Role of fast sodium reactors in closure of the nuclear fuel cycle in the nuclear power system

A V Gulevich1, V M Dekusar1, A A Kamaev1, D A Klinov1, A L Moseev1, B A Vasiliev2, A V Vasyaev2, S F Shepelev2
1 Joint-Stock Company State Scientific Center of the Russian Federation Physics and Power Institute, Obninsk, Russia
2 Joint Stock Company "Afrikantov Experimental Design Bureau for Mechanical Engineering" (JSC “Afrikantov OKBM”) Nizhniy Novgorod, Russia

gulevich@ippe.ru

Abstract. Currently, nuclear society has recognized that further development of Russian nuclear power industry will be carried out under the two-component framework represented with thermal and fast reactors operating within the total closed fuel cycle. Several scenarios of the nuclear fuel cycle closure within Russian two-component nuclear power system (NPS) have been currently discussed among the industry specialists. These scenarios are based on various philosophies of the NFC closure (centralized NFC closed by thermal and fast reactors fuel or station NFC for closure of the fuel cycle of BREST reactors only), various fast reactor technologies and various types of the fuel used: UOX/MOX or mixed nitride U-Pu [1-4].

The key difference is in different understanding of fast reactors role in NPS fuel cycle closure. This results in varying requirements to fast reactors and the terms of implementation of such requirements. This report focuses on the role of fast sodium reactors as a system-forming component of the future two-component nuclear power system operating within the total fuel cycle with thermal reactors.

1. Introduction
Currently, Russian nuclear society has recognized that further development of Russian nuclear power industry will be carried out under the two-component framework represented with thermal and fast reactors operating within the total closed fuel cycle.

Rosatom’s management set up the task of accelerated application of fuel cycle closure technologies at the industrial trial level and then their practical implementation in demonstration and trial industrial processes.

Several scenarios of the nuclear fuel cycle closure within Russian two-component nuclear power system (NPS) have been currently discussed among the industry specialists. These scenarios are based on various philosophies of the NFC closure (centralized NFC closed by thermal and fast reactors fuel or station NFC for closure of the fuel cycle of BREST reactors only), various fast reactor technologies and various types of the fuel used: UOX/MOX or mixed nitride U-Pu [1-4].

The key difference is in different understanding of fast reactors role in NPS fuel cycle closure. This results in varying requirements to fast reactors and the terms of implementation of such requirements.

This report focuses on the role of fast sodium reactors as a system-forming component of the future two-component nuclear power system operating within the total fuel cycle with thermal reactors.
2. Role of BN reactors in Federal Target Program “Nuclear Power Technologies of New Generation”

Currently, under the Federal Target Program «Nuclear Power Technologies of New Generation» (FTP NPTNG), two types of fast reactors have been developed: BN-1200M commercial reactor of new generation with a sodium coolant, and BREST OD-300 trial and demonstration reactor with a lead coolant. MNUP fuel is used as the basic fuel in both variants. Although, the use of MOX fuel is being reviewed for BN-1200M, at least, at the start-up stage.

Although the sodium technology has been improved and justified for the industrial level, in FTP NPTNG the fast neutron reactor with the lead coolant was determined as more perspective based on the assumption that it will satisfy the perspective requirements to the new nuclear technology. However, to exclude risks associated with exploration of the new technology, FTP NPTNG also provides for the development of the reactor with a sodium coolant of new generation. The prerequisite for implementation of the new fast reactor project is assurance of its commercialization, i.e. serial construction, to do which certain safety and economic efficiency characteristics must be achieved. This condition was detailed in the Technical Requirements of the Proryv Project summing up developments in designing CNFC technologies with fast reactor technologies.

Research and developments performed by this time, including results of the expertise of 2015 and 2017, demonstrate that it is possible to achieve stated objectives under the BN-1200M reactor project. BN-1200M Project is based on utilized production solutions supported, among other, with the successful operation of BN-800 reactor, which was put into operation in 2016. This makes it possible to consider the start of BN-1200M reactors construction in approximately 2028, which is critical for transition to the two-component Nuclear Power System, where fast sodium and thermal reactors operated within the total CNFC [3].

One the alternative variants of the nuclear power industry development is continued exploitation of VVER reactors with potential closure of the fuel cycle by own plutonium in these reactors using MOX fuel or Remix fuel waiting till creation of a commercial fast neutron reactor with a lead coolant. Taking into account the need in elaboration of the new reactor technology using the experimental and demonstration BREST OD-300 reactor, make take place after 2040 only.

As to the use of own plutonium in VVER reactors, it is a well-known fact that this will not solve the nuclear power industry problems, which require closure of the nuclear fuel cycle - efficient use of uranium-238 ad burn out of accumulating RW in the form of minor actinides. Besides, specific features of VVER and BREST reactors will lead to active competing for the use of natural uranium reserves.

3. “BN (MOX) - VVER (UOX and MOX)” Two-Component System

Designers of the BN-1200M believe that the priority task of this direction of the nuclear power industry development will be early inclusion of fast sodium reactors in the existing nuclear power system with the perspective of significant expansion of business in the industry. Assessment performed in the IAEA [5] by leading states’ specialists in the sphere of fast reactors showed that fast sodium reactors passed all stages of the technology development and are sufficiently elaborated to satisfy sustainable development requirements made up by the international society. Russia is the leader in this reactor type development.

Efficiency of sodium fast reactors within the two-component NPS is determined not only with approximation of their economic indicators to the thermal reactors (TR) indicators, but also the ability to solve accumulated problems in the nuclear power industry of the country and the world, which significance will continue to grow. On the other side, the perspective of increasing the TR projected resource to 80 and even 100 years means that they may enter the 22nd century. Moreover, programs aimed at thermal reactors improvement in terms of spectral regulation and achievement of coolant’s super critical parameters, have been currently elaborated.

This results in that fast and thermal reactors are not compared in the two-component NPS [3] under discussion, but reviewed in terms of their synergetic development with minimal process and economic
risks based on single MOX fuel and RW aqueous processing technologies, which demonstrated their working efficiency, and pursuant to the existing requirements of the national legislation and IAEA standards and recommendations. The synergetic interaction results in the important economic effect for sustainable development of this two-component system.

VVER technology, being the first component of the 2-component NPS has been elaborated and is reliable, however, its economic indicators must be improved. Existing and projected VVER will partially or fully use plutonium as fuel produced by fast reactors and will replace 235U.

The basis of the second components of the two-component nuclear power industry may serve improved power units with reactor BN-1200M.

Russia is sufficiently experienced in application of fuel cycle closure technologies and perspective technologies for thermal reactor SNF processing, and BN reactor MOX fuel production and processing. Launch of BN-800 reactor with the use of MOX fuel in it will allow elaborating the MOX fuel processing technology on production scale. At this time there are certain developments regarding mixed nitride fuel, perspective technologies of its processing are being elaborated.

Main advantage of the FN and VVER two-component nuclear power system is the total fuel cycle (UOX and MOX). This NPS is not focused on accelerated replacement of reactors with fast reactors, and the synergy of both components is realized through the following:

- potential significant based on the thermal and fast reactors ratio reduction of natural uranium consumption within the system;
- absence of a strict requirement to Pu isotopic composition in MOX fuel results in the ability to use warehouse Pu (plutonium) from VVER SNF and arms-grade plutonium to launch new BN reactors, thereby solving the problem of VVER SNF conversion to a significantly more compact form of BN SNF;
- it is possible to feed thermal reactors with MOX fuel from BN SNF plutonium (with the commercial effectiveness demonstration!), as well as to use excessive MOX fuel for launching new BN reactors (and BRESTs in the perspective) taking into account expansion of plutonium reproduction in sodium reactors;
- guaranteed provision of the whole package of services and expansion of export capabilities of VVER regarding SNF acceptance from foreign stations and fuel supply thereto throughout the whole life cycle thereof, which has been partially implemented already.
- the non-proliferation regime has been maintained in the course of exportation to non-nuclear countries of thermal reactors only, as this implies exporting fuel services and not fast reactor and radiochemical technologies, which have a potential of plutonium production and extracting;
- there are no risks of launching the small and large series of power units with BN reactors as under any scenario of the nuclear power industry development after 2050 (pessimistic or optimistic) those will be required as either “burying” facilities for nuclear power industry, or fuel and energy drivers ensuring sustainable economy growth.

The ratio between the BN and VVER number under the NPI in question depends on the nuclear power industry development strategy and the type of raw materials it uses.

At the same time, a very illustrative characteristic of the two-component nuclear power system (see figure 1) is the ratio between the number of fast and thermal reactors operating within the steady-state nuclear power system exploiting plutonium, after depletion of cheap natural uranium (in this system the breeding ratio of the plutonium fuel reproduction in thermal and fast reactors equals to 1).

The figure shows that at the existing level of reactor technologies, around 5 BN reactor will be needed to provide one VVER-1200 (MOX) with fuel, therefore, to develop this system, thermal reactors must be modernized with the transition to improved systemic parameters, which will ensure significant improvement of their fuel characteristics, including the isotopic vector of reproduced plutonium.

For perspective VVER-S technologies (BR–0.85-0.9), approximately one FN will be required per two VVER-S.
Fast reactors with BR=1 (option with mixed nitride fuel with no reproducing screens) are inefficient for creation of the two-component system with thermal reactors.

![Graph showing the ratio of VVER-1200 (MOX), VVER-S and BN reactors for steady-state NPS as a function of breeding ratio of BN reactors.](image)

**Figure 1.** Ratio of VVER-1200 (MOX), VVER-S and BN reactors for steady-state NPS as a function of breeding ratio of BN reactors.

4. **Scenario studies of the nuclear power industry development in Russia**

We will review two scenarios of the two-component NPS development. The first one implies development of Russian nuclear power industry by 2100 up to 85 GW (without units export), the second one - up to 170GW (with export). At figure 2 scenarios are marked with a) and b) letters, correspondingly.

According to the planned introduction of NPS facilities in Russia, the head reactor such as BN-1200 is scheduled to be put into operation in 2031, then a series of four reactors is to be commissioned by 2040.

![Graph depicting two-component NPS structure in Russia.](image)

**Figure 2.** Two-component NPS structure in Russia.

In presented NPS structures, at the first stage of NFC closure (before 2035) nuclear power engineering development is based on the Target Road Map [3]. After 2035, the ratio between the thermal and fast reactors being commissioned depends on the plutonium reproduction characteristics and balance in the system, as well as the needs in development. BN reactors with BR=1.5 are put into operation after 2070 to ensure the NPS development growth and production of excessive plutonium.
consumed at VVER-S using MOX fuel. BR ~ 1.5 may be reached with mixed nitride fuel in case of exploitation of the upper edge reproduction area (along with the lower and side ones) with safety confirmation taking into account passive protection system and other solutions.

Main restrictive factors of the power system in question are as follows:
- fuel resources (uranium, plutonium produced in reactors and arms-grade plutonium, which can be used in peaceful purposes);
- reactor technologies (thermal and fast neutron reactors);
- support infrastructure (fuel production and processing plants, SNF and radioactive wastes storage facilities).

Main characteristics of the system components are technical and economic indicators.

The design model includes all necessary components of the NFC energy process stages: conversion, enrichment, fuel production, fuel irradiation in a reactor, cooling and temporary storage of spent fuel, spent fuel processing, storage of products generated after processing.

The model allows for analyzing nuclear materials flows and carrying out the mathematical analysis and optimization of the NPS structure. The model implies repeated use of plutonium excreted from thermal reactor fuel.

Scenarios consider the following reactor types of Russian design:
- RBMK; VVER-440, VVER-1000; VVER-TOI, VVER-S (improved VVER);
- BN-800, BN-1200(1,2), BN-1200(1,5) (fast sodium reactors with BR=1.2 and 1.5 correspondingly).

Thermal reactors (RBMK, VVER-440, VVER-1000, VVER-TOI) consume UOX fuel, and fast reactors and VVER-S consume MOX fuel.

Plutonium extracted from SNF of VVER-440, VVER-1000, VVER-TOI, VVER-S is repeatedly used for production of MOX fuel.

Calculations were performed with the use of code CYCLE [6] with the following model assumptions:
- production losses are taken into account;
- the forecast interval is limited with the interval of 2010—2100’;
- simulation increment is 1 year;
- accepted uranium resources amount to 700 kt and are distributed by cost categories [7].
- in this study, plutonium (not uranium) is the fuel resource for fast reactors. Today 56 tons of extracted plutonium are placed at the storage area.

Consumption of natural uranium by 2100 under the scenario with achievement of the NPS capacity of 85 GW amounts to 390 kt (figure 3a), under the export scenario ~700 kt (figure 3b).

![Figure 3. Consumption of natural uranium under two NPS development scenarios, tons.](image-url)
Figure 3 a) shows that under (a) scenario around ~300 kt of natural uranium remain, under b) scenario, the nuclear power industry after 2100 may be developed only with the use of fast and improved thermal reactors without application of natural uranium.

SNF handling infrastructure development by 2030: plant RT1, commissioning of PDF (250 t SNF/year - 2021, 400 t SNF/year - 2025).

SNF processing facilities after 2030 will be put into operation based on the needs occurring in the system, provided that plutonium operation reserve is maintained at the required level. Annual SNF processing facilities loads by 2100 for scenarios a) and b) are 800 and 1200 t SNF/year, correspondingly.

At figure 4 integral volumes of Russian SNF in storage areas for scenarios a) and b) correspondingly are shown.

Both scenarios dispose of reserves of domestic SNF produced as shown at figure 4. However, it should be noted that under scenario (a) SNF will be completely liquidated by 2095, and in case of accelerated power industry development (scenario b) SNF (including SNF of RBMK-1000) processing will be completed by ~2050.

![Figure 4. SNF amount in storage areas, t.](image1)

![Figure 5. Plutonium balance at the warehouse, t.](image2)

Figure 5 shows the balance of plutonium at warehouses for both scenarios. It is obvious that plutonium balance at the warehouse for both scenarios is at the operating level.
Analysis of calculation results shows that serial construction of BN-1200M reactors from 2028 at the average introduction rate of one reactor per two years will by 2040 make it possible to exploit in the nuclear power fuel cycle around 80 t of plutonium, dispose of ~8800 tons of SNF and reduce annual consumption of uranium approximately by 20% per 1 GW of the established capacity.

5. Two-components system with fast reactors such as BN and BREST type
In the long-perspective, if BREST demonstrates its economic advantages, one more variant of two (or even three)-component nuclear power system comprising two types of fast reactors with various breeding ratios, in which BN with BR >1 provide resources for system development and BREST reactors with BR~1 produce cheaper electricity, is possible. In such system BRESTS will gradually replace VVERs due to better economic and safety features and under the competition for natural uranium resources. However, by the end of the century, the limited fleet of thermal reactors is still possible. Preferable fuel in the fast reactor system is dense: nitride or metal.

The work [8] provides for the example of the development of the fast (BN and BREST) and thermal reactors (VVER, VVER-TOI) system, where capital expenses of BNs are higher by 10%, and that of BRESTs by 10% lower. figure 6 from this work shows that in this case the «fast» component of nuclear power system will be divided in the fuel-supply (BN-1200) and electricity generation (BREST-1200) sub-components, where both exist as equal companions. BNs in this system preserve their functional role of the NPS fuel base and producers of start-up fuel for BRESTs.

6. Conclusions
At this time, fast sodium reactors have passed all stages of the technology developments and have been elaborated to the extent sufficient to satisfy the sustainable nuclear power development requirements of the international society.

Main advantage of the BN and VVER two-component nuclear power system is the total closed fuel cycle (UOX and MOX).
Nuclear power industry development scenarios reviewed with fast sodium and thermal reactors make it possible to provide a solution of all deferred problems by as soon as 2100 with no accelerated launch of fast reactors such as BREST on uranium with the guaranteed fulfilment of all export obligations of Russia.

Serial construction of BN-1200M reactors from 2028 at the average introduction rate of one reactor per two years will by 2040 make it possible to exploit in the nuclear power fuel cycle around 80 t of plutonium, dispose of ~8800 tons of SNF and reduce annual consumption of uranium approximately by 20% per 1 GW of the established capacity.

Further transition to SNF processing out-loaded from BN-1200M reactors and use of plutonium in VVER reactors make it possible to develop the two-component nuclear power system with the minimum consumption of natural uranium. Here, in the far perspective, new technical solutions might be applied in order to improve the fuel reproduction ratio (up to 1.5), which in BN-1200M reactors is currently estimated at the level of 1.2 for MOX fuel and 1.3 for mixed nitride fuel.

Following the completion of the experimental trial exploitation and demonstration of natural safety characteristics and commercial efficacy, fast neutron reactors with a lead coolant can be introduced in the nuclear and power system, which does not exclude further development of two fast reactor types development and their existence as equal companions within the two-component nuclear power system.

References
[1] Adamov E O, Dzhalavyan A V, Lopatkin A V 2012 Concept Provisions of the Nuclear Power Industry Development in Russia till 2100 Atomnaya Energiya 112 issue 6 pp 319-331
[2] Adamov E O 2018 Role of Fast Neutron Reactors in the NPS Development Strategy in Russia 11th International Scientific and Technical Conference MNTK-2018 report subjects
[3] Alexeev P N et al 2016 The Two-Component Nuclear Power System with Thermal and Fast Reactors within the Closed Nuclear Fuel Cycle ed Ponomarev-Stepnoy N N (Moscow: Technosfera)
[4] Gulevich A V, Klinov D A, Bakanov M V, Troyanov V M 2018 The Two-Component Nuclear Power System with the Closed Fuel Cycle and Role of Thermal and Fast Neutron Reactors 11th International Scientific and Technical Conference MNTK-2018, report subjects.
[5] 2012 Assessment of Nuclear Energy Systems based on a Closed Nuclear Fuel Cycle with Fast Reactors (Vienna: IAEA) IAEA-TECDOC-1639/Rev.1 p 61
[6] Kalashnikov A G, Moseev A L, Dekusar V M, Korobeynikov V V, Moseev P A 2016 Development of CYCLE Software System for the Systemic Analysis of Nuclear Fuel Cycle Bulletin of Higher Educational Institutions. Nuclear Power Engineering 1 pp 91-99
[7] 2016 Uranium 2016: Resources, Production and Demand A Joint Report by the NEA and IAEA, NEA No. 7301, (NEA OECD)
[8] Andriyanov A A et. Al 2018 Optimization Models of the Two-Component Nuclear Power System with Thermal and Fast Reactors within the CNFC Bulletin of Higher Educational Institutions. Nuclear Power Engineering 3