

# Status and Prospects of Activities on Algorithms and Methods in VVER-1000 Core Control

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## Introduction

VVER-1000 reactors, in common with analogous PWRs, possess an axially instable power density field because of the non-equilibrium processes of redistribution of Xe-135 nuclei in the volume of the reactor core. This instability results in so-called xenon oscillations of the power density distribution. To prevent and suppress such oscillations is one of the reactor control problems. For VVER-1000s the period of the xenon oscillations is about 300 hours; the amplitude depends on the mechanism of their excitation, and initial deformation of the power density distribution; the convergency of the oscillations is maximum at the beginning of the campaign to decrease with fuel burnup. To describe the xenon oscillations use is made of an axial offset (AO). This quantity characterizes an axial non-uniformity of the power density distribution to be equal to the percent ratio of the difference between the released powers in the upper and lower halves of the core to the total released power. In the "ascending phase" of the xenon oscillations where the power is redistributed from the lower half of the core to its upper half the offset increases; in the "descending phase" where the power is redistributed from the upper to the lower half of the core the offset decreases.

The problem of the xenon oscillations was worked out in Russia - even before the appearance of large-size, high-capacity VVERs for which this problem would be actual [1, 2].

In the process of designing a pilot VVER-1000 unit (Novovoronezh-5) the generation of the xenon oscillations was predicted for this type of reactors and the basic parameters of the oscillations were determined by computer simulation. After commissioning of the pilot unit and the first units with commercial VVER-1000s, in 1980-1985 a number of experiments were made to study the xenon oscillations [3, 4]. Figure 1 shows the plots of "free" xenon oscillations obtained during the investigations in the first campaign of Zaporozhye-1 NPP. The oscillations were excited by lowering the control rods (CRs) of a working group down to a position of 40 - 50% core height with the reactor power unchanged. The first curve was plotted after the operation for 40 eff.d at 73% of rated power; the second curve corresponds to 175 eff.d and 97% of rated power.

As seen in the figure, the xenon oscillations become divergent in the second half of the campaign at full-power operation. Nevertheless, as the practice shows, in the steady-state operation of the reactor the power density distribution is sufficiently

stable. This is explained by an interesting side effect arising from the operation of an automatic power controller (APC). The fact is that, as the burnup increases, the effect of the axial oscillations of the power density distribution on the total power of the reactor begins to manifest itself. In stabilizing the power the APC moves the CRs in a way to ensure a negative feedback to a change in the AO and suppresses the xenon oscillations. Thus, the APC serves also as a regulator of the axial power density profile, though it was not designed for this purpose. Figure 2 gives the mechanism of APCs operation in that case and an example of the automatic suppression of the xenon oscillations by the APC at Novovoronezh-5 NPP (12th campaign, 244 eff.d).

In the case of strong disturbance of the steady-state operation of the reactor resulting, as a rule, from variations in its power, there appears a need for controlling the power density distribution. In the course of the above investigations of the xenon oscillations algorithms for their suppression were developed and appropriate instructions for NPP personnel were worked out. The algorithms are of a discrete character and resemble Westinghouse's BANG-BANG CONTROL algorithms. As a rule, a single group of control rods is used for the control. Provision was also made for an auxiliary group of half-length control rods which should be dropped into the lower half of the core, if the descendent phase of xenon oscillations was intensively developed.

The experience in operating VVER-1000s had demonstrated that the available control algorithms allow, with a fair degree of assurance, the stabilisation of the axial offset and the prevention of intensive xenon oscillations. In this case there is no need

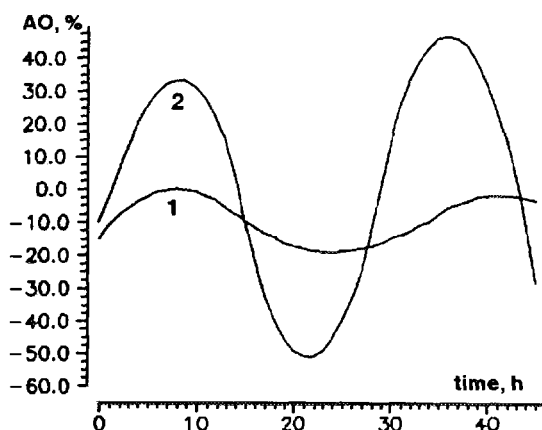


Figure 1 Free axial xenon oscillations in the core of commercial VVER-1000: (1) 40 eff.d.; (2) 175 eff.d.

to use the half-length control rods which may be replaced by full-length ones. The corresponding works are under way at most of NPPs with VVER-1000s.

At present the further works on improving the control of the reactor power and power density distribution in VVER-1000s are oriented to the following problems:

- Even though present-day VVER-1000s operate under steady-state conditions, there may occur situations (equipment failures or an accident to the power supply system) involving a sufficiently deep and complex power cycling. In these cases the NPP personnel must be provided with efficient means of monitoring and predicting the state of the reactor;
- The abandonment of the half-length CRs imposes more strict limits on the permissible deformation of the power density distribution. This requires modification of the control algorithms;
- The development of power-cycling regimes demands the appropriate algorithms, the automation of the control and the computation of fuel power density.

## 1 Transients Simulation and Monitoring, Operators Support and Control Automation

Of great importance for the control of the power density distribution is an adequate assessment of the current state of the reactor and the prediction of its response to various control actions. A computerised operators' adviser (OA) may provide a solution to this problem. In particular, such work is in progress now as applied to Novoronezh-5.

One of the OA elements is planned to be a computer code reactor simulator (RS) realising a physical reactor model based on a BIPR-7 code commonly used for design and operational calculations of VVERs [5]. According to the present-day views, the RS must be capable, in the on-line application, based on the data of the conventional monitoring system, to reconstruct the current state of the reactor, to predict the behaviour of the reactor as well as to allow the operator to follow some variants of the control and to seek advise.

One of the basic problems in controlling the axial power density profile is to determine the current phase of the xenon oscillations and to present the control process as a continuum of the reactor states in the form convenient for the assessment of the current situation, the prediction of the subse-

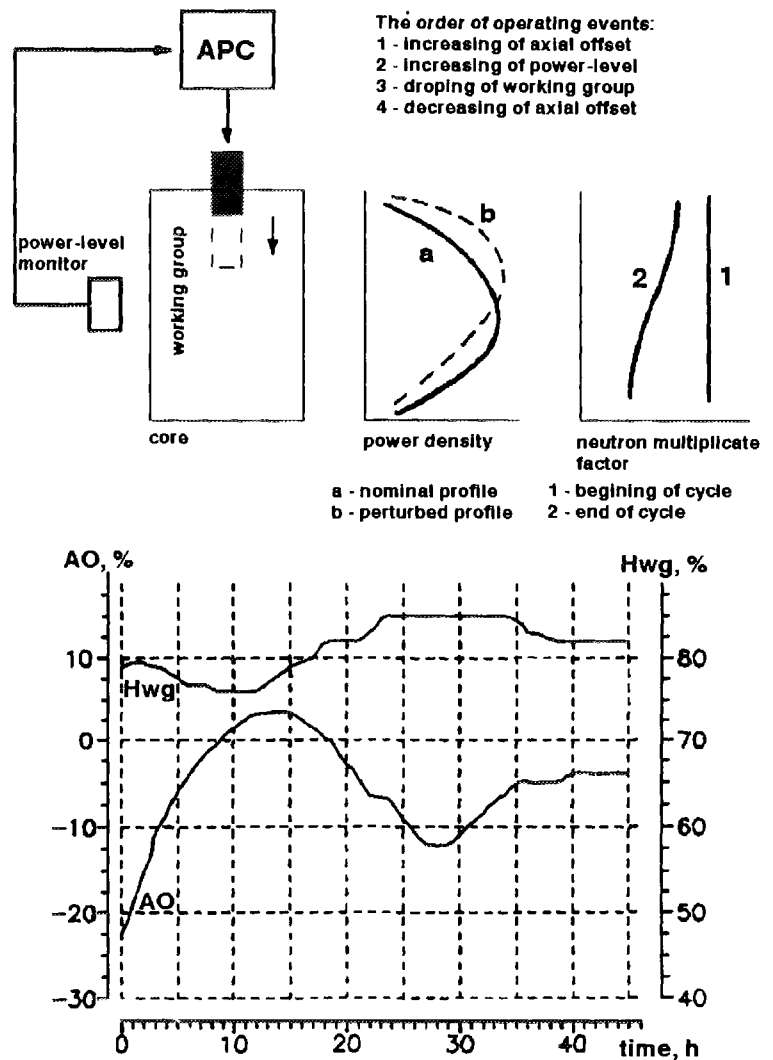


Figure 2 Suppression of the xenon oscillations by the automatic power regulator (Novovoronezh NPP, unit 5)

quent events and the selection of control actions. To solve this problem in the OA it is planned to use an "offset-offset" diagram [6]. This is a two-dimensional phase diagram plotted against the instantaneous, AO, and the equilibrium, AO\*, offsets. In this case the instantaneous offset corresponds to the current power density distribution. The equilibrium offset is related to the power density distribution in the equilibrium state (from the viewpoint of the relationship between the concentrations of iodine and xenon nuclei in the core) at the current values of the reactor thermal power, the fuel burnup and the CR positions.

Figure 3 schematically shows an offset-offset diagram. The rectangle bounded by the values  $AO_{max}$ ,  $AO_{min}$ ,  $AO^*_{max}$  and  $AO^*_{min}$  encloses a permissible area. The points on diagonal AA correspond to the steady states. The free xenon oscillations will show up as oscillations of a point along a vertical with respect to its intersection with diagonal AA, that is, with respect to a steady-state point (determined by CR positions) to which the current point will tend as the oscillations decay. The control actions (the movement of the CRs) form a trajectory

of the process. The trajectory may be specified in advance or determined starting from the situation at each instant of time. The position of the current point with respect to the boundaries of the permissible area and diagonal AA allows one to estimate the degree of instability of the current reactor state as well as the amplitude of the xenon oscillations and the scope of controllability.

The first trajectory in Fig. 3 corresponds to the free damped oscillations; the second trajectory is representative to the control process holding the offset within the permissible area. Here the control actions consist in the movement of the control rods in the upper half of the core. In so doing the values AO and AO\* change simultaneously, and in the

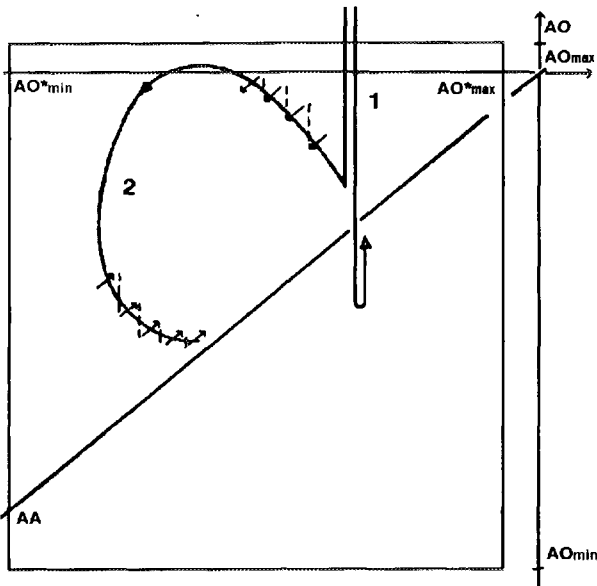


Figure 3 Offset-offset diagram

"instantaneous" movement of the rods the point on the diagram moves along diagonal AA.

In practice the movement in a specified trajectory can be performed in steps when the "instantaneous" control action and the development of free oscillations alternate. In this case a sawtooth trajectory takes place. Such an algorithm is particularly convenient for an automated control, because it can be simply interpreted technologically: the intersection of the specified trajectory by the current point represents an on or off signal for the CR drive. The feasibility of an automatic offset controller on this basis is now under study.

The visualisation of the information required for the reactor control is one of the functions of the OA. Figure 4 schematically shows the format of visualisation of the processes of control of the axial power density distribution in the reactor on the PC display in the OA system. Use is made of the values directly measured in the reactor as well as those calculated with the use of the RS. The display screen is divided into four zones:

- the static characteristic of the equilibrium offset at the current instant of the campaign and the current reactor power is displayed in the left top corner;
- the offset-offset diagram is plotted in the left bottom corner;
- the current position of the working group of the CRs is shown in the right top corner, where the histogram of the power density distribution along the core height is also plotted;
- the time variation of the instantaneous offset is plotted in the right bottom corner.

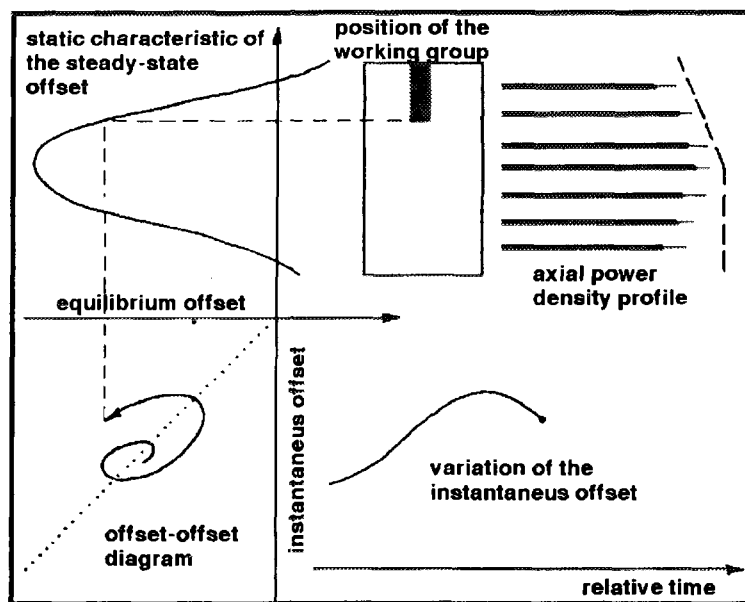


Figure 4 Screen format to visualize the control of the axial power distribution in the graphic module of the reactor simulator.

## 2 Development of Control Algorithms

In connection with the renunciation of half-length CRs the challenge is to suppress the intensive xenon oscillations in the descending phase with the use of full-length CRs.

An algorithm is suggested based on the following principles:

- the control is realised by the movement of two CR groups: a working group (WG) and a special control "grey" group (CG). These 8 -CR groups compensate simultaneously for changes in reactivity. The CG is chosen so that, when the WG moves up to the top core boundary, the CG drops down to the core bottom;
- when the CG moves in the upper half of the core, the effects of the two groups on the axial power

density distribution are mutually subtracted - the value of the offset varies only slightly;

- when the CG moves in the lower half of the core the effects of both groups on the axial power density distribution are summed - the offset changes in the positive direction.

Figure 5 shows qualitatively the dependence of the offset on the WG position in the case of the reactivity compensation by liquid boron (method 1) as well as the dependencies of the CG position and the offset (AO) on the WG position in the case of the movement of the groups for the purpose of the reactivity compensation (method 2). Point A corresponds to an initial WG position, point B to the CG position at the half height of the core and point C to the CG position at the bottom of the core. The integral efficiency of method 1 is higher by DAO than that of method 2. This is explained by the effect of the boron concentration in the coolant on the temperature coefficient of reactivity. The differential efficiency for method 2 is two times higher when the CG moves in the lower half of the core.

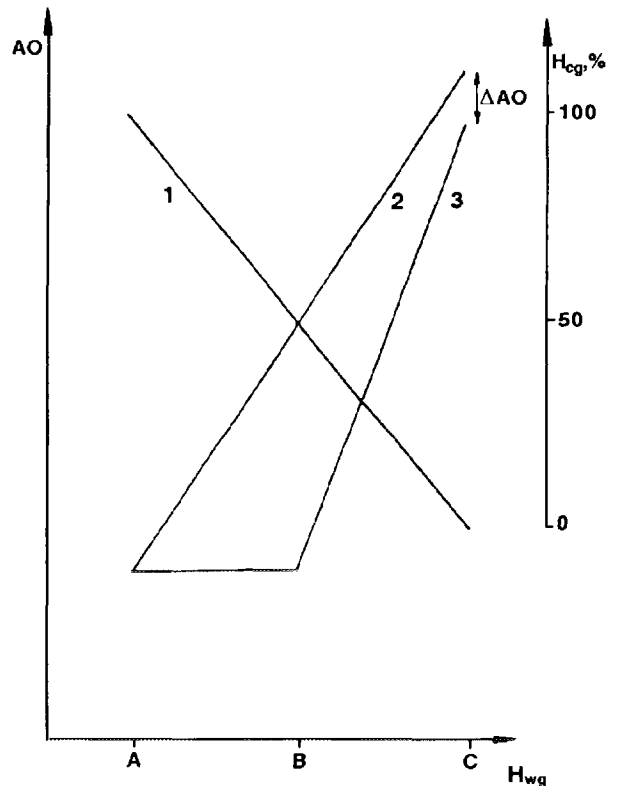
The same dependences calculated by the BIPR-7 code for O and 240 eff. days of the 12th campaign at Novovoronezh-5 are shown in Figs. 6 and 7.

The computer simulation of the control processes supports the efficiency of the algorithm proposed in suppressing the xenon oscillations.

The algorithms currently used for the control of the VVER-1000 reactor in power cycling are oriented to the use of the "black" WG and the sequential movement of the CR groups with an interval equal approximately to the full height of the core (the group begins to move at the instant when the preceding group reaches the boundary of the core). This leads to excessive deformations of the power density distribution which excite the xenon oscillations and restricts the controllability. Figure 8(a) shows a variant of the computer simulation of a real episode of the reactor control when the power was reduced from 100% to 50% (Novovoronezh-5, 12th campaign, 123 eff. d).

In the course of works on the replacement of the half-length CRs and the implementation of the power cycling regimes, under consideration are control algorithms involving less "black" CR groups and a shorter interval between the groups. Figure 8(b) shows a variant of computer simulation of the case considered above where the power is reduced with the use of two CR groups: a working group and a control "grey" group. The interval between the groups is 50 - 60% of the core height. The time dependence of the liquid waste volume in the boron control system is given in Fig. 8(c). The advantages of the modified variant are evident.

A program for testing the modified control algorithms at Novovoronezh-5 is in the preparation stage.



**Figure 5 The offset control:**  
 (1)  $H_{cg}(H_{wg})$  overcompensation by rods;  
 (2)  $AO(H_{wg}, C_B)$  overcompens. by boron;  
 (3)  $AO(H_{wg}, H_{ca})$  overcompens. by rods.

### 3 Estimation of the Fuel Element Thermal Load in Reactor Power Changes

A method of estimating the value and rate of change of the linear power rating in the fuel element in power cycling is under development. The method is based on the BIPR-7 and PERMAK calculations [7].

The BIPR-7 code allows the thorough simulation of the reactor control as well as the calculation of the accompanying xenon-related transients and the redistribution of the released power in the volume of the reactor core. The value of the relative released power  $K_k$ , relating to an elementary calculation cell - a fuel assembly fragment - and not accounting for the power distribution among the fuel elements yields the most detailed power density field.

The PERMAK program allows one to calculate the value of  $K_k$  - the relative released power of an individual fuel element in a certain layer of the core, but does not permit the simulation of the xenon-related transients and the axial deformation of the power density distribution accompanying the reactor control in the process of power cycling.

The linear power rating ( $W/cm$ ) of a given fuel element in a given segment of the core can be estimated as follows:

$$q_i = \overline{q}_i K_v K_k$$

where  $\overline{q}_i$  is the average linear power rate.

The following assumptions are made:

- the relative power density distribution throughout the fuel elements in the core is axially independent;

- the xenon-related transients do not distort the relative power density distribution throughout the fuel elements inside a fuel assembly;
- when the CRs move, the maximum deformation of the power density distribution in the fuel occurs in the fuel element sections nearest to the ends of the moving absorber rods. In this case the degree of deformation is axially independent.

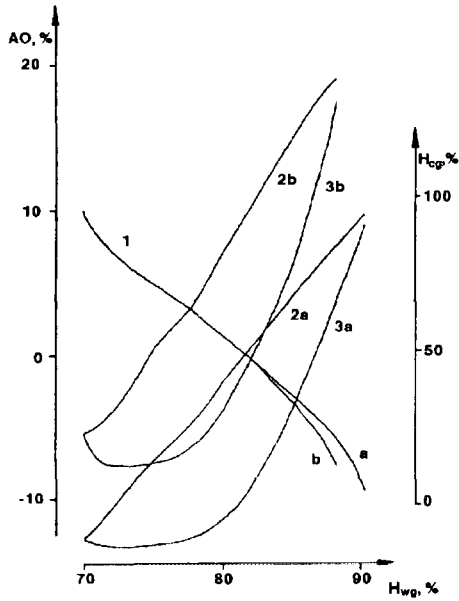


Figure 6 Offset control at cycle beginning; (1), (2), (3) as in Fig. 5; power level: (a) 100 %, (b) 50 %.

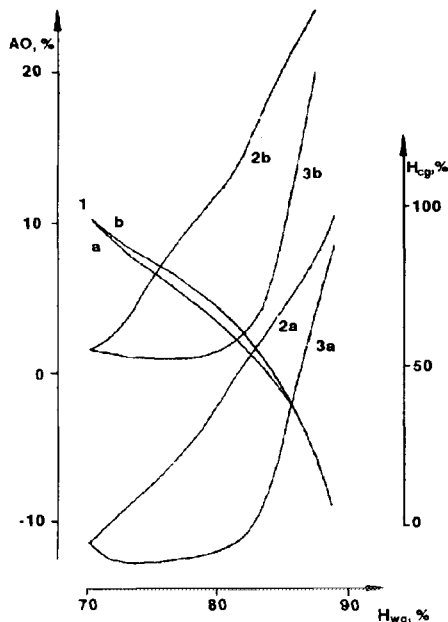


Figure 7 Offset control at 240 eff. days; (1), (2), (3) as in Figs. 5&6; power level: (a) 100 %, (b) 50 %.

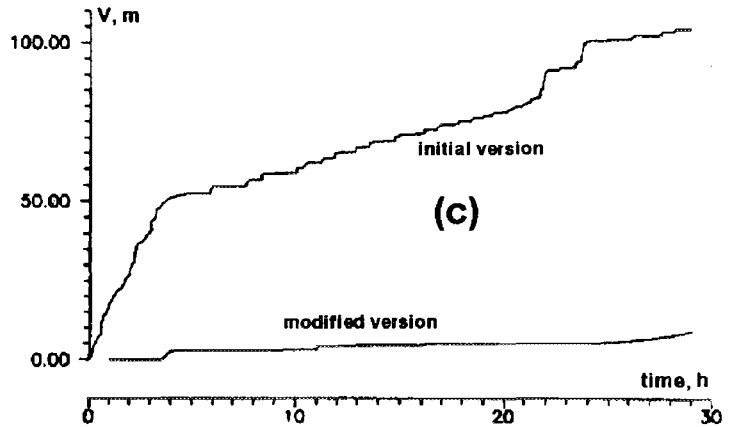
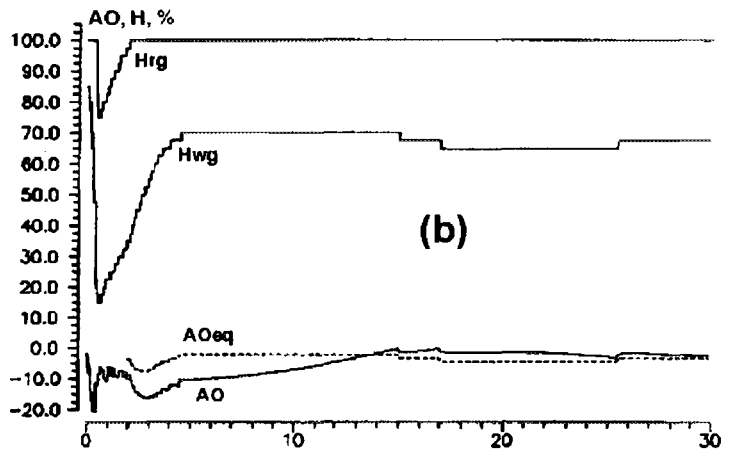
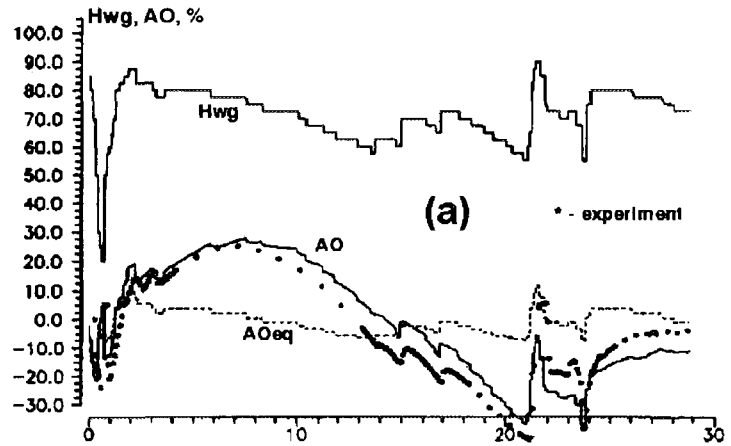


Figure 8 Power drop from 100% to 50%: (a) initial control version; (b) modified control version; (c) volume waste in the boron control system.

To substantiate the above assumptions, PERMAK calculations were made for different layers along the core height. The results of the calculations are presented in Figs. 9 - 11.

With allowance for the above assumptions the linear power rating of the fuel in power cycling is calculated as follows:

- the fuel fragments (the fuel element sections) for the calculation of the linear power rating are chosen on the basis of the results of the BIPR simulation; in particular, a fuel element adjacent to the absorber guide tube is taken to determine the maximum rate of change in the linear power rating;
- for a given instant of the campaign, PERMAK calculation of the power density distribution throughout the fuel elements is performed for a single layer (at the half-height of the core) at different positions (in a given layer) of the CRs participating in the reactor control;
- the time variation of the linear power rating  $q_i$  is calculated by the above formula with the use of the  $K_i$  values determined by the BIPR calcula

tions for the core cells containing the chosen fuel fragments; here the value of  $K_k$  (from the PERMAK calculation) is chosen (discretely varied) depending on the presence or absence of the CRs in the core layer enclosing the chosen fuel fragment;

- the analysis of the time variation of  $q_i$  yields the value of the rate of change in the linear power rating.

The changes in  $q_i$  in reducing the reactor power from 100% to 50% with a rate of 1%/min are plotted in Fig. 12. The maximum rate of change in the linear power rating is attained in the fuel assemblies where the WG control rods move to be 24 W/(cm.min) at a linear power rating change of 120 W/cm. In this case the average linear power rating changes with a rate of 1.6 W/(cm.min) by 83 W/cm. Thus, the allowance for the micro nonuniformity of the power density distribution in power cycling results in an excess of the local rate and magnitude of change in the linear thermal load on the fuel over the respective values averaged over the core by a factor of 15 and 1.5, respectively.

				18	19		
				1.171/083	1.725/312		
				1.168/083	1.723/312		
				1.171/083	1.759/312		
				1.172/083	1.759/312		
			14	15	16	17	
Layer number	9 →		1.037/006	1.084/055	1.267/322	1.694/312	
from the	7 →		1.032/003	1.067/016	1.257/312	1.718/312	
core bottom	5 →		1.036/003	1.071/055	1.263/312	1.732/312	
	3 →		1.031/295	1.067/016	1.267/312	1.757/312	
		8	9	10	11	12	13
		1.104/043	1.072/051	1.210/315	1.082/322	1.220/160	1.796/315
		1.119/068	1.068/012	1.132/315	1.050/003	1.227/159	1.834/315
		1.125/068	1.072/012	1.137/315	1.050/003	1.231/159	1.895/315
		1.125/068	1.070/012	1.139/315	1.050/003	1.235/159	1.868/315
	1	2	3	4	5	6	7
	1.082/043	1.149/285	1.094/279	1.105/055	1.312/322	1.148/329	1.463/322
	1.036/179	1.186/285	1.112/279	1.072/008	1.040/059	1.145/309	1.487/322
	1.039/179	1.200/285	1.118/285	1.074/008	1.040/088	1.147/309	1.511/322
	1.039/179	1.207/285	1.120/285	1.076/008	1.038/088	1.149/309	1.511/322

Figure 9 Distribution of the relative released power of the fuel elements with the maximum power density in the absence of clusters (value of the maximum / position of the maximum)

					18	19	
					1.163	1.714	
					1.160	1.705	
					1.163	1.741	
					1.164	1.742	
			14	15	16	17	
Layer number	9 →		1.034*	1.066*	1.251*	1.694	
from the	7 →		1.042*	1.060*	1.225*	1.701	
core bottom	5 →		1.045*	1.055*	1.231*	1.715	
	3 →		1.038*	1.059*	1.235*	1.740	
		8	9	10	11	12	13
		1.106	1.053*	1.118*	1.040*	1.206*	1.798
		1.116	1.062*	1.044*	1.058*	1.215	1.821
		1.122	1.065*	1.048*	1.058*	1.218	1.829
		1.122	1.063*	1.047*	1.059*	1.222	1.855
	1	2	3	4	5	6	7
	1.083	1.136	1.049*	0.781*	1.127*	1.141*	1.468
	1.036	1.162	1.073*	0.737*	1.008*	1.120*	1.469
	1.038	1.176	1.011*	0.737*	0.995*	1.122*	1.494
	1.039	1.162	1.011*	0.738*	0.992*	1.123*	1.493

**Figure 10** The distribution of the relative released power of the fuel elements (with the maximum power density in the absence of clusters) in case of a cluster lowered in fuel assembly 4 (asterisks denote the values which are not maximum in the fuel assembly)

					18	19	
					-0.7	-0.6	
					-0.7	-1.0	
					-0.7	-1.0	
					-0.7	-1.0	
			14	15	16	17	
Layer number	9 →		-0.3	-1.7	-1.3	0.0	
from the	7 →		1.0	-0.7	-2.5	-1.0	
core bottom	5 →		0.9	-1.5	-2.5	-1.0	
	3 →		0.7	-0.7	-2.5	-1.0	
		8	9	10	11	12	13
		0.2	-1.8	-7.6	-3.9	-1.1	0.1
		-0.3	-0.6	-7.8	0.8	-1.0	-0.7
		-0.3	-0.7	-7.8	0.8	-1.1	-0.9
		-0.3	-0.7	-8.1	0.9	-1.1	-0.7
	1	2	3	4	5	6	7
	0.1	-1.1	-4.1	-29.3	-14.1	-0.6	0.3
	0.0	-2.0	-3.2	-31.3	-3.1	-2.1	1.2
	0.1	-2.0	-9.6	-31.4	-4.3	-2.2	1.1
	0.0	-3.7	-9.7	-31.4	-4.4	-2.3	-1.2

**Figure 11** The distribution of the relative deformation of the released power in the fuel element with the maximum power density in lowering a cluster in fuel assembly 4 (as a percentage of initial power level)

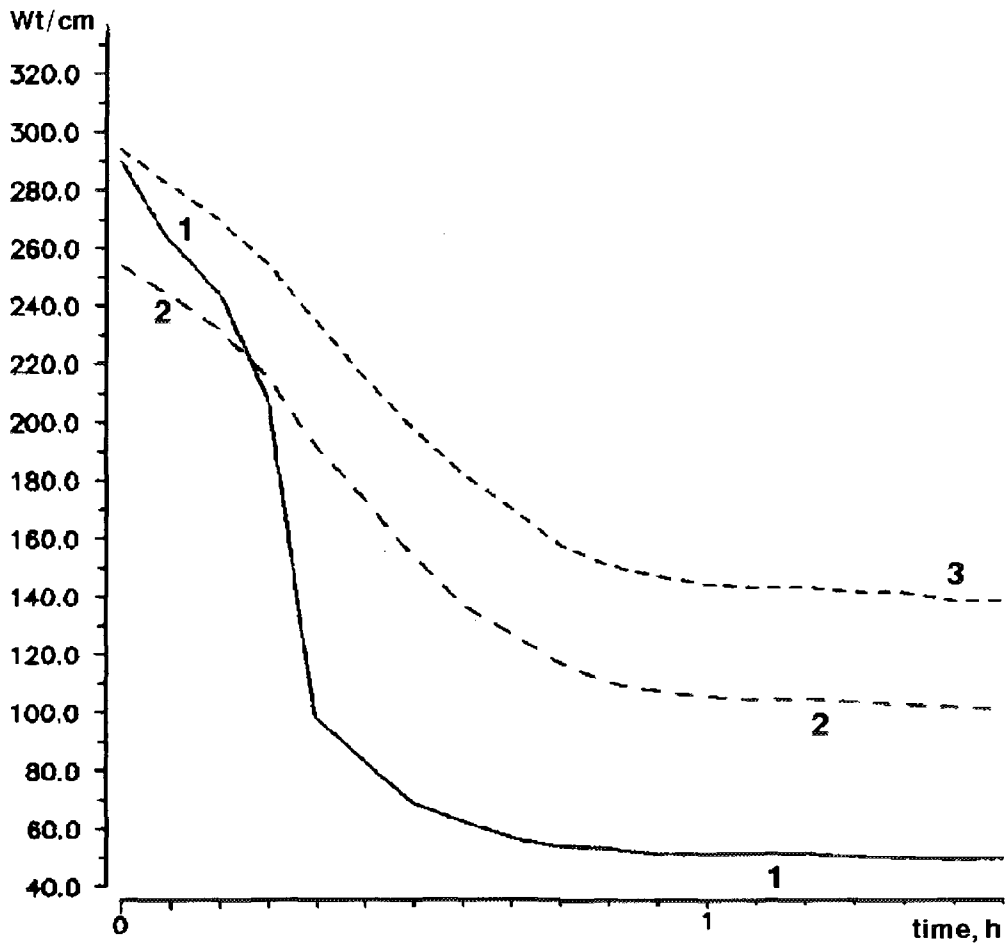


Figure 12 Variation of the linear power rate at the half-height of the core:  
 1 fuel assembly 4 (here the control group is moving);  
 2 fuel assembly 5;  
 3 fuel assembly 21.

## Conclusion

The operating experience as well as the calculations and the experimental investigations show that in VVER-1000s under steady-state operating conditions at occasional power cycling it is essentially possible to ensure the control of the power density distribution with a high degree of reliability.

The work in progress now on the modernization of the means and methods of reactor control will allow the most complete realization of the given possibility. The operability of VVER-1000s under the conditions of power cycling is also under study.

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