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Influence of boron enrichment in control rods on neutron-physical characteristics of the core of the reactor VVER

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Abstract. Boron is widely used in nuclear power as a neutron absorber material, thereby creating the possibility of controlling a nuclear reactor by changing the neutron multiplication factor. Natural boron contains about 20% ^{10}B and 80% ^{11}B with absorption sections respectively 3840 barn and 0.05 barn. The paper deals with changes in neutron-physical parameters of the reactor core of VVER type when the isotope content of ^{10}B in boron carbide of absorber rods (AR) of the control and protection system (CPS) and in boric acid solution in the coolant of the VVER reactor is varied, and also analyzes the practicality of increasing the enrichment of ^{10}B isotope in the control rods (CR). The model of VVER-1200 fuel assembly (FA) was used for calculations. In the course of work were modelled and the calculations of the three models of the coolant with different boric acid concentrations, as well as two models of AS with different enrichment in the isotope ^{10}B .

1. Introduction

At present, boron carbide is the most widely used as an absorbing material in the control rods of CPS. The choice of this material is due to its high neutron absorption efficiency in a wide range of energies, high melting point, manufacturability and relatively low cost [1]. The most important characteristic of boron carbide is the thermal conductivity, which determines the temperature conditions in which the cores of the absorbing elements in the reactor work. It averages 22-33.5 W/(m \cdot °C) depending on density [1]. The coefficient of thermal conductivity has a strong dependence on the content in the sample of the isotope ^{10}B .

The chemical stability of boron carbide is explained by strong covalent bonds between carbon and boron atoms and a low concentration of non-localized electrons. Boron carbide well resists the action of mineral boiling acids.

As a result of neutron absorption by isotope ^{10}B , α -particles with high kinetic energy and low path length are obtained, so when increasing the enrichment of boron, it should also be borne in mind that:

- 1) absorbers made of boron or its compounds are heated and require their cooling;
- 2) α -particles during prolonged irradiation of boron by neutrons violate the structure of the material, which leads to the deformation of construction made of it [2].



Typically, B₄C is compressed into tablets.

The compatibility of boron carbide with structural materials is considered to be the main criteria for the efficiency of absorbing elements. As materials of shells of absorbing elements, stainless steels and alloys, as well as zirconium alloys, are most often used. In the control rods of VVER type nuclear reactors, boron carbide powder is widely used as the core of absorbing elements, which is in direct contact with a shell of steel [3].

In power reactors of high power, unevenness in the core is observed, therefore the control rod systems are cumbersome, which affects the cost of the control system and the reliability of its operation. There are several reasons for using absorber materials dissolved in the coolant, in particular, reducing the number of absorbing rods along with the drives and electrical equipment of the control system, which saves cost.

Of the potentially useful elements (boron, cadmium and gadolinium), boron compounds, although they have the smallest neutron absorption cross section, however, their physico-chemical properties (solubility and resistance) are most preferable under the conditions of the first circuit. Boric acid is evenly distributed over the fuel assemblies, and therefore, when the concentration is changed, the distribution of energy release in the core is not impaired. It was also found that the concentration of boric acid with alkaline additives (potassium, NH₄ and lithium) does not significantly increase the corrosion rate of the contour materials in the water of the primary circuit in the reactor core. The presence of boric acid does not cause special complications in the purification of the water of the primary circuit, including the boric acid itself. In this regard, water regimes of the first circuit using boric acid have found wide application both in our country and abroad. If the absorbing rods are used to react quickly to the requirements of reactor operation (power changes, stop and start), the control of the boric acid concentration is maintained in the critical state during slow transient processes (burnout, xenon poisoning).

The concentration of boric acid varies over time in accordance with the requirements of operation, which occurs remotely and automatically at the command of the reactor operator.

The aim of this work is to study the influence of the degree of enrichment of boron in the boron carbide of CR and the boric acid in the coolant on neutron-physical characteristics (NFC) of core of reactor VVER.

2. Materials and methods

For calculations in the work, the Code UNK software complex was used. The basic programs of the Code UNK package are oriented to perform calculations with accuracy limited only by the capabilities of computer technology, that is, the ability to perform calculations with a large number of energy groups, with a large number of spatial zones. Unlike conventional engineering programs, the mathematical models of physical processes realized in the programs of the Code UNK package have minimal simplifications of real processes. In fact, there are two of them and both concern the UNKCELL program. The first approximation is that when calculating the neutron spectrum in a cell or reactor cassette, an approximation is used for isotropic neutron scattering and isotropic neutron sources. Second, the isotope cross sections in the region of unresolvable resonances are determined within the framework of the group approximation with standard blocking by the equivalence theorem.

Small approximations of real physical processes and the fact that all programs are developed on the basis of deterministic techniques and algorithms allow the Code UNK software package to be classified as a package of precision deterministic programs. This means that the accuracy of calculating the various characteristics of the reactor, subject to the saturation of the spatial and energy grids, will correspond to the accuracy of statistical calculations based on the Monte Carlo methods.

The Code UNK program has its own nuclear data library completely generated from the files of the estimated nuclear data ENDF/B-6, JEF-2.2, JENDL. In the version of the program

used in the program, the library contains 337 isotopes. The main program library contains 89 groups of isotope sections (24 groups in the deceleration region from 14.5 MeV to 2.15 eV and 65 thermal groups from 1 to 2.15 eV) [5].

A special feature of the UNKCELL program is the detailed calculation of the neutron spectrum in the resonance energy region. This is achieved by performing calculations in a large number of energy groups (about 7000). For these calculations, the nuclear data library of resonant isotopes contains group sections in the fine-group partition. This library is also derived from the ENDF/B-6 estimated nuclear data files.

The spatial distribution of the neutron field in the cell is calculated by the method of probabilities of the first collisions. Analytic formulas for calculating probabilities are used for simple geometries. For complex two-dimensional geometries, the probabilities of the first collisions are calculated numerically.

The UNKCELL program consists of three main program modules:

MACSEC – calculation of macroscopic cross section of the cell;

CELLHI – calculation of the spatial energy distribution of neutrons in a cell or cassette;

AVR – averaging program, in the calculated cell spectrum, group constants and functionals.

All UNKCELL program modules are written in the algorithmic language FORTRAN-77.

The calculation of the cell or cassette of the reactor involves the execution of three consecutive stages:

1) Calculation of macroscopic cross section of various materials that make up the cell. At this stage, the corresponding values are selected from the nuclear data library of different isotopes as a function of temperature and the dilution cross-section calculated by the program. A macroscopic cross sections library is being created. This part of the calculation is performed by the MACSEC program.

2) Direct calculation of the spatial energy distribution of neutrons in the cells and calculation of the effective multiplication factor. In accordance with the generated task, the calculation is carried out either within the framework of the 89 group approximation or in 7000 energy groups. In the first case, resonance blocking is carried out within the framework of the approximation of the equivalence theorem, in the second case, a detailed calculation of the neutron spectrum in the resonance energy region is carried out. This part of the calculation is performed by the CELLHI program.

3) The calculation results are processed on the basis of the obtained neutron field distribution in the cell. The averaged characteristics can be calculated as the average over the entire cell volume, and by its individual zones. In calculating the average characteristics of the cell, the following macroscopic cross sections and functionals are calculated in a given number of energy groups: the absorption, fission, elastic scattering, inelastic scattering cross sections, the mean cosine of the scattering angle, the cross-section matrix of the intergroup transitions in the deceleration region and the thermalization region. The value of k_{eff} is calculated as the ratio of the integral over the fission cell to the absorption. Calculation of the microscopic cross sections of absorption and fission of various isotopes that make up the cell for the purpose of their subsequent use for calculation of fuel burnup is carried out. This stage of calculation is performed by the AVR program.

To perform the calculations, a model of the VVER-1200 reactor fuel assembly. A fuel element with a fuel pellet diameter of 7.60 mm and a diameter of a central hole in a fuel pellet of 1.2 mm was used as the fuel element. Enrichment of fuel is limited to 4.95%. In the design of the VVER-1200 reactor, to reduce the concentration of boric acid in the coolant and to equalize the power density field, part of the fuel assemblies integrated with the fuel burned up the absorber in the form of gadolinium oxide (Gd_2O_3). But the work will use fuel assemblies without the gadolinium fuel rod, since the aim of the work is to study the effect of boron on the neutron-physical parameters of the core.

Figure 1 shows the VVER-1200 core model.

The main technical characteristics of fuel assemblies are presented in table 1. Data are taken from source [7].

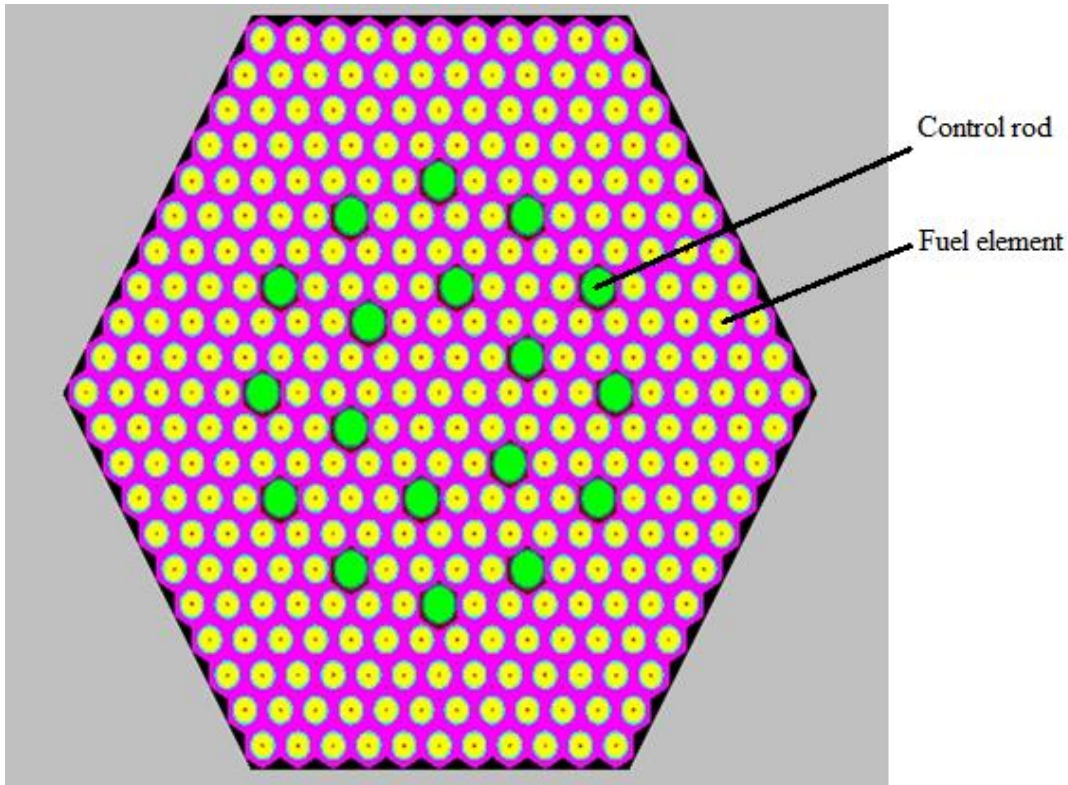


Figure 1. Model FA of VVER-1200.

Table 1. Main technical characteristics of VVER-1200 FA.

Characteristic	Value
Shape of fuel assemblies	Hexagonal prism
Height of FA (mm)	4570
FA size «flat-to-flat» (mm)	235
Number of fuel rods in FA (pieces)	312
Step between fuel elements (mm)	12,75
Fuel	UO ₂
Fuel density (kg/m ³)	10.4·10 ³
Cladding	Alloy Zr+1%Nb
The outer diameter of the cladding (m)	9.1·10 ⁻³
The inner diameter of the cladding (m)	7.72·10 ⁻³
The height of a column of fuel in cold condition (m)	3,73
The outer diameter of the fuel pellet (m)	7.57·10 ⁻³
Diameter of the central hole in the fuel pellet (m)	1.5·10 ⁻³

The content of the ^{10}B isotope in the boron of the control and protection system control rod (CPS CR) and in boric acid in the VVER-1200 project is assumed to be equal to the natural (19.8% at.). At the beginning of core life, the critical concentration of boric acid in the coolant is 5.39 g/kg.

In the course of the work, 3 models of a cell of a fuel assembly with different contents of ^{10}B in a coolant were considered:

Model 1. Heat carrier without boric acid.

Model 2. The coolant with boric acid with a natural isotope content of ^{10}B is 19.8%.

Model 3. The coolant with boric acid with isotope ^{10}B content of 90%.

To simplify the simulation, it is considered that the concentration of boric acid does not change during the reactor life time. This does not make a big contribution when comparing models.

To analyze the effect of the degree of boron enrichment in the boron carbide of the neutron-absorbing rod system on the NFC of the fuel, two fuel assemblies of the VVER-1200 reactor were modeled:

1. Using a CPS CR with boron carbide with natural enrichment of ^{10}B .

2. Using a CPS CR with boron carbide with an enrichment of 90% to ^{10}B .

3. Results and Discussion

Calculations of NFC of the core in the software-computing complex Code UNK for boron carbide with natural enrichment and enrichment of 90% in ^{10}B isotope were performed. The density of boron carbide B_4C was estimated to be equal to 1.7-1.8 g/cm³ [4]. The dependence of the value of the multiplication factor on enrichment is shown in table 2.

Table 2. Values of the multiplication factor depending on the enrichment at the beginning of the fuel campaign.

The enrichment in the isotope ^{10}B	CR in the upper position	CR in the lower position
Natural	1.463	0.909
90%	1.463	0.791

As a result of the calculations, it can be concluded that the amount of CR can be reduced by 4 practically without changing the NFC of the core while enriching the boron carbide to 90% by ^{10}B . At the beginning of the fuel campaign with the lowered AR $k_{\text{eff}}=0.909$. This, in turn, makes it possible to increase the fuel load at the same core volume, which allows increasing the duration of the reactor operation without overload. However, the enrichment by the isotope ^{10}B entails additional capital investments.

When considering three models of FA with different content of ^{10}B in boric acid in the coolant, it turned out that the model 3 is not suitable for comparison, as the effective multiplication factor at the beginning of the fuel campaign was 0.896.

The concentration of boric acid (enriched to 90%) in water was calculated, at which the effective multiplication factor at the beginning of the fuel campaign would be equal to the effective multiplication factor at the beginning of the fuel campaign for model 2. The concentration of the boric acid amounted to 1.165 g/kg (model 4). The analysis of the results shows that without changing the NFC of the core can be dosed into the coolant much lower concentration of boric acid in the enrichment of 90% on ^{10}B .

Enrichment change can affect the value of the temperature coefficient of reactivity at the temperature of the coolant, which, of course, should be taken into account in the design. An increase in the content of boric acid in the coolant makes a positive effect of reactivity at the coolant temperature, as shown in table 3.

Table 3. Values of the effective multiplication factor, reactivity and temperature coefficient of reactivity for the coolant temperature for models 1, 2, 4 at the beginning of the fuel campaign.

Model	Coolant temperature, K	k_{eff}	Reactivity, $\Delta k/k$	$\alpha_{T_{\text{coolant}}}$, 1/K
1	584.8	1.462731	0.31635	$-0.3 \cdot 10^{-6}$
	484.8	1.463379	0.31665	
2	584.8	1.275554	0.216	$5.5 \cdot 10^{-6}$
	484.8	1.27465	0.21547	
4	584.8	1.275365	0.2159	$5.5 \cdot 10^{-6}$
	484.8	1.274454	0.21535	

The change of the multiplication factor for each model depending on the burnup time is shown in figure 2.

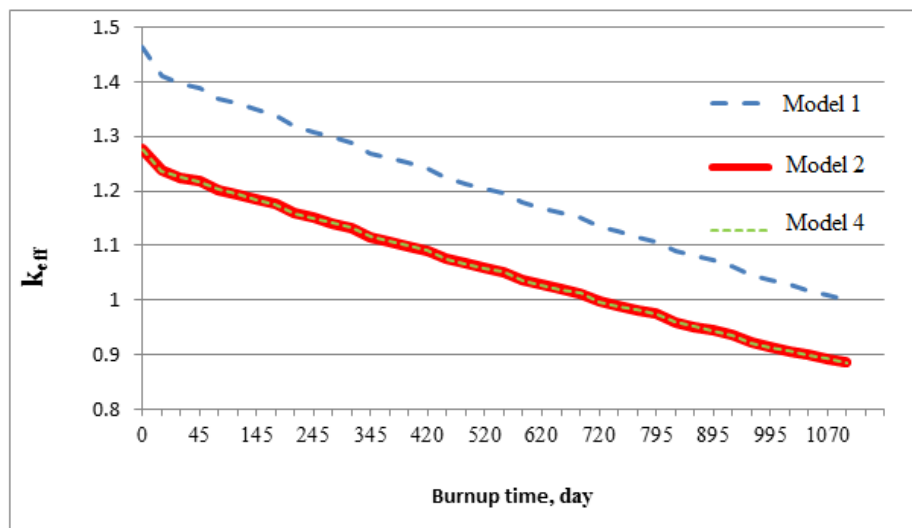


Figure 2. The change in the effective multiplication factor from the burnup time in different usage patterns of boron.

It should be noted that when using MOX fuel or REMIX fuel in a nuclear reactor, the absorbing ability of rods with natural boron enrichment by ^{10}B isotope will not be enough to compensate for excess reactivity. In this regard, it is necessary to increase the content of ^{10}B . This means that increasing the enrichment of boron makes sense.

4. Conclusion

As a result of calculations it was found that highly enriched boron allows reducing the number of CPS CR. It can be concluded from this that the use of enriched boron carbide in AR makes it possible to load more than 1/3 of the core with fuel assemblies with MOX fuel, and also makes it possible to increase the fuel enrichment to 6% and higher in the isotope ^{235}U , which is not possible with the regular CR.

The use of an enriched boron isotope of ^{10}B in boric acid has both positive and negative sides. The advantages include the possibility of dosing a lower concentration of boric acid into a coolant. Of the minuses can be noted the price increase, which is connected with the necessity of enrichment, it is also theoretically less smooth control of the reactor.

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