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Study of the control-rod shadowing effect on the thermal and fast neutron fluxes in the Bushehr VVER-1000 reactor using the MCNPX Code

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Abstract

In this study, the input data required to model and perform neutronic calculations for the Bushehr Nuclear Power Plant (BNPP) with the MCNPX code were prepared. A comprehensive workflow was developed and implemented to solve the statistical transport equations, from which the neutron flux was obtained. Subsequently, key parameters, including the thermal and fast fluxes, were evaluated at Hot Zero Power (HZP) under three core conditions: a clean core, insertion of control-rod group 10, and insertion of all control-rod groups. The results indicate that, owing to the relatively large spacing and arrangement of control-rod groups 9 and 10, they do not shadow one another; instead, an anti-shadowing effect (ASE) is observed. Consequently, inserting these rods increases the neutron flux in the core, thereby enhancing the overall worth of the control rods.

1 Introduction

The BNPP is a Russian-designed light-water reactor of the VVER-1000 type [1–3]. Numerous studies have been conducted on different aspects and parameters of this reactor—such as neutron flux distribution, fuel arrangement, and control-rod worth—and their results have been published in internationally recognized journals. Neutronic calculations of the BNPP core have previously been performed using the WIMS and CITATION codes [4,5]. However, considering the capabilities of the MCNPX code—both in terms of geometry modeling and the accuracy of the obtained results—its use can provide more reliable and practically useful outcomes [6]. While the VVER-1000 reactor core can also be analyzed with WIMS (a lattice-cell code) and CITATION (a neutron-diffusion code), these tools require approximations because of their geometric limitations. In particular, VVER-1000 fuel assemblies are hexagonal, whereas WIMS performs cell calculations in circular geometry. Thus, analyses based on WIMS and CITATION involve converting hexagonal fuel assemblies into equivalent circular ones, introducing approximations that lead to discrepancies compared with MCNPX results, which account for the exact fuel-assembly geometry.

In a VVER-1000 reactor, the shadow effect of control rods refers to the reduction in the reactivity worth of one rod when it is inserted in close proximity to another. This phenomenon arises because the first rod absorbs a portion of the neutron flux, thereby creating a "shadow" that lowers the number of neutrons available for absorption by the second rod. As a result, the effectiveness of the second rod is diminished, which in turn decreases the overall reactivity worth of the control system.

2 The Structure of Bushehr Nuclear Power Plant (BNPP)

The Bushehr Nuclear Power Plant (BNPP) is a pressurized light water reactor (VVER-1000) with a thermal output of 3000 MWt. The reactor vessel is constructed of carbon steel with an internal stainless-steel cladding. Inside the vessel, which is sealed by the reactor head, are located the core, thermal and neutron shielding, core barrel, guide-tube supports, and water serving simultaneously as a moderator and coolant. The main technical specifications of the BNPP are summarized in Table 1.

The core contains 163 fuel assemblies, each consisting of 311 fuel rods, 18 guide tubes for control rods or burnable absorbers, and one instrumentation channel.

In Western-style BWR reactors, a combination of silver, indium, and cadmium is used as absorbent materials in the control rods, but in Russian VVER reactors, boron in the form of boron carbide (B_4C) is used as absorbent materials in the control rods. In the lower part of the control rods, the composition $Dy_2O_3TiO_2$ is used which will increase the useful life of the control rods. It should be noted that the material of all the reactor control rods is of the same type and the value of each group of control rods depends only on the place where they enter the core and of course on the neutron flux at that point. In the design of BR, 10 groups of control rods with separate drivers were used, each of which has a specific task and their location is indicated in Fig. 1.

In the VVER-1000 reactor, control rods including groups 9 and 10 are used to compensate for variations in neutron flux to manage the spatial distribution of

Table 1: General characteristics of the BNPP based on FSAR

Characteristics	Values
Rated reactor power (KW)	3000
Number of fuel assemblies	163
Number of fuel assemblies with combustible absorbent	More than 42
Mass of UO_2 (Kg)	79870
Distance between fuel assemblies centers (cm)	23.6
Operating core height (cm)	355
Equivalent diameter of the Core (cm)	316
Linear core transfer rate (W/cm)	166.7
Average fuel power density (KW/(Kg.U)	42.6
Cooling flow rate (m^3/h)	84000
Coolant inlet temperature (Celsius)	291
Mass ratio of water to uranium	1.97

power within the core in order to maintain reactor safety and controlling the nuclear chain reactions, ensuring that the heat generated is relatively uniform across the fuel assemblies. Control rods are primarily used to absorb neutrons for regulating the rate of fission and consequently the reactor's power output. In this regard, different groups of control rods have specific functions within the reactor core, with some designed for reactivity control during normal operation and others for rapid shutdown in emergency situations. Group 10 of control rods are known to have the highest negative reactivity worth, meaning they can introduce the most reactivity reduction and are critical for a rapid shutdown and group 9 of control rods are designed to influence the spatial distribution of power within the core, contributing to a more uniform thermal margin and preventing localized overheating.

3 Investigating the Shadowing Effect of Control Rods of Groups 10 and 9

The Shadowing Effect (SE) occurs when the value of each of the two control rods decreases when they are placed next to each other. This is because the flux effective on the first control rod decreases when the control rod is placed next to the other, which reduces the number of neutrons absorbed by the first control rod and reduces the amount of negative reactivity changes, thus reducing the value of the first control rod. The Anti-Shadowing Effect (ASE) occurs when the value of each of the two control rods increases when they are placed next to each other. This is because the flux effective on the first control rod increases when the control rod is placed next to the other which increases the number of neutrons absorbed by the first control rod and increases the amount of negative reactivity changes, thus increasing the value of the first control rod. Therefore, it can be concluded that the shadowing effect refers to the interaction between the control rods, and the degree of this interaction, δ which is given by the following Equation, will estimate the value of shadowing [7]:

$$\delta = \frac{\boldsymbol{\Delta}\rho_{\mathbf{1,2,\ldots N}} - \sum_{\mathbf{i=1}}^{\mathbf{N}} \boldsymbol{\Delta}\rho_{\mathbf{i}}}{\boldsymbol{\Delta}\rho_{\mathbf{1,2,\ldots N}}}. \tag{1}$$

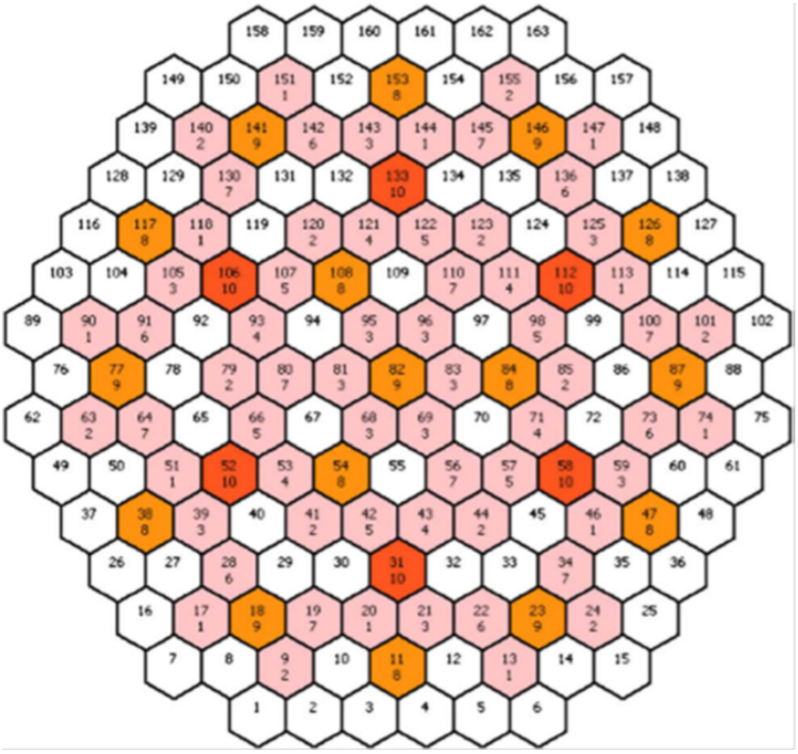

Figure 1: Distribution of Control rod groups among 163 fuel assemblies in VVER-1000 core reactor which has hexagonal shape

Depending on $\delta < 0$ or $\delta > 0$, it refers to a shadowing or anti-shadowing effects, respectively. Also, $\Delta\rho_i$ is the reactivity worth of control rod and N refers to the number of control rods. In summary, the shadow and anti-shadow effects are not represented by a single parameter, but are rather observed through changes in neutron flux and power distribution within the reactor core, particularly in response to control rod movements and fuel burnup.

4 Verification of Simulations

In this research, the necessary information from Bushehr Nuclear Power Plant which is a kind of VVER reactor, was provided to perform its simulation and neutronic calculations with the MCNP code. Then, the results obtained from the code were justified with at least one of the practical data related to this reactor, means the control rod integral value which is given in Table 2. In this regard, at first the integral value of the control rod for all control groups and group 10 was calculated by the code and then the obtained values were compared with the data available in the Bushehr FSAR and the error rate was within acceptable limits based on Table 2.

Table 2: Control rod integral value

Integral Values	FSAR	MCNP	Error Rate
Total control rods versus $\%\delta\rho$	9.20	9.4832	0.026860
Group 10 control rod versus $\%\delta\rho$	0.77	0.6206	0.004756

After ensuring the simulation method, other desired calculations were performed. Then, the thermal neutron flux obtained through the MCNPX code was compared with the results previously obtained by the Wims and Citation codes in Hot Zero Power (HZP) state and the results are shown in Fig. 2. It should be noted that Hot zero power (HZP) state is not a real case and is defined for initialization of the 3D core neutronics model. In this state, thermal-hydraulic feedback has been fixed so that the thermal-hydraulic core model does not play a role in the calculations. In HZP state, the power level is 0.1% of the nominal power; the fuel temperature is 552.15 K and the moderator density is 767.1 kg/m3. Control rod groups 1 to 8 are all rods out (ARO), control rod group 9 is 36% inserted into the core, and control rod group 10 is all rods in (ARI) [8].

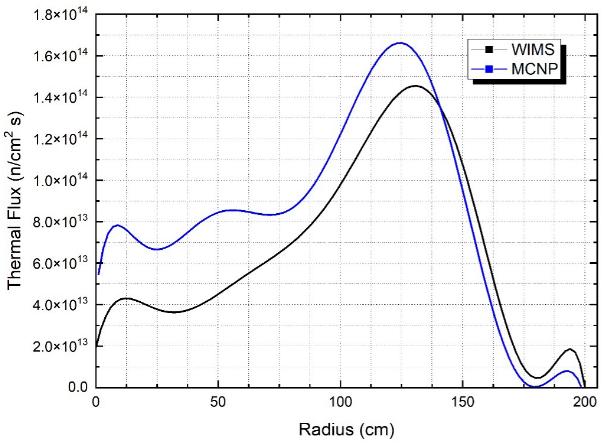

Figure 2: Comparison of heat flux obtained by MCNPX, Wims, and Citation codes

By comparison of thermal neutron fluxes obtained from MCNPX and Wims-Citation codes, it can be concluded that the flux change trend is almost the same and the MCNPX code provides more realistic results due to having more complete library information for lower energy cross sections.

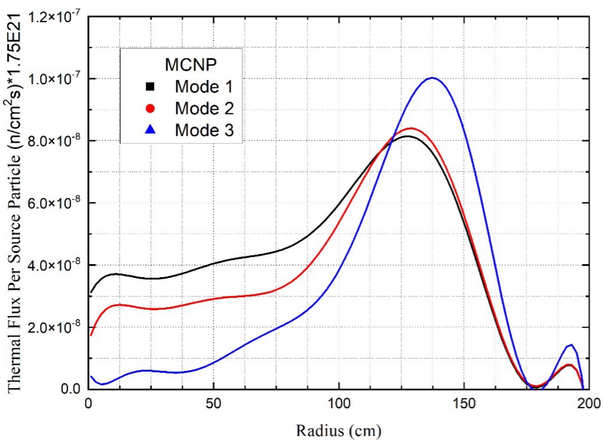

Figure 3: Comparison of heat flux obtained by MCNPX, Wims, and Citation codes

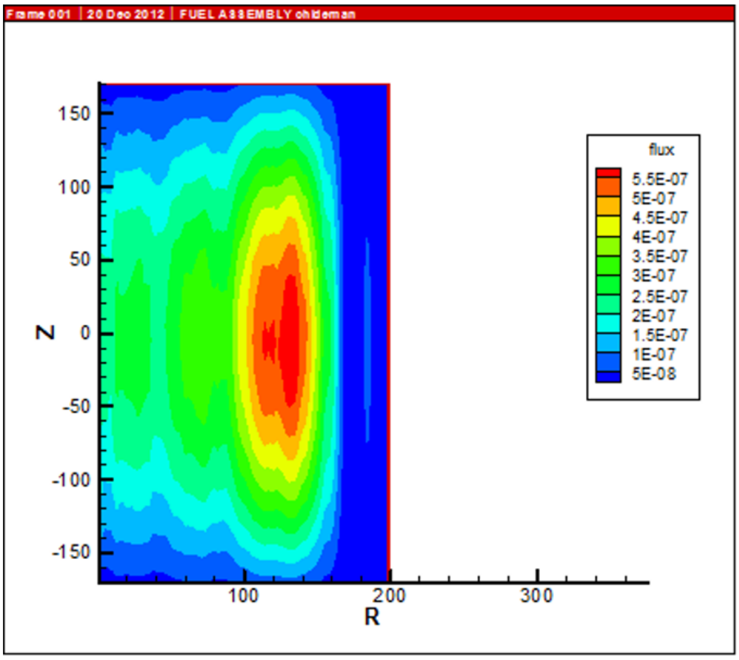

Figure 4: Heat flux contour for Mode-1

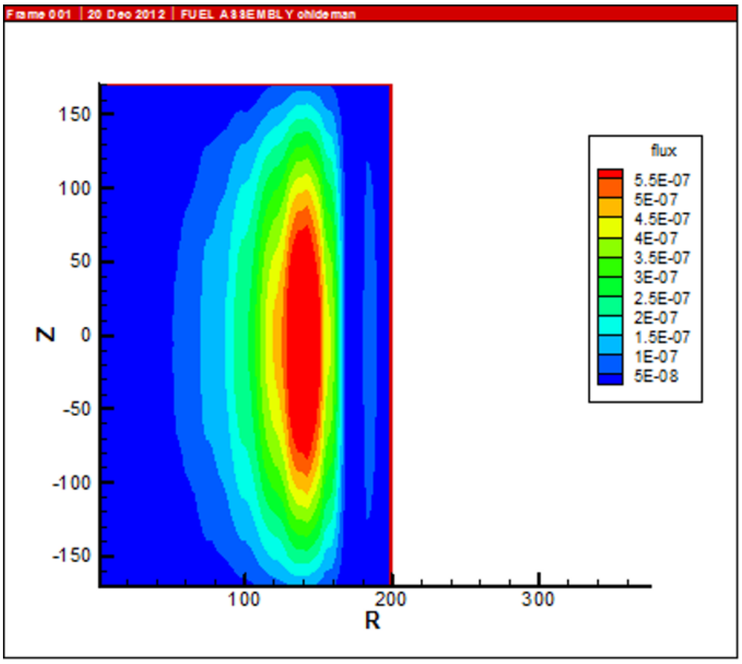

Figure 5: Heat flux contour for Mode-2

Table 3: Results of the changes in the core reactivity

Groups	k_{eff}	ρ	$\Delta\rho$
9	1.006245	0.006206	0.002993
10	1.006110	0.006073	0.003127
9&10	0.999130	0.000871	0.008329

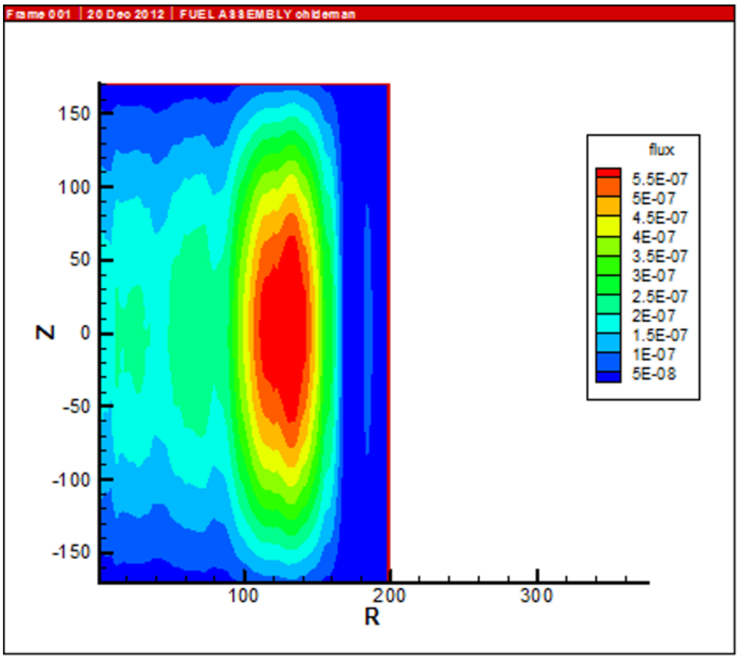

Figure 6: Heat flux contour for Mode-3

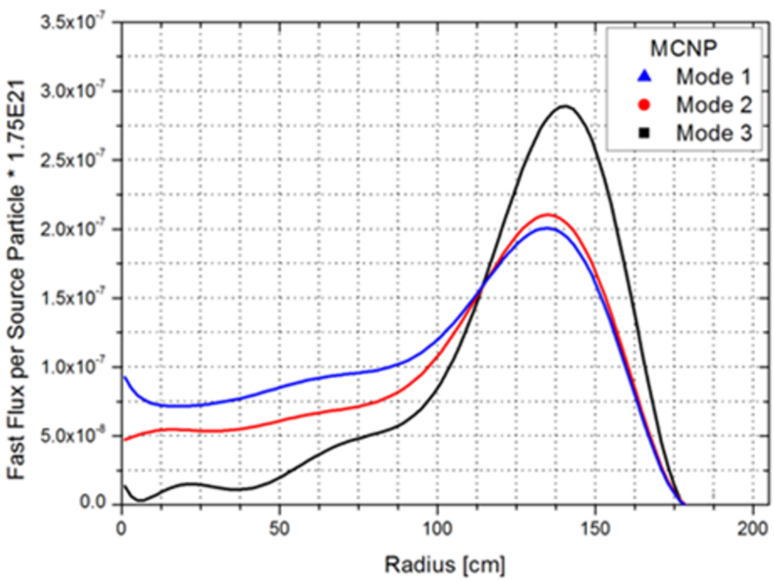

Figure 7: Comparison of fast flux obtained by MCNPX, Wims, and Citation codes

5 Simulations

In order to simulate the shadowing effect of the control rods, we consider the following three modes. Clean Core mode (Mode-1), when a group of 10 control rods is placed in the core (Mode-2) and when all the control rods are placed in the core (Mode-3). The thermal neutron fluxes for the above three modes are calculated and shown in Fig. 3 and the thermal flux contours are also given in Figs. 4-6 [9,10].

The fast neutron fluxes for modes 1, 2 and 3 were calculated and the results are shown in Fig. 7 and the fast flux contours are also given in Figs. 8-10.

For groups 9 and 10, the shadowing effect was investigated and the obtained results are given in Table 3.

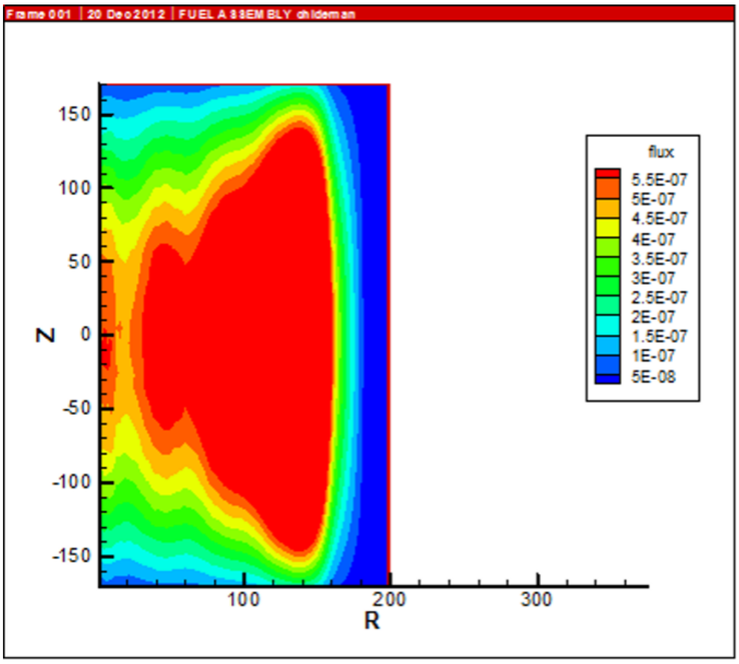

Figure 8: Fast charging contour for Mode-1

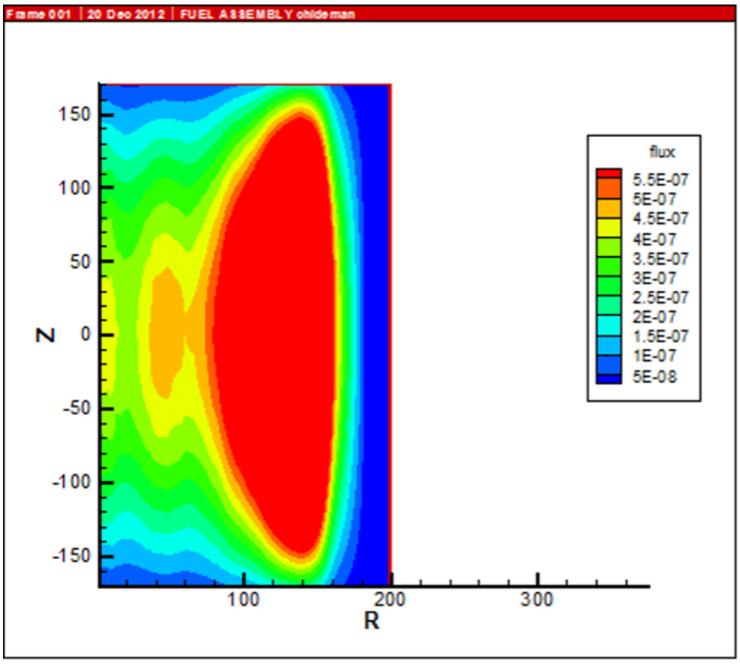

Figure 9: Fast charging contour for Mode-2

Finally, the value $\delta = 0.360948$ was obtained which means that the ASE has been occurred. This can be explained according to Figs. 1-4 by the fact that due to the large distance between the control rods of groups 9 and 10 and the way they are arranged, not only they do not have a SE on each other, but they also have an ASE and enhance the value of the control rods.

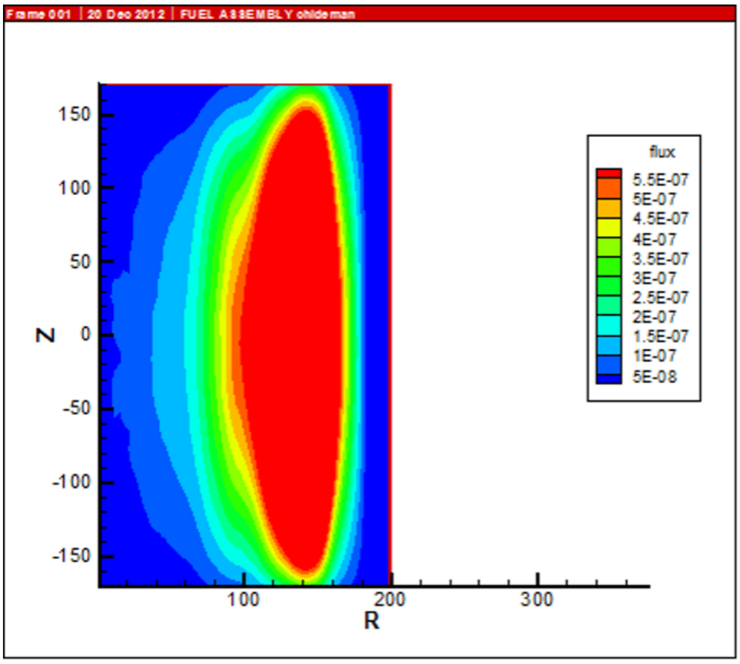

Figure 10: Fast charging contour for Mode-3

6 Conclusion

Comparison of the thermal and fast neutron fluxes in Modes 1–3 shows that the flux reduction is not linear with the number of inserted control rods. Both thermal and fast fluxes exhibit a peak at a radius of about 150 cm, which increases in magnitude and shifts toward the vessel wall as more rods are inserted. This behavior must be accounted for in safety analyses, as it can produce localized hot spots and potentially damage nearby components, including vessel walls and fuel assemblies.

Several measures can mitigate the observed peaking. In addition to control-rod strategies, xenon (a strong neutron absorber) can drive oscillations and affect power stability, while the boric-acid concentration in the primary coolant also plays a role. If it exceeds a critical threshold (e.g., $\sim$1200 ppm for the VVER-1000 at BNPP), positive thermal feedback may arise and challenge reactor control.

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