Potential Capabilities of Operating Reactor BOR-60 and Reactor MBIR under Construction to Perform Experiments on Transmutation of Minor Actinides

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Abstract. The paper presents a summary review of the most important experiments performed in the BOR-60 reactor on transmutation of minor actinides and isotopic composition of high burnup nuclear fuel:

– testing of fuel elements and fuel assemblies with different nuclear fuels,

– behavior of irradiated nuclear fuel at achievement high burnup,

– plutonium burning and transmutation of minor actinides.

A comparative analysis has been done with reference to the BOR-60 operating reactor and the MBIR reactor under construction in terms of their main design parameters and neutronics that affect the capabilities to perform experiments on transmutation of minor actinides.

Key Words: reactors BOR-60&MBIR, experimental capabilities, transmutation of Minor Actinides.

Introduction

Fast reactor BOR-60 is one of the world’s leading research reactors in large-scale testing of fuel elements, FA and control rods of different designs as well as advanced fuel compositions and structural materials, testing of closed nuclear fuel cycle technologies, transmutation of minor actinides, and disposal of plutonium. BOR-60 is a unique experimental reactor with a neutron spectrum ranging from the hard one in the core to the intermediate one in the lateral blanket, and a high neutron flux density values (Fn) [1]. There is a possibility to carry out experimental research in the BOR-60 blanket in a softened neutron spectrum with the use of moderating assemblies [2].

1. BOR-60 experimental capabilities

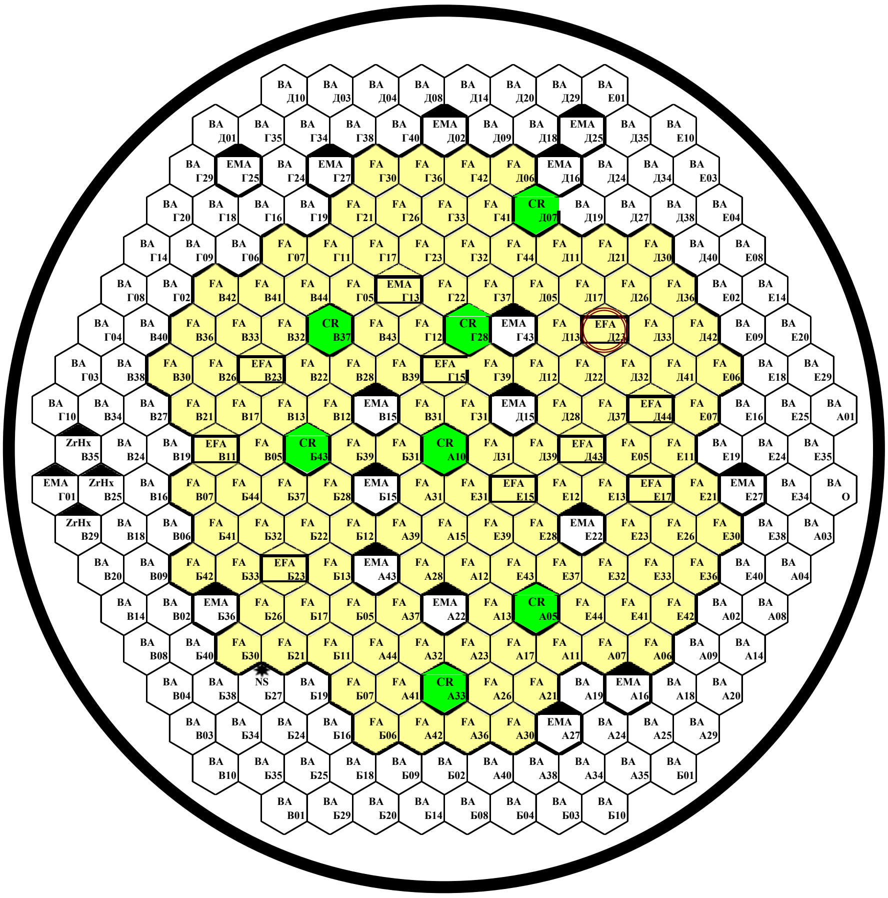
Table I presents the main BOR-60 parameters.

TABLE I. BOR-60 MAIN PARAMETERS.

Parameter	Value
Thermal power, MW	up to 60
Sodium flow rate through the reactor, m^3/h	up to 1200
Sodium velocity in the core, m/s	up to 8
Coolant temperature, ºC: - reactor inlet - reactor outlet	 310÷340 up to 540
Standard fuel	UO_2 or UO_2-PuO_2
Enrichment in U-235,%	45÷90
Max Pu content,%	30

Max volumetric heat rate, kW/l	1100
Max neutron flux density, $cm^{-2}s^{-1}$	$3.5\cdot10^{15}$
Average neutron energy, keV: - core - blanket	 150÷400 1*÷100
* – in the cell surrounded by zirconium hydride	

In BOR-60 the assemblies are arranged in a hexagonal grid. The number of the cells totals to 265 (*see FIG. 1.*). Up to 156 cells are provided for FA, 7 cells – for control rods, and the remaining positions are loaded with blanket assemblies (breeding and/or steel). The number of FA loaded in the reactor during its operation has ranged from 75 to 128 depending on nuclear fuel (NF) burnup and properties, core arrangement and experimental rigs. Experimental assemblies can be loaded in any position except for the cells intended for control rods.



FA – standard FA, EFA – experimental FA, CR – control rods,
EMA – experimental material assemblies, BA – blanket assemblies, ZrHx – moderating assembly
FIG. 1. BOR-60 core arrangement (2014).

The BOR-60 reactor has four horizontal experimental channels and nine vertical experimental channels behind the reactor vessel with a rather high neutron flux density. These channels are used mainly for irradiation of electrical engineering materials and doping of silicon [3].

The reactor design enables variations of the core dimensions in a wide range. A large number of experimental assemblies can be loaded in different reactor cells, and Fn in some cells can differ by three times. BOR-60 has an instrumented position (D23) which provides for online data display. The main neutronic parameters in several cells are given in Table II [4].

FIG. 2 shows radial distribution of Fn and fast neutron flux density (En>0.1 MeV), (Fn0.1) in the core mid-plane (CMP), and average neutron energy (En).

TABLE II. NEUTRONICS IN BOR-60 CELLS.

Cell, row		E31, 1	A43, 3	D23, 5	D35, 8
Cell center radius relative to the core, mm		45	135	196	360
Max neutron flux density, 10^{15} $cm^{-2}s^{-1}$: - En > 0.0 MeV (Fn) - En > 0.1 MeV (Fn0.1)		 3.4 2.8	 3.1 2.5	 2.5 2.0	 1.2 0.6
Damage dose accumulation rate in steel (DPA), 10^{-6} dpa/s		1.4	1.3	1.0	0.2
Axial peaking factor in the core, relative units	Fn	1.15	1.16	1.15	1.12
	DPA	1.18	1.18	1.18	1.16
Radial peaking factor in the CMP, relative units	Fn	1.00	1.05	1.09	1.13
	DPA	1.01	1.06	1.11	1.31
Neutron flux density fraction: - En>0.1 MeV, relative units - En>0.8 MeV, relative units		 0.83 0.30	 0.82 0.28	 0.80 0.25	 0.50 0.07
Average neutron energy, keV		350	320	250	40
Neutron fluence *, $10^{22}cm^{-2}$ /year	En>0.0 MeV	6.1	5.5	4.5	2.1
	En>0.1 MeV	5.1	4.5	3.6	1.1
Max damage dose in steel *, dpa/year		26	23	19	4.4
** – 1 year of irradiation - WT≈ 275 GWh*					

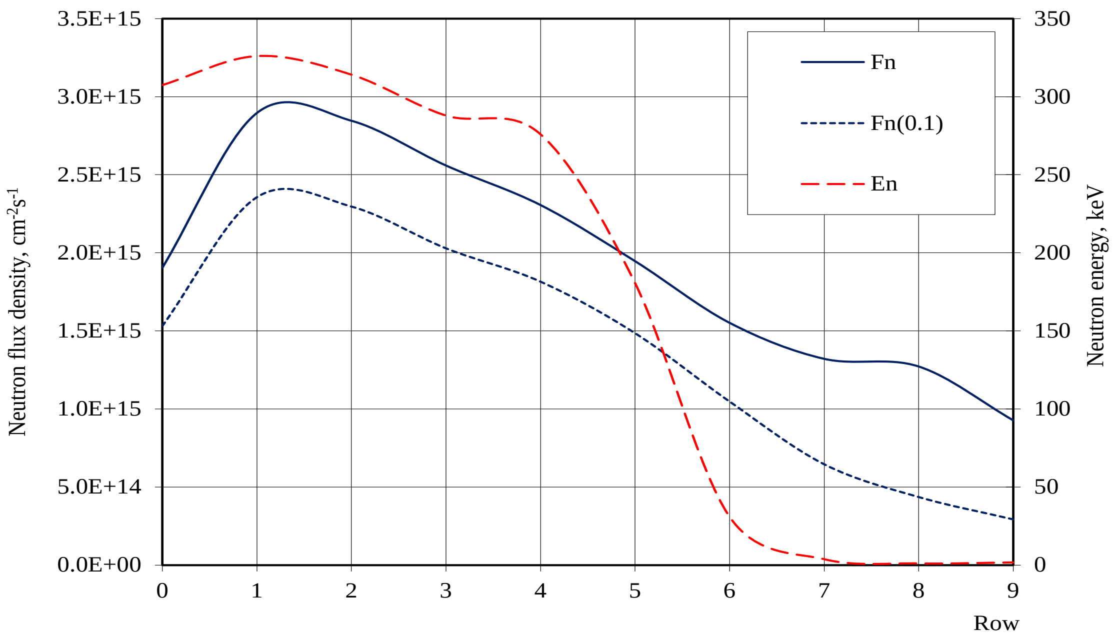


FIG. 2. Radial profiling of the BOR-60 main neutronic parameters.

FIG. 3 and *FIG. 4* show normalized neutron spectra in the core and lateral blanket. *FIG. 4* presents a normalized neutron spectrum in cell G01 when it is surrounded by moderating assemblies (zirconium hydride).

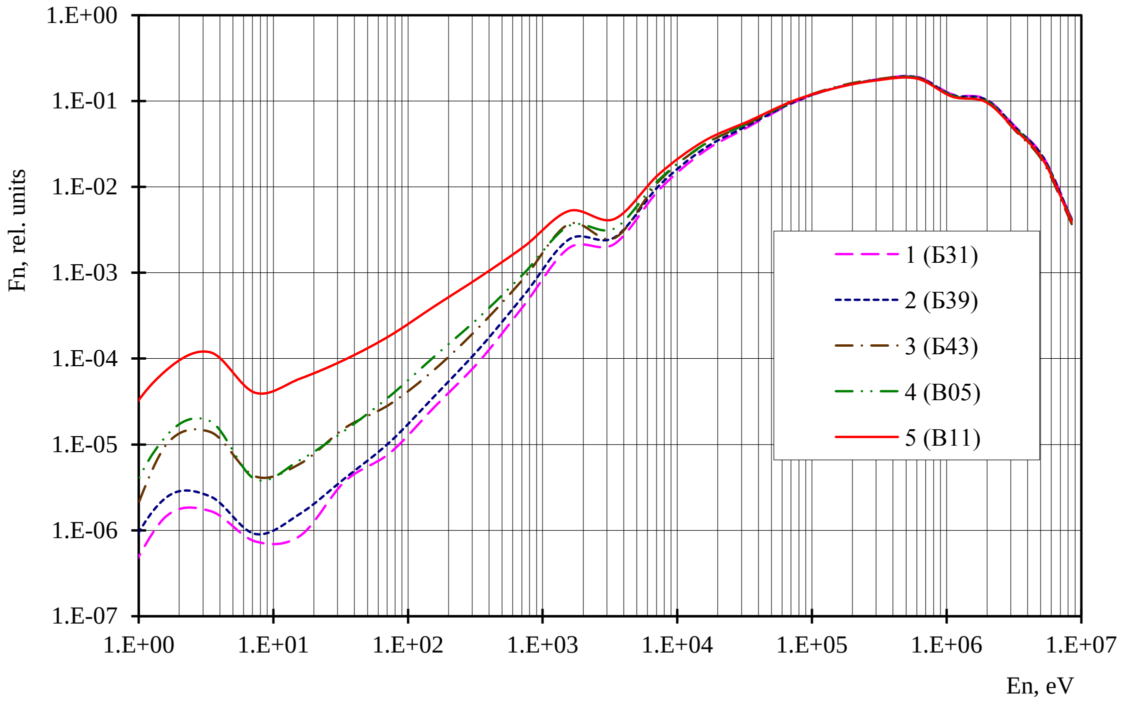


FIG. 3. Neutron spectra in the BOR-60 core (row, cell).

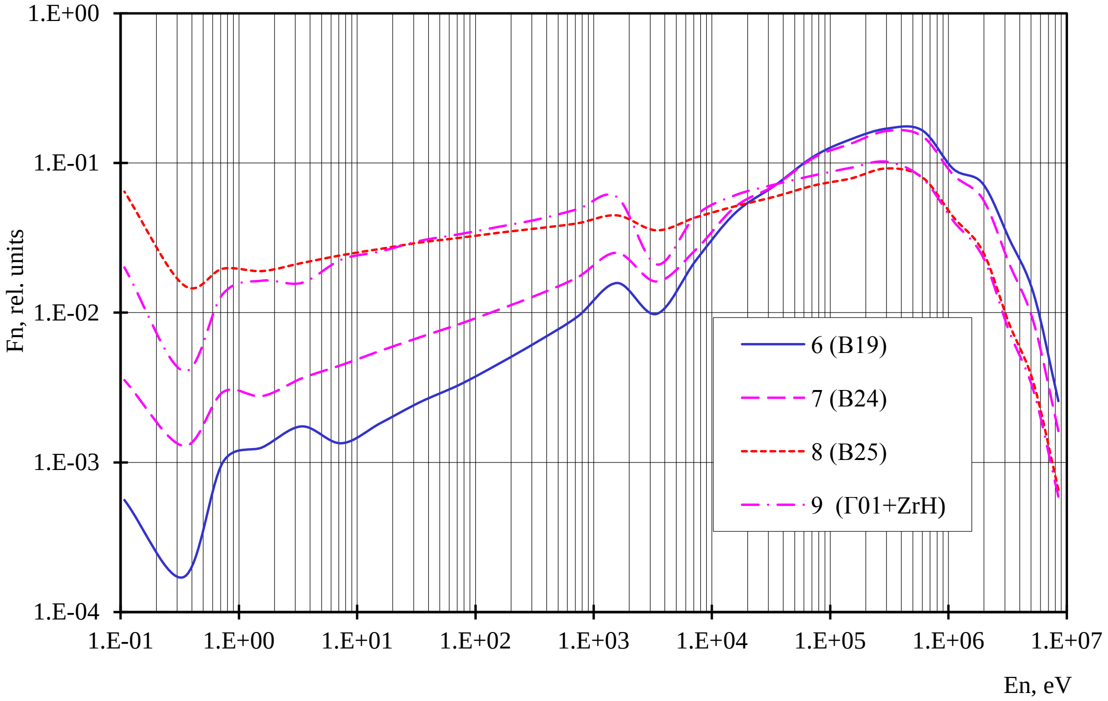


FIG. 4. Neutron spectra in the BOR-60 lateral blanket (row, cell).

2. Experiments performed in BOR-60

Since BOR-60 commissioning large-scale experiments have been performed there including irradiation testing of different reactor materials and fuel compositions. The highlights include irradiation programs in the following trends:

- testing of fuel elements and FA with different nuclear fuels,
- achievement of high fuel burnup (up to 34 % heavy atoms (h.a.));
- Pu burning and transmutation of minor actinides.

2.1. Burnup and isotopics of irradiated nuclear fuel

Particular attention in RIAR is traditionally paid to experimental research of isotopic composition and behavior of irradiated nuclear fuel at high burnup. FA with different nuclear fuels were tested (oxide, metal, metal-ceramic, carbide, nitride; pellet and vibropac) with a burnup achieving 27 % h.a. Comprehensive research was performed to determine the isotopics including actinides and fission products in a FA, specific fuel elements, and samples. Thorough calculations, experiments and analysis are carried out on irradiation conditions of the fuel elements and FA under testing (RIAR has a balanced set of qualified and verified computer software and methods the modifications of which have been applied for considerable time). Nuclear fuel irradiation parameters and isotopics were obtained with the use of different computer codes and constants as well as by applying radiochemical methods and mass spectrometry. On several fuel elements the maximum burnup of 34 % h.a. was achieved.

The discrepancies between the calculated and experimental values normally do not exceed 5% for U, 10% for Pu, the nuclear fuel burnup being 0.7÷2.5 %. There is a good agreement for Am-241 (3÷7%), Cm-242 (6%), and Cm-244 (5%) [5, 6].

2.2. Burning and transmutation of actinides

Plutonium burning, transmutation of actinides, and irradiation of nuclear fuel containing Np [7] and Am [8] were performed under the program on testing closed nuclear fuel cycle technologies.

Numerous experiments on thorium-related issues have been performed in RIAR. Thorium was irradiated to obtain the average neutron cross-sections and U-233 breeding rate, as well as to test the fresh fuel fabrication and spent thorium-based fuel reprocessing methods. Thorium was irradiated in BOR-60 as fuel elements, samples and capsules.

Calculations, experiments and analysis of the isotopics were performed for the capsules containing different actinides (Th-232, Np-237, Pu-239, Pu-240, Pu-242, Am-241, Cm-243, and Cm-244) irradiated in BOR-60 [9]. The capsules were arranged along the height of two fuel elements (8 pcs.) in an experimental dismountable FA.

3. Experimental capabilities of BOR-60 and MBIR

The given data show that BOR-60 has been used intensively and continues to be operated as an experimental and research facility. There are long-term R&D programs under international contracts and projects with funds from the federal target program on nuclear power technologies of the new generation. There are numerous contracts for BOR-60 that will be effective for the next few years. The research carried out in BOR-60 will continue up to its decomissioning.

At present, RIAR has a license for BOR-60 operation up to 2020, and the work is being carried out to prolong its operating lifetime beyond 2020. By the end of its lifetime the federal target program on nuclear power technologies of the new generation in 2010–2015 and until 2020 envisages construction of a multipurpose fast research reactor (MBIR). The MBIR reactor is intended to replace BOR-60 after its final shutdown [10] meeting the demands in research of different reactor designs. The MBIR design provides wider experimental capabilities compared to BOR-60 that enable different irradiation tests. MBIR will have three instrumented cells (similar to D23 in BOR-60) spaced at a different distance from the core, and three loop channels with an isolated coolant circuit (Na, liquid heavy metal coolant, molten salts, gas). The loop channels (with one of them in the core and two in the lateral blanket) will occupy the area of seven cells. They will provide online monitoring of the experimental parameters. *FIG. 5* shows MBIR core arrangement. The irradiation volume of each cell is increased by more than three times compared to BOR-60 cells, which will also increase significantly the reactor experimental capabilities [11].

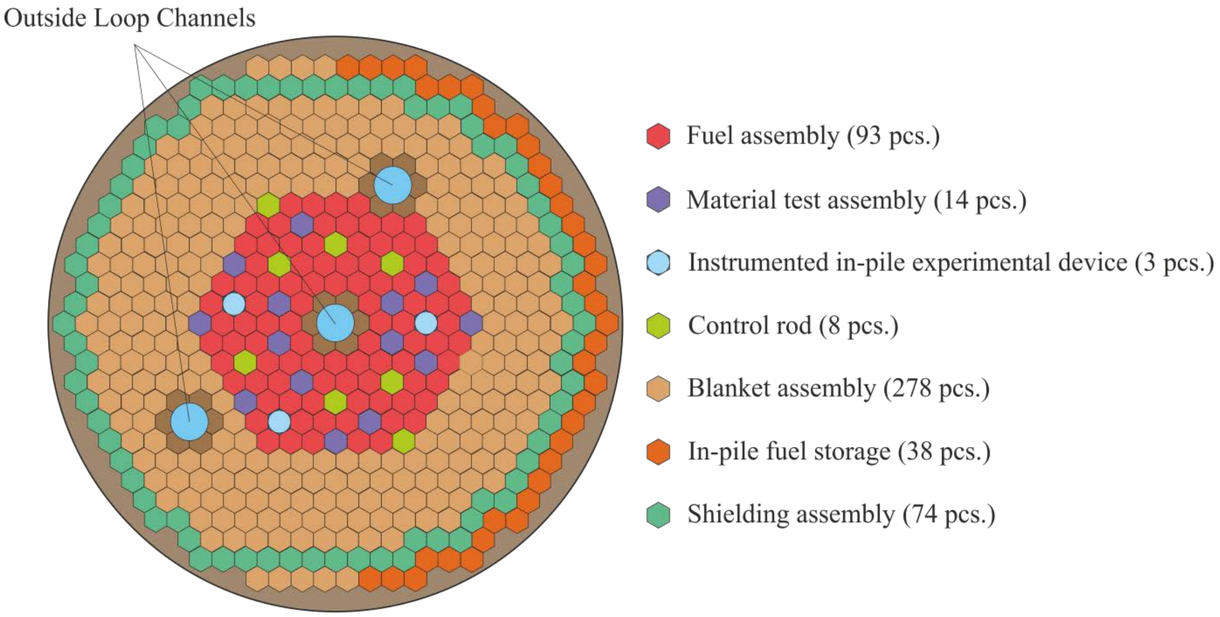


FIG. 5. MBIR core arrangement.

The MBIR main parameters affecting transmutation of minor actinides are as good as those of BOR-60: max neutron flux density makes up ~ 5.2×10^{15} $cm^{-2}\times s^{-1}$. The average neutron energy varies in the core up to 600 keV, and in the lateral blanket – up to 100 keV. *FIG. 6* and *FIG. 7* illustrate the comparison of BOR-60 in its current state and MBIR potential in terms of radial distributions of their main neutronic parameters in the core mid-plane affecting transmutation of minor actinides [11]. *FIG. 8* shows normalized neutron spectra in different parts of BOR-60 and MBIR.

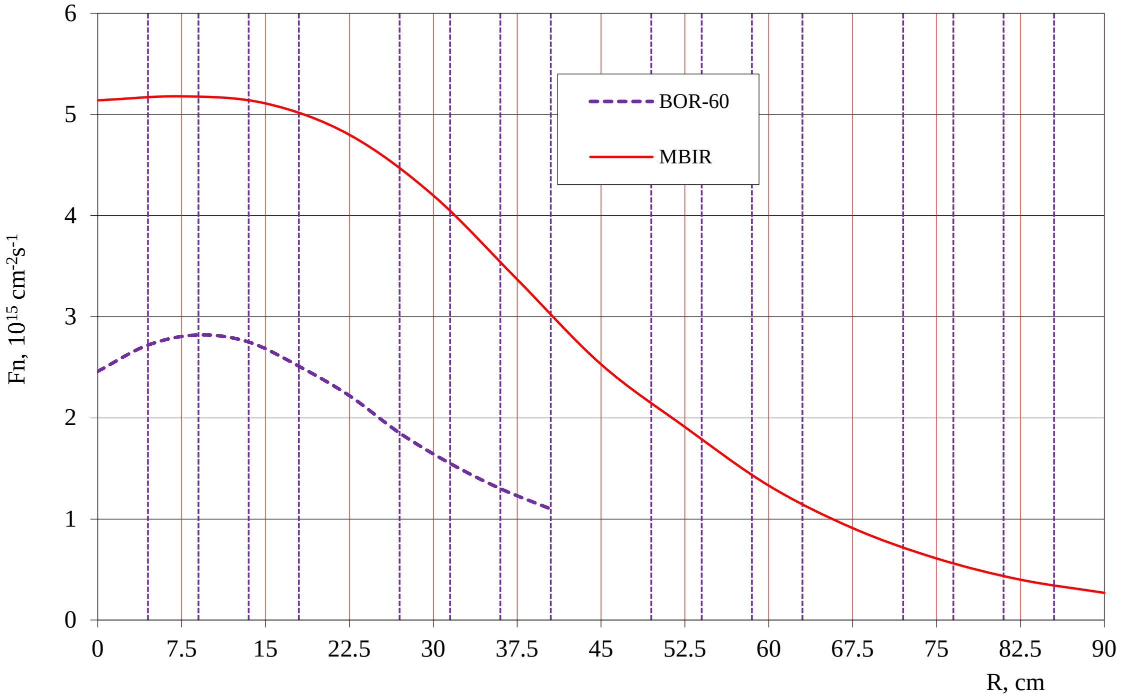


FIG. 6. Radial distribution of the neutron flux density in the CMP of BOR-60 and MBIR.

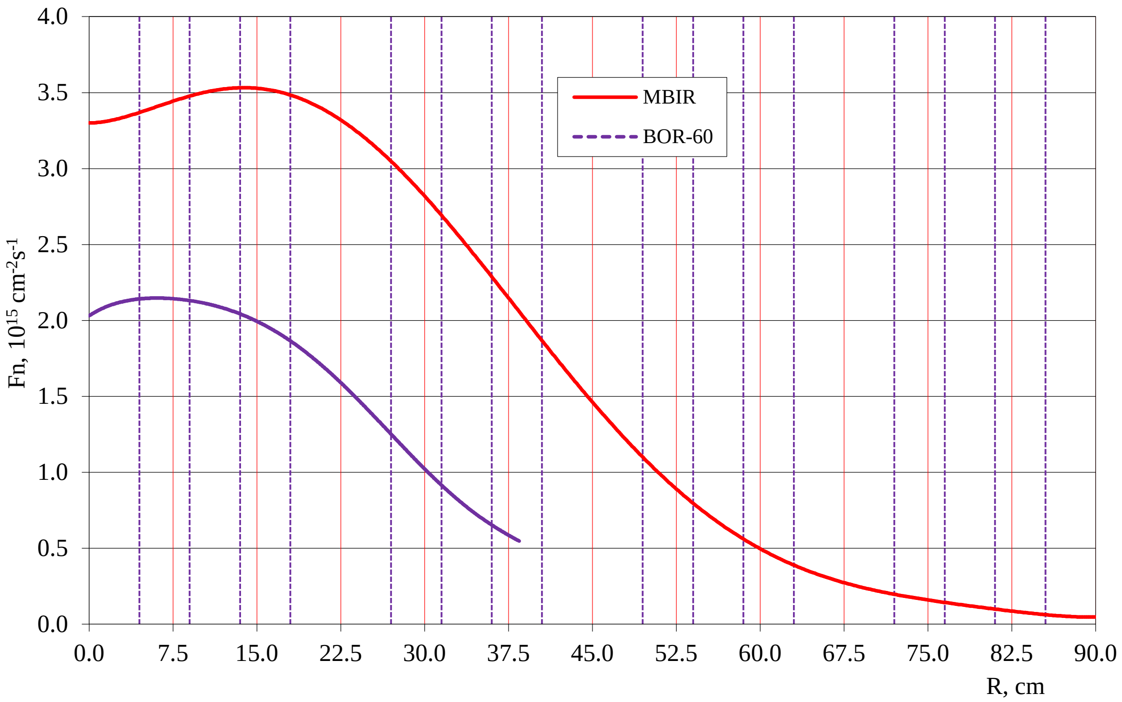


FIG. 7. Radial distribution of the neutron flux density in the CMP of BOR-60 and MBIR (En>0.1 MeV).

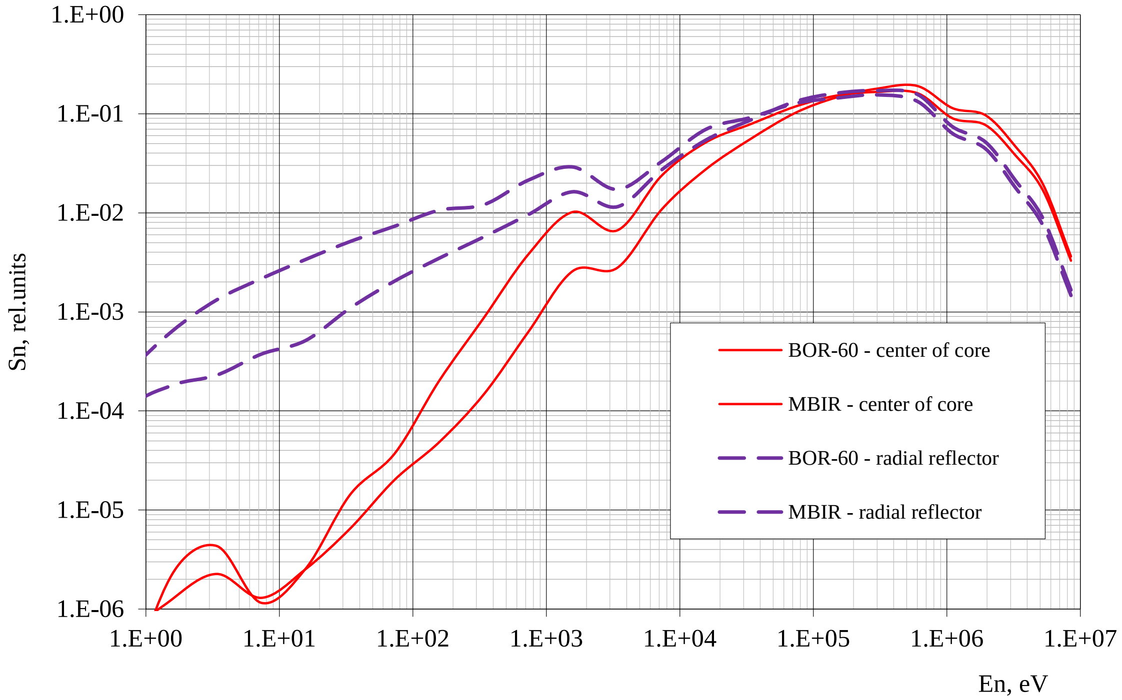


FIG. 8. Neutron spectra in different parts of BOR-60 and MBIR.

The MBIR reactor being constructed at the RIAR site will have wider experimental capabilities that will enable promptly conveying all operational and research experience gained in BOR-60. Thus, long-term research programs launched in BOR-60 will be completed in MBIR [11]. Moreover, such long-term programs are currently being implemented.

Conclusion

The BOR-60 reactor has unique parameters to carry out experimental research in different trends including transmutation of minor actinides.

The systematization and analysis of the performed experiments as well as new specifying calculations will allow improving significantly the reliability in showing the feasibility of actinide transmutation depending on the neutron spectrum, different fuel cycles and promising trends of nuclear reactor development.

The research launched in BOR-60 may be continued in the MBIR reactor that will have wider experimental capabilities.

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