values of the boric acid concentration in the coolant as a function of time in the event of the algorithm with different control methods in the closing phase under options 3.1 and 3.2. It can be seen in Fig. 4a that assembly 12 travels up to 95% of the withdrawal height somewhere towards 130 hours for the first control method. For the second method, boron regulation took place not only to keep the axial offset near the equilibrium value but also to retain the control assembly positions in the scheduled limits.

As can be seen in Fig. 4b, assembly 12 was never anywhere higher than 93% of the withdrawal height, and was at a 90% level for a very long time (for 110 to 150 hours).

Fig. 5 present the positions of the control rod assemblies and the core inlet coolant temperature values as a function of time for the algorithm with different methods of control in the closing phase under options 4.1 and 4.2.

Fig. 5a shows that the coolant temperature did not change in an interval of 120 to 145 hours and leads to assembly 12 withdrawn using the APC to 95% of the core height, which is not recommended by the operating schedule. To keep assembly 12 somewhere at 90% of the core withdrawal height, the core inlet coolant temperature was reduced additionally by about 1 °C (to a value of 294.7 °C), as graphically shown in Fig. 5b.

Conclusions

The findings for the considered CPS rod travel options obtained using the PROSTOR code show the following water exchange consumptions:

- options 1 and 2 – 0 t/day;
- option 3.1 – 220 t/day;
- option 3.2 – 250 t/day;
- options 4.1 and 4.2 – 0 t/day.

Among the algorithms that have been considered, the APC-based algorithm using temperature regulation and manual control of the CPS control rod assembly (option 4.2) is the best one for minimizing the water exchange consumption. This algorithm provides for all safe operation conditions with the scheduled control of assemblies. The core inlet coolant temperature range used complies with the interval of the permissible secondary circuit pressure values of 6.6 MPa to 7.0 MPa. More than that, this interval of the pressure values turns out to be even narrower with the given algorithm. Using practically this algorithm is highly important somewhere towards the end of life when large quantities of liquid waste from water exchange are possible. The investigated algorithm is most efficient towards the end of the fuel life end since the critical boric acid concentration in the coolant at the time is rather low, due to which the temperature reactivity effect is greater.

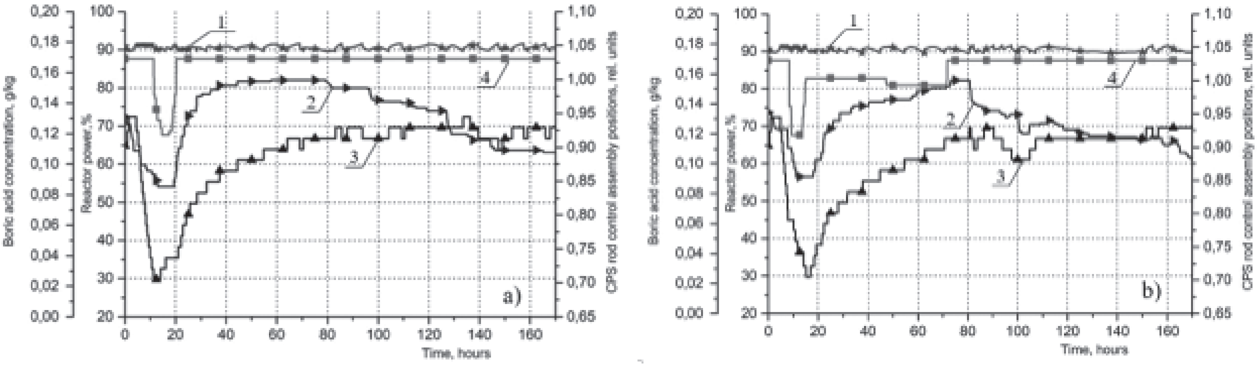

Figure 4. Variation of the reactor parameters in the xenon oscillation suppression process: **a.** Option 3.1; **b.** Option 3.2. Key: 1 – reactor power, %; 2 – boric acid concentration, g/kg; 3 – position of CPS rod assembly 12, rel. units; 4 – position of CPS rod assembly 11, rel. units.

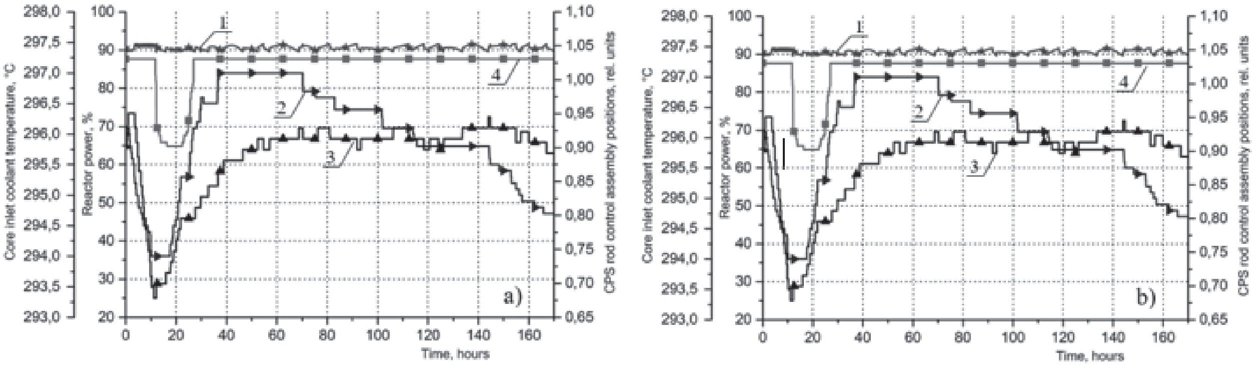

Figure 5. Variation of the reactor parameters in the xenon oscillation suppression process: **a.** Option 4.1; **b.** Option 4.2. Key: 1 – reactor power, %; 2 – core inlet coolant temperature, °C; 3 – position of CPS rod assembly 12, rel. units; 4 – position of CPS rod assembly 11, rel. units.

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