ON THE POSSIBILITY OF USING VARIOUS TYPES OF FUEL IN THE MBIR REACTOR CORE

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Abstract. MBIR is a 150 MWt multipurpose research sodium cooled fast reactor, designed for a broad range of experimental studies in various lines of research. Vibropacked MOX-fuel with relatively high plutonium weight content (under 40%) is accepted as the standard fuel for MBIR reactor facility. At the same time, there is a principal possibility of using alternative types of fuel in this reactor: both uranium fuel (based on enriched uranium dioxide) and highly dense uranium-plutonium fuel (mixed nitride and mixed metal), which are of interest for innovative fast reactors. Moreover, at the initial stage of MBIR operating, it is possible to use combined vibropacked oxide fuel (based on plutonium and enriched uranium), which is accepted as the standard for reactor BOR-60 (content of plutonium under 24%).

Types of fuel under consideration differ not only by density, but also by other characteristics that are important for neutron physics of the reactor. Particularly, they have different nuclear properties of fission materials (plutonium or uranium-235), different quantity of diluent (oxygen etc.) nuclei per heavy nucleus etc. All this factors define the neutron spectrum and critical parameters of the core.

One of the important requirements for this reactor is high maximum neutron flux density (not less than 5*1015n/cm2sec). Special emphasis in this report is placed on the analysis of the dependence of neutron flux density and the rate of damaging dose accumulation from type of fuel, as well as the analysis of MBIR neutron flux distinctive features compared to energy reactors

Key Words: MBIR, types of fuel, core.

Vibropacked MOX fuel is accepted as regular fuel for the MBIR reactor. At the same time, the reactor offers a technically feasible possibility of using alternative types of fuel as well: both uranium (based on enriched uranium dioxide) and dense U-Pu (nitride, metal) fuel which are of interest for the future of nuclear power. Also of interest is combined vibropacked oxide fuel (based on plutonium and enriched uranium), which is now the regular fuel for the BOR-60 reactor.

The fuel types considered do not only differ in density but also in quite a few other parameters which are essential for the reactor neutronics. These are the principal differences of fissile materials (Pu or U-235), the number of light nuclei (oxygen, etc.) per one heavy nucleus, etc. All of them determine the core neutron spectrum and critical parameters.

One of the most essential requirements for this reactor is high density of neutron flux (not less than $5*10^{15}$n/cm^{2}sec), which, in turn, depends on the type of the fuel used. Special attention is paid to the analysis of dependence of the neutron flux density and dpa rate on the fuel type.

The reactor facility called MBIR (multipurpose research sodium-cooled fast reactor) is designed for a broad range of studies and experiments, from studies on promising types of nuclear fuel, absorbing and structural materials, coolants to issues concerning the closure of the fuel cycle and production of isotopes. Besides, this reactor facility provides for theoretical studies and medical research on neutron beams. Power reactors can hardly be used for this purpose – the procedure for obtaining permits from Rostekhnadzor for irradiation in a power reactor does not allow products that lack justification in research reactors to be placed into the core. As far as research reactors are concerned, the procedure for obtaining permits is much simpler. For the moment, BOR-60 research reactor serves the purpose, yet its lifetime is coming to an end. Therefore, a new research facility is needed. MBIR is seen as such a facility [1].

A fundamental requirement for MBIR is to provide a high density of neutron flux – not less than $5 \cdot 10^{15}$(cm^{-2} sec^{-1}). Such a density is achieved when regular vibropacked U-Pu fuel is used. However, one cannot rule out the possibility that regular fuel will not be justified or ready for use by the time of the reactor startup, as was the case with BN-800. Thus, for the initial stage of reactor operation it is reasonable to consider the possibility of using alternative fuels.

Transition to the substitute fuel should be as smooth as possible, not affecting other design solutions. Various types of fuel have been considered in fact, with no changes allowed in the core layout.

The most developed fuel in NP is pelletized oxide fuel based on enriched uranium (UO_2). It is this fuel that is used in thermal reactors, in BN-600 and, during the initial phase, in BN-800. Due to its low activity it does not require specialized remote fabrication techniques and can be produced at any plant that has the necessary permissions. However, it has a fundamental disadvantage for MBIR: under otherwise equal conditions, neutron flux with uranium fuel will be by ~20% less than with mixed U-Pu fuel. It is related to neutronic characteristics of U-235, namely to lower yield of fission neutrons as compared with plutonium.

The required flux value ($5 \cdot 10^{15} cm^{-2}$ sec^{-1}) can only be obtained with mixed uranium-plutonium MOX fuel, but fabrication of such fuel demands special protection (if low radiation plutonium is used) or even a remote technique (in case of reactor grade plutonium).

There are two MOX fuel fabrication techniques in Russia: pelletization (pelletized mixed oxide fuel) and vibropacking (vibropacked mixed oxide fuel). Industrial fabrication of pelletized MOX fuel for BN-800 has entered a phase of commissioning operations on the site of the Integrated Mining and Chemical Plant; however, fuel fabrication for MBIR is not intended there.

Semi-industrial technique of vibropacking is used in SSC Research Institute of Atomic Reactors. The fuel was extensively tested in BN-600. Thus far, its functionality has been justified to the extent of Pu mass fraction of 24% at most, which is sufficient for BN-600- and BN-800-type reactors. Meanwhile, Pu mass fraction in MBIR should be 38-39%. Functionality of such fuel has not been justified so far.

Combined fuel can be seen as modification of vibropacked fuel. It is derived from the oxides of enriched uranium (to 15-20%) and plutonium (20-24%), thus plutonium content remains within the justified limits whereas enriched uranium compensates for the shortage of fissile material. Such fuel is regular for the BOR-60 research reactor [2].

It is impossible to ignore mixed nitride uranium-plutonium (MNU-Pu) fuel which is regarded as the basis for future commercial power fast reactors in the BREAKTHROUGH project [3], namely for BREST-300 and BN-1200. Advantages of nitride fuel over oxide one are well known: it has a higher density and thermal conductivity, it is perfectly compatible with liquid-metal coolant and cladding materials, especially in an emergency. It is quite consistent with the technique of its predecessor, i.e. oxide fuel. Nitride fuel makes it possible to meet modern requirements to reactor safety in full, including the possibility for reactors to operate with the closed fuel cycle, without separating uranium and plutonium when reprocessing spent nuclear fuel.

Metal fuel for fast reactors has been considered from the very moment their design was started due to its high density and thermal conductivity, minimum number of light nuclei, which provides the best possible breeding. This fuel was used in the first American sodium cooled fast reactor - «EBR-2» (1965). American experts consider this fuel not for the sake of breeding but because of the low-cost techniques of fuel fabrication (casting) and reprocessing (electrochemistry) in the closed fuel cycle as well as guarantee of the reactor inherent safety [4]. Economic analysis has shown that the fuel cycle of the reactor with such fuel is indeed a lot cheaper (as compared with ceramic fuel, powder technique for its fabrication and water radiochemistry).

The fuel has a relatively low melting point, thus, it should be used with sodium interface sublayer. Helium interface sublayer causes increase in its temperature above the melting point and demands a large decrease in power release. Such consideration of the fuel was perfunctory, with helium interface sublayer, without regard for its functionality.

All the fuel types considered have already been exploited in various experimental power and demonstration sodium-cooled fast reactors. The key parameters of these reactors are given in Table 1 [5].

TABLE I – KEY PARAMETERS OF EXPERIMENTAL POWER SODIUM-COOLED FAST REACTORS WITH DIFFERENT TYPES OF FUEL

Reactor	CEFR	FFTF	BOR–60	BR–10	EBR–II
Fuel	UO_2	UO_2 $+PuO_2$	Vibropacked MOX	UN	U–Zr
Country	China	USA	Russia	Russia	USA
Power, MW(t)	65	400	60	5—8	62.5
Equivalent core diameter, cm	60. 6	120. 2	46. 0	41. 2	69. 7
Core height, cm	50. 0	91. 4	45. 0	40. 0	34. 3
Fuel volume fraction	0.430	0.310	0.480	0.445	0.318
Fissile isotope fraction, %	65	20.3/24.6	45	90	67
Peak cladding temperature, C	620	680	710	580	580
FE diameter/cladding thickness, mm	6.0 / 0.4	5.84/0.38	6.0/0.3	8.4 / 0.4	4.42/0.31
Peak / average fuel power density, MW/m^3	1867 / 1132	1857 / 114	1940 / 1615	2182 / 1588	2704 / 1610
Peak / average core power density, MW/m^3	803 / 487	576 / 345	931 / 775	971 / 707	860 / 716
Peak neutron flux, $10^{15} n/cm^2 sec$	2.97	7.00	3.50	0.86	2.70

Enriched uranium dioxide as fuel for fast reactors has only been used in domestic reactors. The experimental BOR-60 reactor was initially operated on pelletized uranium fuel which is used to this day in operating the BN-600 power reactor. The only exception is the Chinese experimental CEFR reactor as Russian experts took a big part in its design, construction and commissioning and pelletized uranium fuel was fabricated at a Russian plant.

Pelletized MOX fuel (UO_2+PuO_2) was used in the overwhelming majority of foreign experimental (FFTF – USA, Rapsodie – France, KNK-II – Germany, JOYO – Japan), demonstration (Phoenix – France, MONJU – Japan, PFR – Britain) and commercial (Super-Phoenix - France) reactors of this type because industrial fabrication of the fuel was set up in these countries.

Vibropacked MOX fuel fabricated in semi-industrial way at the Research Institute of Atomic Reactors is actually used for only one experimental reactor - BOR-60 [2]. It should be noted that the fuel is combined – it is made of enriched uranium dioxide and plutonium. The reason for using enriched uranium is that the fuel loses its functionality when Pu content is above 24%, therefore enriched uranium has to be used in order to provide reactor criticality. A few dozen experimental assemblies with standard vibropacked MOX fuel were fabricated and irradiated in BN-600. Maximum fuel burnup in them was 7÷10% h.a.

Experimental assemblies with nitride uranium fuel have been irradiated in the BR-10 reactor in Russia since 1970 [6]; the fuel was fabricated by different techniques, its porosity varying, and it had two kinds of interface sublayer (sodium and helium). These studies provided a basis for making ~200 FAs for two full loadings with nitride uranium fuel, the maximum burnup reaching 8.7% h.a. Experimental assemblies with mixed nitride U-Pu fuel are currently being irradiated in the BN-600 reactor [7].

Metal fuel was used in sodium-cooled fast reactors most widely. Uranium-molybdenum alloys (U- 7%Mo and U- 10%Mo) were used in the experimental reactors such as DFR (Britain) and Enrico Fermi (USA). Metal fuel based on the three-component alloy (U-Pu-Zr) was used in EBR-2.

Parameters of the MBIR reactor facility with the fuel types mentioned are given in Table 2

TABLE II – SUMMARY TABLE OF THE KEY PHYSICAL PARAMETERS OF THE MBIR REACTOR FACILITY WITH DIFFERENT TYPES OF FUEL

Fuel	Pelletized UO_2	Pelletized MOX	Combined vibropacked MOX	Pelletized UN	UPuZr-base metal
Pu mass fraction, %	–	36.5	24	26.43	20.87
U-235 fraction in uranium, %	50.3	–	24.6	–	–
Peak flux, 10^{15} n $cm^{-2}sec^{-1}$	4.25	5.30	4.89	4.81	5.19
Peak fast flux, 10^{15} n $cm^{-2}sec^{-1}$	3.05	3.59	3.34	3.44	3.84
Maximum displacement per atom, dpa/100 eff. days.	12.7	15.2	14.2	14.1	14.9

Of all the considered types of fuel in the MBIR reactor facility it is only MOX fuel (mixed oxide) and metal fuel (three-component alloy) that provide neutron flux not less than $5*10^{15}$ n/cm^2sec. Combined vibropacked MOX fuel (enriched uranium dioxide + 24% of Pu dioxide), which appears the most workable for the initial stage of MBIR operation due to the preparedness of the production facilities, almost reaches the required value (flux $4.9*10^{15}$ n/cm^2sec). Nitride U-Pu fuel does not reach the required flux value ($4.8*10^{15}$ n/cm^2sec) because of parasitic neutron absorption by nitrogen while uranium fuel does not provide more than $4.2*10^{15}$ n/cm^2sec because of a low yield of secondary neutrons in U-235.

Metal U-Pu fuel possesses the best set of neutronic parameters (neutron flux, dpa rate, minimum Pu critical loading) but it requires significant change in the reactor design.

Basic difference between uranium and uranium-plutonium fuel is also the effective delayed neutron fraction ($\beta_{эф}$), which is crucial for reactor control. $\beta_{эф}$ is 0.72% for uranium loading and 0.31 - 0.36% for uranium-plutonium loading.

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