ARRANGEMENT OF THE BN-600 REACTOR CORE REFUELING AT TRANSITION TO THE INCREASED FUEL BURNUP

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Abstract. It is planned to switch the reactor core to an extended fuel life-time equal to 752 equivalent full power days (efpd) with five-batch refueling scheme of the major part of FSAs while using cold-worked radiation resistant steel EK164-ID on fuel claddings in order to increase fuel burnup in BN-600 reactor. To provide the transition from the existing four-batch refueling pattern to a five-batch refueling pattern, it is necessary to establish a special FSA refueling procedure during the transition period. This period is mainly characterized by forming five FSA refueling groups, which differ by their in-core residence time.

Key words: reactor core, fuel burnup, refueling pattern, transition period.

1. Introduction

It is well-known that the problem of achieving high fuel burnup in fast neutron reactors is mostly associated with providing radiation resistance of fuel cladding structural material under high-dose radiation conditions.

Over the time of BN-600 operation, for a long period the activities aimed at increasing fuel burnup had been carried out along with gradual radiation resistance enhancement of fuel cladding material, i.e. cold-worked ChS68-ID austenitic steel. Its improvement made it possible to extend the life-time of the major part of FSAs in the core from the initial 480 efpd to 560 efpd. Until 2013, the BN-600 reactor operated with the 01M2 core and designed fuel life-time equal to 560 eff. days with a four-batch refueling pattern for the major part of FSAs and a five-batch refueling pattern for the 36 peripheral FSAs [1].

Since 2013, within the period from 65th to 72nd fuel cycle, the reactor core was operating in the pilot operation mode with FSA life-time extended to 592 efpd while retaining four-batch refueling pattern. The performance efficiency of fuel claddings made of ChS68-ID steel was experimentally confirmed at damage dose up to 87 dpa, which complies with the specified FSA life-time at the average burnup of the unloaded fuel equal to 74 MWd/kg. By summer 2017, it is planned to finalize the licensing procedure of this operation mode to be a standard one.

Further increasing of fuel burnup in the BN-600 reactor is associated with transition to a new structural material for fuel cladding with better radiation-resistant characteristics, i.e. cold-worked EK164-ID austenitic steel. It is expected that performance characteristics of claddings made of EK164-ID steel will be retained under damage dose not less than 110 dpa [2], based on the post-irradiation examination (PIE) results of pilot FSA fuel claddings irradiated in the BN-600 reactor.

For this reason, it is planned to switch the core to extended FSA life-time equal to 752 efpd. The operator, Beloyarsk NPP (Rosenergoatom Concern), has admitted expedient to maintain the existing core refueling mode, consisting of two refuelings per year in spring and autumn, with winter cycle length of 160 efpd, and the summer cycle length of 136 efpd. With the new five-batch refueling pattern of the major part of FSAs, maximum fuel burnup will be ~ 15% h.a. at the average burnup of unloaded FSAs ~ 90 MWd/kg.

In order to switch the reactor operation mode from the existing four-batch pattern to a five-batch refueling pattern, it is necessary to establish a special FSA refueling procedure for the transition period. This period is mainly characterized by forming five FSA refueling groups which differ by their in-core residence time.

The paper gives consideration to the main principles and approaches to management of FSA refueling activities during transition to a new operation mode of the reactor core. The paper provides the refueling pattern of the major part of FSAs. It also contains data on reactor critical parameters and compliance with regulatory requirements for safety related to reactivity balance.

2. Characteristics of the Existing 01M2 Core

Reactor core 01M2 comprises: FSAs with enriched uranium dioxide fuel, control and protection system (CPS) absorber rods and neutron source, radial blanket (RB) (consisting of SAs with fertile material from depleted uranium dioxide) and in-vessel storage.

The reactor core is divided into three zones to ensure radial flattening of power distribution [low enrichment zone (LEZ), medium enrichment zone (MEZ) and high enrichment zone (HEZ)], comprising fuel with different enrichment 17%, 21% and 26% (U-235), respectively. The layout of the existing 01M2 core is given in FIG. 1.

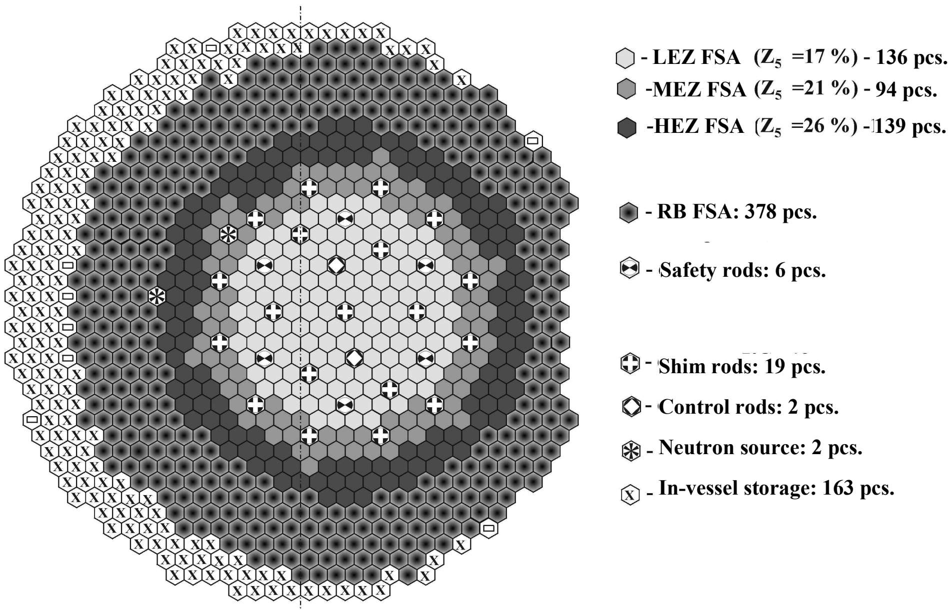

FIG. 1. BN-600 core (01M2) layout

Table I provides the main technical characteristics of 01M2 core, and Table II contains the FSA main performance parameters.

TABLE I: MAIN TECHNICAL CHARACTERISTICS 01M2 CORE

Characteristics	Value
Core diameter, m	2.06
Core height, cm	103
Radial blanket average thickness, cm	40.9
Axial blanket height (upper/lower), cm	30 / 35
Number of FSA, pcs.	369
Number of radial blanket SA, pcs.	378
Number of CPS absorber rods, pcs.	27
Fuel type	$UO_{2\ enriched}$
Fertile material in blankets	$UO_{2\ depleted}$
Fuel loading into the reactor core, t	12.1
Fertile material loading, t: into the axial blanket into the radial blanket	 8.3 29.4

TABLE II: MAIN PERFORMANCE PARAMETERS OF FSA IN THE CORE WITH FUEL LIFE-TIME OF 592 EFPD

Parameter	Value
Operating cycle length, efpd - winter (short) - summer (long)	 ≥118 ≤178
Number of FSA refueling batches, (No. of operating cycles) - major part of FSAs - peripheral FSAs	 4 5
Fuel life-time, efpd - major part of FSAs - peripheral FSAs	 592 710-770
Fuel pin maximum linear power, kW/m	48
Maximum temperature of fuel cladding, ^{o}C	710
Maximum damage dose, dpa	87
Maximum (peak) fuel burnup, % h.a.	11.8
Average fuel burnup, MWd/kg	74

3. Possible Options of the Reactor Core with Increased Fuel Burnup

Transition of 01M2 core operation from the existing operation mode with four-batch refueling pattern with fuel life-time of 592 efpd to an extended fuel life-time equal to 752 efpd with five-batch refueling pattern leads to reduction of reactivity margin by ~ 1.0% Δk/k.

It is necessary to increase the loading of fissile material (U-235) into the core to compensate for the reduction of reactivity margin in case of fuel burnup increase. There are various ways to increase the quantity of fissile material:

- by changing the reactor core configuration, i.e. expanding the reactor core boundaries by increasing the number of peripheral FSAs or by increasing the fuel column height,

- by increasing U-235 mass fraction in uranium or by increasing the fuel density while retaining the reactor core configuration in both cases.

At the present point in time, two options of the reactor core with fuel life-time of 752 efpd are under consideration based on the preliminary analysis results:

- the first option includes expanding the reactor core through enlarging the HEZ by ~ 20 FSAs while retaining the uranium fuel enrichment,

- the second option includes increase of U-235 content in all enrichment zones by ~ 3% relatively while retaining the core layout (changes concern only the ratio of HEZ FSAs with different amount of refuelings aimed at alignment of performance parameters).

Fuel life-time for the major part of FSAs has been selected 752 efpd with five-batch refueling pattern on the assumption that uranium fuel burnup is ~ 15 % h. a. and damage dose on fuel cladding of EK164-ID steel is not less than 110 dpa. Fuel life-time for the peripheral FSAs with six-batch refueling pattern is equal to 888 efpd.

Table III provides the main performance parameters of FSAs in the core with extended life-time to 752 efpd.

As for the option with expanded core, the level of linear heat rating and FSA power appear to be lower than the ones in the second option, which relates to lower power density of the core.

Taking into account the fact that radial power distribution in the considered options of the core with extended FSA life-time is slightly different from the one in 01M2 core, it will be necessary to provide redistribution of sodium flow rate for FSA and updating of thermal hydraulic characteristics of both options.

Provision is made for both options of the core with extended fuel life-time to retain practically on the same level the reactivity margin and the relevant critical states of the reactor as in the existing standard 01M2 core. Table IV provides core critical parameters for different fuel life-time.

The analysis of reactor reactivity balance showed that the reactor core with extended fuel life-time equal to 752 efpd and increased fuel burnup complies with the regulatory requirements for reactor nuclear safety relative to core reactivity balance, although there is a slight reduction of safety rods’ worth in the option with expanded reactor core.

The efficiency of fuel use is enhanced due to extending FSA life-time, which is expressed in reduction of fuel annual consumption by 30-40 FSAs depending on the option of the core.

TABLE III: MAIN PRFORMANCE PARAMETERS OF CORE WITH EXTENDED FSA LIFE-TIME OF 752 EFF. DAYS

Parameter	Value
Cycle length, efpd - winter - summer	 136 160
Number of FSA refueling batches, (No. of operating cycles) - major part of FSAs - peripheral FSAs	 5 6
Fuel life-time, efpd - major part of FSAs - peripheral FSAs	 728-752 888
Fuel pin maximum linear power, kW/m	46-48*
Maximum damage dose, dpa	101-116*
Maximum (peak) fuel burnup, % h.a.	14.0-14.6*
Average fuel burnup, (MWd)/kg	89-93*

* Parameter values depend upon the core option

TABLE IV: CORE CRITICAL PARAMETERS FOR DIFFERENT FSA LIFE-TIME

Parameter	Existing core	Advanced core	
		with increased number of HEZ SAs	with increased uranium enrichment
Fuel life-time, efpd - major part of FSAs - peripheral FSAs	 592 710-770	 728-752 888	 728-752 888
Number of FSAs, pcs. - major part of FSAs - peripheral FSAs	 333 36	 333 59	 297 72
Average fuel burnup, MWd/kg - at the beginning of a long cycle - at the end of a long cycle	 26 47	 33 52	 36 56
Reactivity margin at the beginning of long cycle, % $\Delta k/k$ ($N=100\%\ N_{nom}$)	3.28	3.11	3.03
Required additional reactivity margin to increase fuel burnup, * % $\Delta k/k$	-	1.05	1.10

* At the assumption of "fresh" core. Is not realized during operation due to the partial refueling mode

4. FSA Refueling Pattern During the Transition Period from a Four-Batch Refueling Pattern to a Five-Batch Refueling Pattern

It is necessary to develop in detail a special refueling procedure for the transition period from the existing four-batch refueling pattern to a five-batch refueling pattern. To transfer to a new refueling pattern, a general principle of its planning has been adopted.

Each of the four existing FSA groups, intended for the major part of the core, is subdivided into two subgroups: the main group and the auxiliary one. During transition to a new refueling pattern, FSAs included into the four main subgroups form four groups of the new refueling pattern. Refueling of these FSAs is carried out according to a standard pattern by replacing spent FSAs by fresh subassemblies. FSAs included into the four auxiliary subgroups eventually form the fifth group of the new pattern.

Forming of the fifth group will require early unloading of the four auxiliary subgroups in spite of their incomplete residence time losing 1-2 intervals until the end of their design lifetime. Most of these subassemblies are replaced by the fresh ones.

To reduce losses related to early unloading of FSAs, one of the four auxiliary FSA subgroups is temporarily (for two operating cycles) placed into the in-vessel storage to be subsequently returned into the core for final burnup. As a result, the transition to a five-batch pattern is carried out during six reactor refuelings.

The developed FSA refueling pattern of the major part of subassemblies in the core used during transition from a four-batch refueling pattern to a five-batch refueling pattern is given in Table V.

During the transition period, FSA groups with different in-core residence time are rearranged according to the new arrangement of FSAs from different refueling groups in the core with extended fuel life-time.

In the process of transition to a new reactor core with a five-batch refueling pattern along with the planned uniform arrangement of fresh FSAs, the core characteristics will change in accordance with the distinctive features of each fuel cycle.

At the same time to provide the required reactivity margin for each fuel cycle during the transition period, different measures can be taken: preliminary FSA loading with fuel increased enrichment, changing of enrichment zone boundaries and reactor core expansion.

The final scheme of FSA reloading is developed with account of the actual state of the core at the beginning of the transition period and the quantity of FSAs with different in-core residence time. The experimental SAs of different types irradiated in the core are also taken into account.

TABLE V: FSA REFUELILNG SCHEME DURING THE TRANSITION PERIOD FROM FOUR-BATCH REFUELING PATTERN TO A FIVE-BATCH REFUALING SCHEME

Transition cycle No.	Operating cycle length, efpd	State of cycle	The residence time for the group with the specified fraction of FSAs, number of operating cycles							
			1		**2**		**3**		**4**	
			1/5	1/20	1/5	1/20	1/5	1/20	1/5	1/20
1	160	beginning	0	0	1	1	2	2	3	3
		end	1	1	2	2	3	3	4	4
2	136	beginning	1	1	2	2	3	0	4	0
		end	2	2	3	3	4	1	5	1
3	160	beginning	2	2	3	0	4	1	0	1
		end	3	3	4	1	5	2	1	2
4	136	beginning	3	3	4	1	0	2	1	2
		end	4	4	5	2	1	3	2	3
5	160	beginning	4	3	0	2	1	3	2	3
		end	5	4	1	3	2	4	3	4
6	136	beginning	0	4	1	3	2	4	3	4
		end	1	5	2	4	3	5	4	5
7	160	beginning	1	0	2	0	3	0	4	0
		end	**2**	**1**	**3**	**1**	**4**	**1**	**5**	**1**

Legends:
□↗ - reloading into the in-vessel storage with subsequent unloading from the reactor
– –> - rearrangement in the core with intermediate storage in the in-vessel storage

5. Conclusion

Achieving of increased burnup of uranium fuel of ~ 15 % h.a. in BN-600 reactor is possible when employing steel EK164-ID with better radiation resistant properties for fuel cladding. For this reason, it is planned to change-over the exiting 01M2 core from four-batch refueling pattern to a five-batch refueling pattern with fuel life-time extended to 752 efpd.

Seasonal scheduled outages (spring-autumn) and operating cycle length equal to 136 efpd and 160 efpd is retained in the reactor new operation mode with a five-batch refueling pattern. During the reactor operation the long and short cycles will be interchanged. Two options of core layout with extended fuel life-time are under consideration. In both of them the required additional reactivity margin is provided using different approaches.

A special procedure of FSA refueling is being developed to ensure switching from a four-batch refueling pattern to a five-batch refueling pattern for the major part of FSAs and from the five-batch refueling pattern to a six-batch refueling pattern for the peripheral FSAs. A general principle is adopted for the management of the transition period that was applied previously during transition to 01M2 core. In the process of forming new groups for refueling (the fifth and the sixth ones) it is allowed to perform early unloading of a number of FSA before the end of the new extended fuel life as well as to temporarily unload some of the FSAs into the in-vessel storage with subsequent reloading into the core for final burnup.

The final scheme of FSA refueling management during the transition period will be developed on defining specific date of starting transition to the core with extended fuel life-time.

6. References

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