SPECIFIC FEATURES OF BN-1200 CORE IN CASE OF USE OF NITRIDE OR MOX FUEL

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Abstract. The BN-1200 reactor core has been developed for the options using the well-mastered MOX fuel and the advanced nitride fuel. Among the features of both the MOX fuel core and nitride fuel core, it should be noted that the core has a reduced power density compared with BN-600 and BN-800, the flattened configuration with the upper sodium plenum and the upper absorber shield of natural boron carbide, as well as the fuel of one enrichment (plutonium content) is used in all fuel subassemblies (FSAs).

Because of the difference in the neutronic characteristics of the nitride and MOX fuels, the above-mentioned core options have certain differences in their designs:

- For the MOX-fuel core the configuration with an axial breeding interlayer is applied in order to reduce the burnup reactivity loss and to ensure a 1-year operating cycle length. An additional advantage of such core configuration is that the damage dose accumulation rate is reduced.

- When the nitride fuel is used, the plutonium breeding ratio in the core is self-sufficient to completely supply the reactor with plutonium in closed fuel cycle, and unlike the MOX fuel core the nitride fuel core does not have the axial and radial blankets. To minimize the reactor reactivity margin and to enhance power distribution, the peripheral FSAs use fuel pins of larger diameter (10.5 mm).

Key words: BN-1200, reactor core, MOX fuel, nitride fuel.

1. Introduction

The "*New Generation Nuclear Power Technologies*" Federal Target Program provides for the development of the mentioned technologies based upon the fast neutron reactors with the closed nuclear fuel cycle. As part of the above Program, the ROSATOM Block for Innovation Management, with Rosenergoatom Concern involved as a potential customer for construction, conducts the activities on the BN-1200 design intended for serial construction of power units. The necessary condition for the reactor operation in the closed nuclear fuel cycle is self-sufficient breeding of the fissile nuclides (Breeding Ratio BR≥1). Additionally, the development of the BN-1200 reactor core should ensure high economic performance of the fuel cycle — first of all, long lifetime should be ensured for fuel subassemblies (FSAs). For the advanced nuclear fuel cycle, a requirement has been established to ensure the technological support for the proliferation-resistant mode, which consists in that the outer blankets are abandoned and plutonium extraction is excluded during the spent fuel reprocessing process. Keeping this in mind, a high plutonium breeding ratio needs to be ensured directly in the reactor core (Core Breeding Ratio (CBR)) [1].

The basic means to increase the Core Breeding Ratio are to increase the size of the core and the volumetric fraction of the fuel (to use larger fuel pins), as well as to use high-density fuel. Making the fuel pins larger (from 6.9 mm in BN-600 and BN-800 to 9.3 mm in BN-1200) ensures also a longer fuel lifetime. As the advanced high-density fuel for BN-1200, mixed uranium-plutonium nitride fuel is being considered. The nitride fuel behavior at the irradiation parameters corresponding to those in BN-1200 is being studied as part of the integrated program for computational and experimental verification of the dense fuel for the fast neutron reactors [2,3].

As the backup option in compliance with the technical assignment for the Proryv (Breakthrough) Project, a core is being developed based upon the technologically mastered MOX fuel that can ensure high burnup. It is presumed that the MOX fuel core will be implemented in case there is a delay in obtaining the required experimental verification of the nitride fuel operability at the acceptable burnup.

This paper considers the features of the BN-1200 reactor core designs that use the MOX fuel and the nitride fuel.

2. General Approaches to the Selection of the Reactor Core Layout

The reactor core layout is determined based upon the following prerequisites:

- Ensure the reduced, vs. BN-600 and BN-800, average core power density (~250 MW/m^3 instead of 400-450 MW/m^3), which will allow a greater volumetric fraction of fuel in the core to be obtained (~0.5 instead of 0.43-0.44) through the use of the larger diameter fuel pins (~9-10 mm instead of 6.9 mm).
- Ensure that the operating cycle length is one year -330 equivalent full power days (efpd) to achieve the high capacity factor -0.9.
- Use a flattened reactor core with an upper sodium plenum and upper absorber shield of natural boron carbide to reduce the sodium void reactivity effect (SVRE) down to the level of β_{eff}.
- Use the fuel with one plutonium enrichment. This solution along with the unification of all the FSAs ensure that the core height will be a maximum possible one in terms of SVRE, and the power distribution will be highly stable vs. time because of the invariable fuel breeding ratio in the entire core volume.

3. MOX Fuel Core Design

Based upon the adopted prerequisites for selecting the reactor core layout, initially an option was proposed with the conventional homogenous reactor core. Keeping in mind the limit for the radiation damage for the EK-164 austenitic steel (up to ~ 120 dpa [4]) adopted as the fuel cladding material at the initial reactor operation phase, the lifetime for such core was limited by three years. With account of the critical parameter and control rod worth uncertainties, the guaranteed compliance with the requirements for the reactivity balance was ensured with the refueling interval being shorter than a year, which corresponded to the four-batch core loading pattern for the main array of the FSAs.

To improve the MOX-fueled BN-1200 reactor core and to increase the fuel lifetime to four years with the one-year operating cycle length, a reactor core configuration with the axial breeding interlayer of depleted uranium dioxide was proposed [5] (Figure 1).

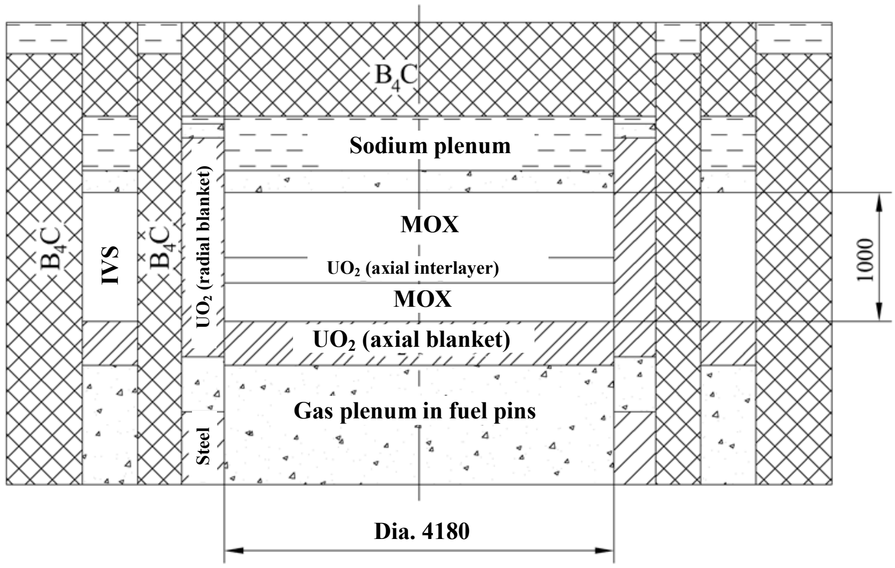


Figure 1: MOX- fuel core with the axial interlayer configuration

The breeding interlayer introduced into the fuel column ensures that:

- The core breeding ratio (CBR) increases from 0.92 to 0.94; the reactor breeding ratio, from 1.19 to 1.25;
- The burnup reactivity loss for 330 efpd (1 year with the capacity factor = 0.9) reduces from 2.0 to 0.9 % ΔK/K.
- The damage dose for the fuel cladding reduces (from 140 to 117 dpa) with the maximum fuel burnup remaining at the level of ~ 14% h.a. in a four-year FSA lifetime.

The effectiveness of using the FSA design with the axial breeding interlayer to reduce the damage dose accumulation rate for the FSA structural materials is related to the reduced level of the maximum neutron flux density explained by the flattened axial distribution of the neutron flux and to higher plutonium enrichment in the fuel. Figure 2 shows fuel pin axial linear heat rate distributions (q_l) and damage dose accumulation rates (DPA) for a conventional (homogenous) core configuration and for a core with a breeding interlayer.

The overall length of the fuel column increases from 85 to 100 cm because an axial interlayer is introduced in it in all FSAs. The interlayer thickness and axial position in the core are optimized based upon the adopted limits for the fuel pin maximum linear heat rate (48 kW/m) and for the SVRE ($\leq \beta_{eff}$).

In should be noted that the fast neutron reactor core concept has been widely studied both in Russia and abroad [6, 7, 8, 9].

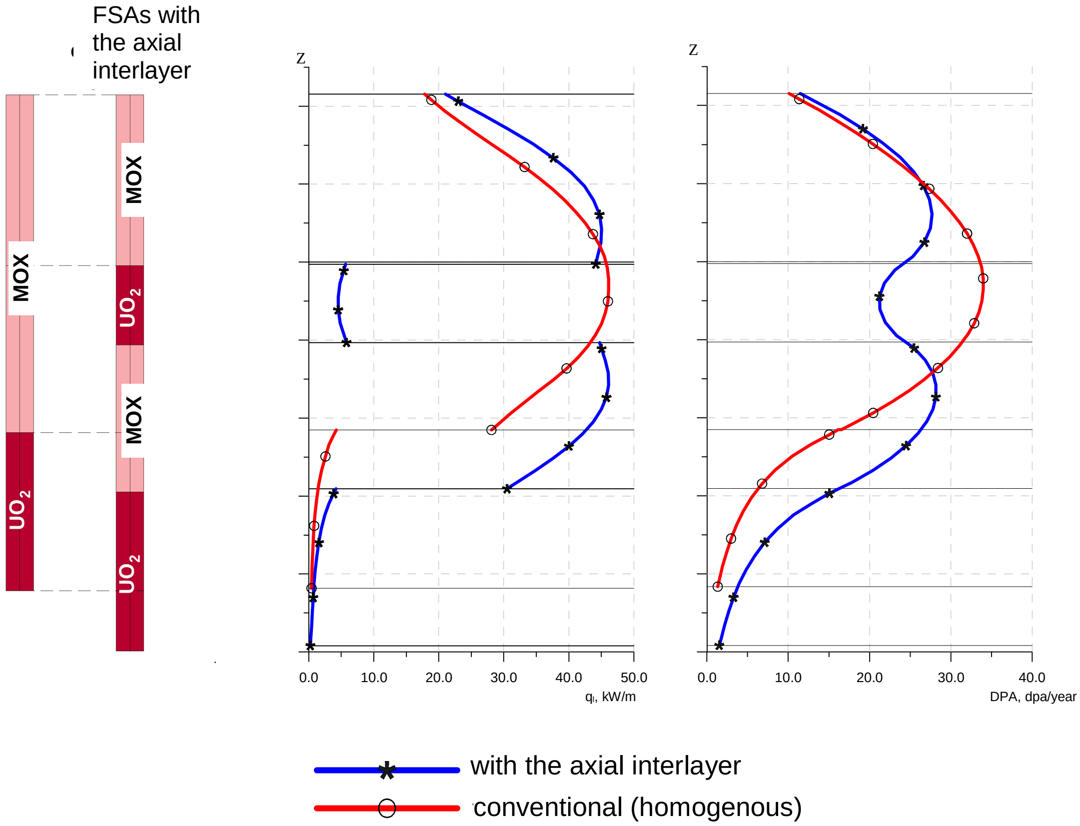
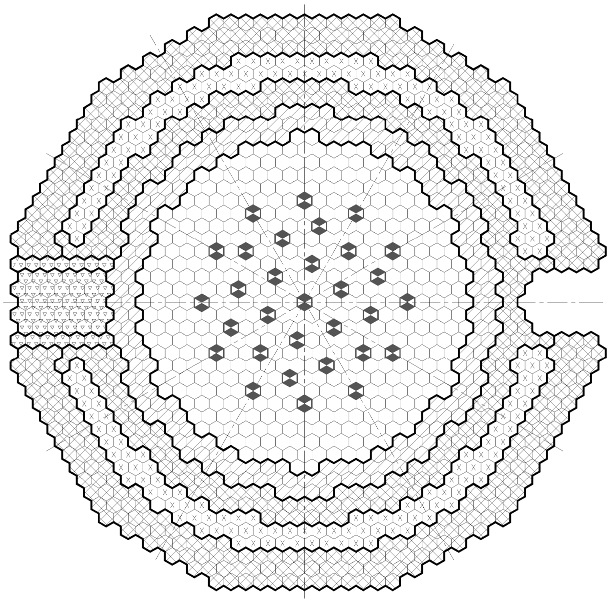


Figure 2: Axial distribution of the fuel pin linear heat rate and damage dose

The BN-1200 reactor core layout [10] is shown in Figure 3.



Designation	Name	No.
	FSAs	432
	Control subassemblies	31
	Radial blanket subassemblies	174
	Steel shield subassemblies	46
	Boron shield subassemblies	527
	In-vessel storage	198

Figure 3: MOX fuel core layout

The reactor core is surrounded by two rows of the radial blanket (RBL) subassemblies. The plutonium additionally gained in the radial blanket (BR_{RBL}=0.1) allows the fuel basis to be expanded for the newly commissioned fast reactors and for the light water reactors if they are partially loaded with the MOX fuel. If necessary, the RBL SAs may be replaced by the steel shielding subassemblies, and the axial blanket may be reduced in height to reduce the plutonium breeding to the level of proper needs (BR~1).

For the neutron protection of the in-vessel storage (IVS) and in-vessel internals, subassemblies with natural boron carbide are used. The in-vessel storage volume was selected to ensure that spent FSAs are held in it for two operating cycles (two years), which made it possible to eliminate the spent fuel drum from the reactor plant design.

The reactor control and protection system includes 31 control assemblies with absorber rods of enriched boron carbide.

The basic characteristics of the BN-1200 MOX fuel reactor core are shown in Table 1. The operating characteristics are shown for the core lifetime of 4 years as adopted for the initial operating phase. If the MOX fuel is used, the limit for the fuel lifetime is determined by the radiation resistance of the EK-164 austenitic steel used for the fuel cladding.

Experimental activities to verify the operability of the MOX fuel pins, including the fuel pins testing in BN-600, are planned with account of the axial breeding interlayer introduced into the fuel column.

TABLE I: BASIC CHARACTERISTICS OF THE BN-1200 MOX FUEL CORE

Characteristics	Value
FSA wrapper tube size across flats, mm	181
Number of fuel pins in the FSA	271
Fuel pin diameter, mm	9.3
Total height of the fuel column and axial interlayer in the FSA, mm	1000
Axial blanket height, mm	400
Fuel smeared density in pins, g/cm^3	9.2
Fertile material (UO_2) smeared density in pins, g/cm^3	9.5
Operating cycle length, efpd	330
FSA lifetime, efpd *	1320
Burnup reactivity margin, % ΔK/K	0.9
Fuel burnup - peak, % h.a. - average in discharged FSAs, MW·d/kg	 13.6 89.7
Peak damage dose for fuel cladding, dpa	117

*For the main array of FSAs. The lifetime of the peripheral FSAs is by 1-2 operating cycles longer.

4. Nitride Fuel Core Design

For the BN-1200 nitride fuel core operating in the advanced nuclear fuel cycle, there are more rigid requirements in terms of the technological support for the proliferation-resistant mode and minimizing the reactivity margin:

- abandon the blankets to eliminate any possibility of high-grade (rich in ^{239}Pu) plutonium production and extraction during the spent nuclear fuel reprocessing;
- reduce the maximum reactivity margin of the reactor at the rated power by the value of 0.5 % $\Delta K/K$.

To meet the above requirements, the nitride fuel reactor core is made in the conventional homogenous configuration with the steel shields used instead of outer blankets (Figure 4). The height of the fuel column is 83 cm, which ensures that the SVRE (at the level of β_{eff}) and the fuel pin heat rate (below 48 kW/m) are acceptable.

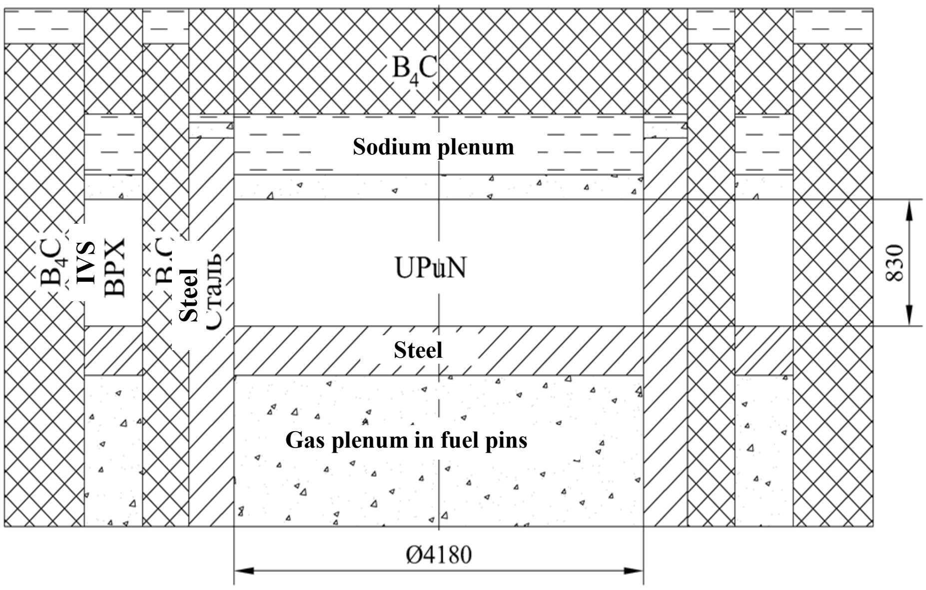


Figure 4: Nitride fuel core configuration

The nitride fuel reactor core layout is the same as for the MOX fuel reactor core (Figure 3).

To minimize the reactor reactivity margin and additionally to flatten the power distribution, the peripheral FSAs use larger diameter fuel pins (OD 10.5 mm). The plutonium breeding level in the core (BR=1.08) is self-sufficient to supply plutonium for operation in the closed nuclear fuel cycle. The excessive breeding of the fissile nuclides (BR>1) is needed to compensate for the negative reactivity inserted by the fission product buildup in the course of the fuel burnup process and to meet the requirement for minimizing the reactivity margin. According to the Technical Assignment for the Proryv Project, it is possible, if necessary, to implement the reactor core with the blankets. In this case, the total breeding ratio will increase to ~ 1.35.

The basic characteristics of the nitride fuel core are shown in Table 2.

TABLE II: BASIC CHARACTERISTICS OF THE BN-1200 NITRIDE FUEL CORE

Characteristics	Value
Number of fuel pins in the FSAs: - main array FSAs - peripheral FSAs	 271 217
Fuel pin diameter, mm - main array FSAs - peripheral FSAs	 9.3 10.5
Fuel column height in the FSA, mm	830
Lower steel shield height in fuel pins, mm	400
Fuel smeared density in pins, g/cm^3	11.5
Operating cycle length, efpd	230-330
FSA lifetime, efpd *	920-1320
Burnup reactivity margin, % ΔK/K	0.3
Fuel burnup - peak, % h.a. - average in discharged FSAs, MW·d/kg	 7.6-11.0 49.2-70.0
Peak damage dose for fuel cladding, dpa	96-131

* For the main array of FSAs. The lifetime of the peripheral FSAs is by 1-2 intervals longer.

The operating characteristics are shown for a range of FSA lifetimes. The first value (3 years) corresponds to the limited peak burnup value of the nitride fuel (~ 8% h.a. [2]), which may be sufficiently reliably verified at the present time. The second value corresponds to the same FSA lifetime as for the MOX fuel core (4 years). The activities to verify this burnup are in progress as part of the advanced program for nitride fuel verification. The prospects of increasing the fuel lifetime with the higher damage dose for the fuel cladding over 120 dpa both for the MOX fuel and for the nitride fuel are associated with using ferritic-martensitic steels that have higher radiation resistance, including the oxide-dispersion strengthened steels.

5. Conclusion

The design features of the MOX fuel and nitride fuel BN-1200 reactor cores are conditioned both by the special properties of the fuel types used and by additional requirements for the advanced nitride fuel core in terms of the technological support for the proliferation-resistance mode and minimizing the reactivity margin.

For the MOX fuel reactor core, a configuration with the axial breeding interlayer is proposed. If the MOX fuel is used, this layout has a number of advantages vs. the homogenous layout. The introduced axial interlayer leads to a reduced burnup reactivity margin and lower damage dose accumulation rate. This enables a longer operating cycle (according to the reactivity balance condition) and longer FSA lifetime (according to the radiation damage for the fuel cladding). For self-sufficient plutonium breeding, there should be the axial blanket in the FSAs.

The requirements for the nitride fuel reactor core are met if the conventional homogenous configuration is used and steel shields are applied instead of the outer blankets. To reduce the reactor reactivity margin at the rated power down to the required level (below 0.5 % Δ K/K) and additionally to flatten the core power distribution, larger diameter fuel pins are used in the two last rows of FSAs.

The same core layout (map with locations of FSAs) is adopted for the MOX and nitride fuel reactor cores, which makes it possible to use in the reactor both the MOX fuel core and nitride fuel core if the fuel operability is timely verified.

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