SELECTING THE LAYOUT FOR THE HYBRID CORE OF THE BN-800 REACTOR

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Abstract. The initial loading of BN-800 reactor includes fuel subassemblies (FSAs) with enriched uranium oxide (major part) and partially (16% of the total quantity) MOX fuel FSAs, which were fabricated using both the pellet technology and vibro-packing technology. With account of this specific core composition it is called the hybrid core.

The core configuration was selected from consideration of simplification of the further transition from the hybrid core to the full MOX core and highest possible adaptation of BN-600 uranium FSAs fabrication to BN-800 uranium FSAs fabrication.

The hybrid core comprises three types of FSAs with the different content of fissile material (enrichment). The fuel enrichment zones boundaries and fuel column height have been retained the same as in the full MOX fuel core. To ensure compatibility of uranium and MOX FSAs, the plutonium content in MOX fuel was defined based on equal reactivity worth for respective types of FSAs. To minimize distortion of the power distribution, the MOX FSAs are arranged at the periphery of the hybrid core (within the high enrichment zone). FSAs with the MOX pellet fuel are arranged in the first row, and FSAs with the vibro-packed MOX fuel are arranged in the peripheral row, under less severe operation conditions.

Key words: BN-800, core, uranium fuel, MOX-fuel.

1. Introduction

The main goal for the development of the fast neutron reactor technology is to implement the closed nuclear fuel cycle concept. The closed nuclear fuel cycle makes it possible to considerably reduce the consumption of natural uranium in the nuclear power generating industry system and to reduce the amount of wastes for subsequent disposal. As of now, the most prepared is the closed nuclear fuel cycle with the use of MOX fuel.

The uranium oxide fuel, which is more simple technologically, was used in BN-350 and now is employed in BN-600 reactor. In view of similar behavior of UO_2 and MOX fuel under irradiation, the operating experience with these reactors, especially with BN-600, is important for mastering the MOX fuel. Under the characteristic conditions of sodium-cooled fast reactors (high temperature level and high neutron flux) the sufficiently high fuel burnup of ~12% h.a. by peak value has been successfully achieved.

Representative results have been obtained in the BN-600 reactor for MOX fuel pins; in particular, 42 FSAs have been irradiated with pellet-type MOX fuel to the peak burnup of 11.8 % h.a. Also, 33 FSAs with vibropacked MOX fuel have been tested.

The BN-800 reactor, developed with account of the successful operating experience with the BN-600 reactor, is oriented to the use of MOX fuel based on plutonium extracted from the spent nuclear fuel (SNF), including SNF from VVERs. This will enable mastering of technologies at different stages of a closed nuclear fuel cycle.

The MOX fuel production for the BN-800 reactor is established at the Mining and Chemical Combine [1, 2] in accordance with the Federal Target Program entitled *Next Generation Nuclear Power Technologies for the 2010–2015 Period and up to 2020.* Because the issue with the organization of activities to fabricate the MOX fuel was solved with a certain delay vs. the planning of the activities to construct the BN-800 reactor, the first fuel loading for the BN-800 reactor [3] is a hybrid one - it is basically formed of uranium oxide fuel, and only a fraction of FSAs (16% of the total number) contain MOX fuel fabricated in the experimental production facilities at MAYAK Production Association and JSC "SSC RIAR" [4, 5] with the use of the pellet technology and the vibropacking technology.

The paper discusses the basic prerequisites for the hybrid core development; a description of the core design is given, and information is provided concerning the basic operating characteristics.

2. Basic Approaches to Forming the Fuel Loading for the Hybrid Core

The basic approaches to forming the hybrid core consist in the following [6]:

- ensure operation of the reactor with the hybrid core at the rated power;
- ensure that the existing uranium FSAs production for the BN-600 reactor be adapted to the maximum extent to fabrication of the uranium FSAs for the hybrid core of the BN-800 reactor;
- use the same FSA design with the pellet-type MOX fuel as for the standard full MOX fuel core;
- retain the same fuel enrichment zones boundaries as in the standard full MOX fuel core;
- assign the FSA life and operating interval the same as for the full MOX fuel core.

3. Core Layout and Characteristics

To flatten the power distribution, three enrichment types of FSAs are used in the hybrid core, in particular, the central core zone is formed of uranium FSAs with ^{235}U enrichment of 18.5% (low-enrichment zone, LEZ); the interim core zone with the enrichment of 21% (medium-enrichment zone, MEZ); the peripheral core zone with the enrichment of 24% (high-enrichment zone, HEZ). MOX FSAs with high-grade (rich in ^{239}Pu) plutonium enrichment of 18.7% and 19.5% for the pellet-type and vibropacked fuel, respectively, are placed in the peripheral core zone to optimize the power distribution and to minimize the impact upon the sodium void reactivity effect.

The core is surrounded by a row of the radial blanket FSAs that contain depleted uranium dioxide. Then, there are steel shielding assemblies (SSA) and boron shielding assemblies (BSA) with natural boron carbide and behind these subassemblies there is the in-vessel storage for spent FSAs.

To compensate for the reactivity margin, to control and to protect the reactor, there are 30 absorber rods of the control and protection system (CPS) in the core, including two control rods with natural boron carbide, 16 shim rods with boron carbide with the 60% ^{10}B enrichment, 9 safety rods with boron carbide with the 92% ^{10}B enrichment, and 3 hydraulically suspended passive emergency protection (PEP) rods with the same boron carbide of 92% enrichment by ^{10}B.

Hot pressed boron carbide is used in the CPS control rods as well as in the boron shielding subassemblies.

In the hybrid core center, there is a neutron source (NS)- two ampoules with californium of $2{\cdot}10^9$ n/s total intensity placed in a steel assembly.

The hybrid core layout is shown in Figure 1.

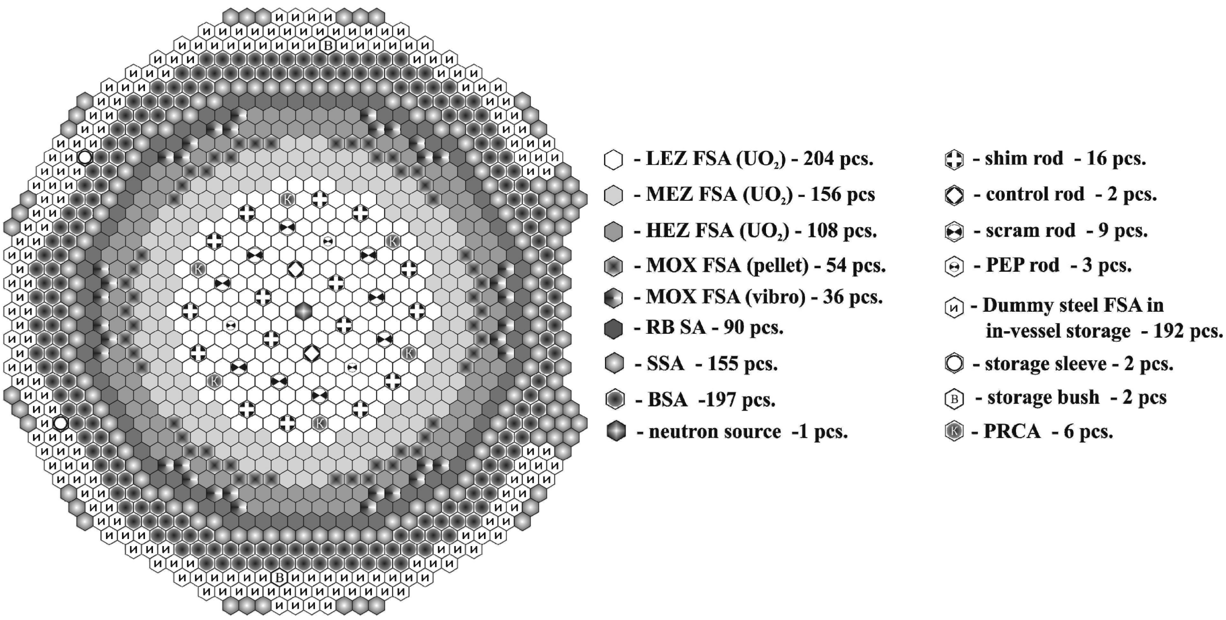

Figure 1: The hybrid core layout (for the first operating interval)

The special feature of the startup core is that instead of 6 FSAs, permanent reactivity compensator assemblies (PRCA) are inserted, which are similar in their design to the boron shielding subassemblies. The permanent reactivity compensator subassemblies compensate for the excess reactivity, which exists in the core because there are no fission products (there are no partially depleted FSAs, the presence of which is characteristic of the steady-state refueling mode).

Table 1 shows basic technical and operating characteristics of the hybrid core.

TABLE 1: BASIC CHARACTERISTICS OF THE BN-800 HYBRID CORE

Characteristics	Value
Core diameter, m	2.56
Core height, m	0.9
Core fuel inventory, t - enriched uranium dioxide - pellet-type MOX fuel -vibropacked MOX fuel	 13.8 1.57 1.08
Operating interval length, EFPD	155
FSA lifetime, EFPD	465
Average fuel burnup, MWd/kg	64

4. Designs and Characteristics of FSAs

The hybrid core incorporates uranium (pellet-type) FSAs, pellet-type MOX FSAs and vibropacked MOX FSAs.

The uranium FSAs and vibropacked MOX FSAs involve both upper and lower axial blankets. The pellet-type MOX FSAs are similar to the standard FSAs of the full MOX core - instead of the upper blanket they have a sodium plenum, and above the sodium plenum there is a bundle of absorber elements with boron carbide (the sodium plenum above the core reduces the sodium void reactivity effect of to the value below βeff) [7].

In the hybrid core, it is easier to meet the requirement for the value of the sodium void reactivity effect because the majority of FSAs contain uranium fuel. That is why it is acceptable to employ vibropacked MOX FSAs similar in design to experimental FSA with vibropacked fuel fabricated for irradiation in BN-600 reactor (with upper axial blanket) [8].

All hybrid core MOX FSAs are fabricated based upon high-grade plutonium.

The basic design characteristics of the FSAs are presented in Table 2.

TABLE 2: BASIC DESIGN CHARACTERISTICS OF THE FSAs

Characteristics	Value
FSA length, mm	3500
Hexagonal wrapper tube size across flats and thickness, mm	96×2
Number of fuel pins	127
FSA wrapper tube material	EP-450
Fuel pin diameter, mm	6.9×0.4
Fuel pin cladding material	ChS-68
Fuel pin length, mm:	
- with uranium fuel	2440
- with pellet-type MOX fuel	2040
- with vibropacked MOX fuel	2400

The FSA scheme is shown in Figure 3.

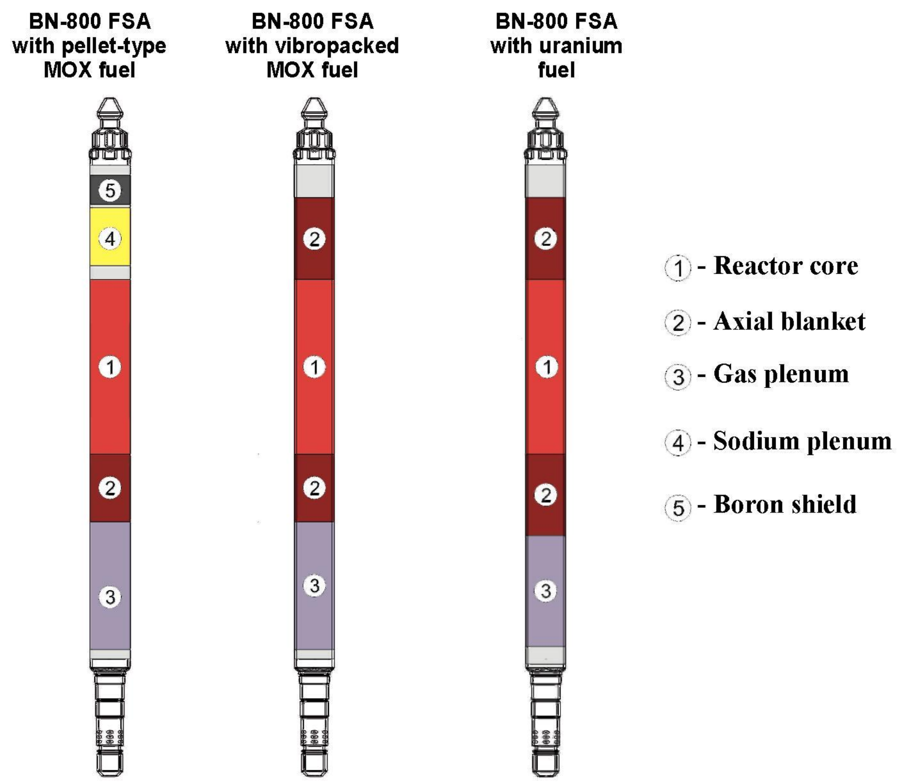

Figure 3: FSA scheme

The operating characteristics of the BN-800 hybrid core FSAs are shown in Table 3.

TABLE 3: OPERATING CHARACTERISTICS OF THE BN-800 HYBRID CORE FSAs

Characteristics	FSA type		
	UO_2	Pellet-type MOX	Vibropacked MOX
Peak heat rate, kW/m	49	43	36
Peak damage dose, dpa	81	75	68
Peak burnup, % h.a.	10.3	8.5	7.4
Maximum fuel pin cladding temperature, °C	710	710	710

The maximum (peak) damage dose value for the fuel pin cladding, which is the main factor limiting the FSA lifetime, is below that verified for the BN-600 fuel pins (87 dpa) with the same cladding steel.

5. Formation of the Reloading Groups in the Course of Hybrid Core Operation

The basic design operation mode of the reactor is a steady-state reloading mode, which is characterized by equal quantities of FSAs, reloaded in one refueling, and equal durations of operating intervals (cycles) between refuelings. For the accepted scattered batch refueling scheme FSAs with different irradiation time are operated simultaneously in the core.

In the main part of the core (480 FSAs), three such batches (groups) should be formed; in the peripheral part (84 FSAs)- four batches.

In the initial phase of reactor operation, a special fuel management scheme, when partially depleted FSAs should be unloaded from the core, is used to bring the core to the steady-state reloading mode.

To minimize the losses from the incomplete FSA irradiation (less then specified lifetime), a pattern was used, where possible, with returning from in-vessel storage to the core the partially depleted FSAs for further irradiation up to specified lifetime.

In each refueling, the core was formed such that the reactivity margin was ensured sufficient for operation within operating interval of 155 equivalent full power days (EFPDs) with account of compliance with the respective regulatory requirements for the shutdown subcriticality margin.

The fuel management scheme developed for the transition period to a steady-state reloading mode is shown in Table 4. It is planned to implement this scheme with account of the number of vibropacked MOX FSAs increased from 36 to 69, and with account of the number of HEZ uranium FSAs respectively reduced from 108 to 75, which is provided by the design. The hybrid core layout at the end of the transition period is shown in Figure 4.

During the first core refueling, the burnup reactivity margin is restored through replacing the 6 permanent reactivity compensator SAs containing boron carbide with the Low-Enrichment Zone uranium FSAs.

The special feature of the second and third reactor refuelings is that the number of FSAs unloaded from the reactor core is by 1.5–2 times greater than in the steady-state reloading mode. In this connection, direct unloading from the core to the spent fuel drum is provided for a number of spent FSAs, for which there is not enough space in the in-vessel storage.

Two butches of partially depleted FSAs unloaded into the in-vessel storage during the second refueling come back to the core during the third refueling.

If this pattern is implemented, the distribution of FSAs into butches, corresponding to the steady-state reloading mode, will be practically obtained at the beginning of the fourth operating cycle.

The average burnup of the FSAs unloaded in the initial period will be ~85% of the nominal value (64 MWd/kg) for the steady-state reloading mode.

TABLE 4: STATUS OF THE REACTOR CORE DURING THE HYBRID CORE OPERATION PERIOD (OPERATION TIME SHOWN AS A NUMBER OF CYCLES)

No. of the operation cycle	Status	Main array FSAs (480 FSAs)			Peripheral FSAs (84 FSAs)			
		1 group	2 group	3 group	1 group	2 group	3 group	4 group
1	BOC	0	0	0	0	0	0	0
	EOC	1	1	1	1	1	1	1
2	BOC	1	1	1	1	1	1	1
	EOC	2 →	2	2 [2]↑	2 →	2	2	[2]↑
3	BOC	**0**	**2**	**2 0**	**0**	**2**	**2**	**0**
	EOC	**1**	[3]↗	[3]↑ [1]↑	**1**	[3]↗	[3]↑	1
4	BOC	1	0	**2**	1	0	2	1
	EOC	2	1	[3]↗	2	1	[3]↗	2

Legend:

- [ ]↗ - unloaded to the in-vessel storage followed by a discharge from the reactor.
- → - reshuffled in the core with an interim stay in the in-vessel storage
- [ ]↑ - unloaded to the spent fuel drum

BOC - Beginning of Cycle
EOC - End of Cycle

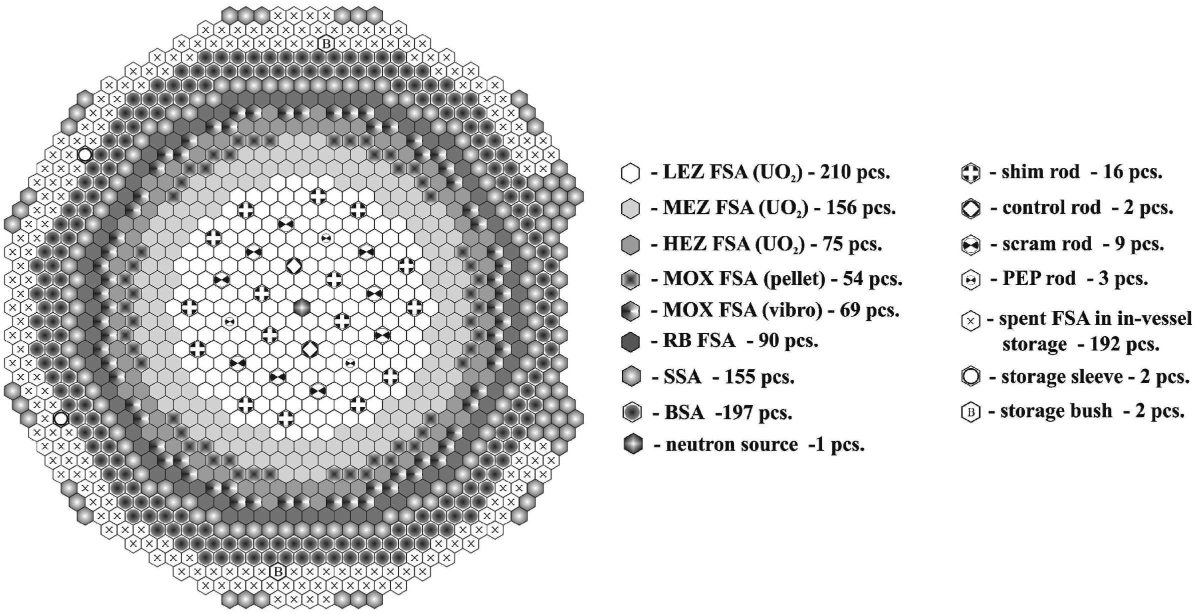

Figure 4: The core layout for the fourth operation interval

6. Conclusion

To ensure operation of the BN-800 reactor in the initial phase until the industrial production of the MOX fuel is commissioned, the hybrid core is used made up of enriched uranium FSAs and MOX FSAs of two types — with pellet-type and vibropacked fuel fabricated in the experimental production facilities at PA "MAYAK" and at JSC "SSC RIAR". The fraction of MOX FSAs in different cycles of core operation is from 16 to 22%. In the period of hybrid core operation, within 2 years (4 cycles of operation), the steady-state reloading design mode is formed, which is characterized by equal quantities of FSAs, reloaded in each refueling.

After the fourth cycle of reactor operation, a transition starts towards the full MOX fuel core. It is planned to make this transition over the 3 sequent reloadings in the process of which spent FSAs of the hybrid core will be replaced by pellet-type MOX FSAs fabricated by Mining and Chemical Combine.

The operating parameters of fuel pins in the initial period of reactor operation will not exceed the verified values; hence, regarding the core operation conditions it will not be required to limit the reactor power.

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