# TWO-COMPONENT ENERGY INDUSTRY UNDER CONDITIONS OF CLOSED NUCLEAR FUEL CYCLE: ECONOMIC BENEFITS

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**Abstract**

Transition to the system of the closed nuclear fuel cycle based on reactors on thermal and fast neutrons is an important stage of formation of two-component energy industry, which provides enhancement of efficiency of uranium resource efficiency. The closed nuclear fuel cycle at the international level can be presented both from the viewpoint of energy security and stability and from the viewpoint of increase of competitiveness of nuclear power solutions. However, countries-owners of fast reactor technologies use different strategies of transfer to the closed fuel cycle. By the example of fast sodium-cooled reactors and VVER/PWR, the paper considers economic expediency of implementation of the closed fuel cycle for the purpose to provide stable ecologically clean energy. The paper presents approaches to estimation of commercial advantages of commercial fast reactor application both within energetic system and in the international context, reveal drivers and limitations of commercialization from viewpoint of economic parameters over the medium term.

## INTRODUCTION

In 2003 the Generation IV International Forum (GIF) representing ten countries announced the selection of six reactor technologies which they believe represent the future of nuclear energy. These were selected on the basis of being clean, safe and cost-effective means of meeting increased energy demands on a sustainable basis, while being resistant to diversion of materials for weapons proliferation and secure from terrorist attacks. They will be the subject of further development internationally. [1]

The selected GIF technologies mainly use a closed fuel cycle to maximize the resource potential and minimize nuclear waste sent to storage facilities. Three of the six selected technologies are fast-neutron reactors with different coolants: lead, lead-bismuth and sodium. [1]

It is important to note that the IAEA coordinates a programme with similarities to GIF objectives, the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). The Project Working Group was established in 2001 and has 22 member countries, including Russia, aiming «to support the safe, sustainable, economic and proliferation-resistant use of nuclear technology to meet the global energy needs of the 21st century». [1] The set goals are accomplished by examining issues related to the development and implementation of innovative nuclear energy systems for sustainable energy supply. As part of INPRO's work, a methodology has been developed to research and assess scenarios of transition to sustainable nuclear energy systems. The sustainability of the BN-1200 based nuclear energy system is currently being assessed in the area of economics and safety of nuclear installations using the INPRO’s methodology.

ROSATOM's management has now adopted a concept for the development of two-component nuclear industry in Russia in the 21st century based on joint operation of thermal and fast-neutron reactors. [2] This concept, in particular, assumes that with intensive development of the nuclear industry, fast reactors will be capable of providing fuel for thermal reactors, and plutonium separated from the VVER spent fuel will be used to fabricate mixed uranium-plutonium fuel for sodium-cooled fast reactors. In this case, the VVER spent fuel storage facilities will be emptied, and the plutonium separated from the spent fuel will be applied as the basis for fast reactor fuel and ultimately for the two-component system as a whole. A similar strategy was evaluated by the French company EDF based on its R&D results intended for the development of a fuel cycle simulation code in 2012. [3]

The transition to the closed nuclear fuel cycle system based on the thermal and fast-neutron reactors is an important stage of establishing the two-component nuclear industry aimed at enhancing the efficient use of uranium resources. The closed nuclear fuel cycle at the international level is of interest both in terms of energy security and sustainability, as well as in terms of enhancing the competitiveness of nuclear power solutions and the efficiency of nuclear fuel use.

Successful mastering and demonstration of sodium-cooled fast reactor technology and of the corresponding closed nuclear fuel cycle technologies at the commercial level contributes to providing the foreign customers with improved VVER reactors and to commercializing power units with fast reactors.

The paper is aimed at determining the business advantages of using commercial fast reactors under different commercialization scenarios, as well as identifying the drivers and barriers to commercialization of fast reactor technology in terms of economic parameters in the mid-term.

For this purpose, the paper addresses the following topics:

* description of the BN technology assimilation level in Russia;
* options of the BN technology commercialization at the international market;
* analysis of economic aspects of fast reactor technology and options for improving the competitiveness;
* options for potential cooperation of world leaders in fast reactor development.

## DESCRIPTION OF THE BN TECHNOLOGY ASSIMILATION LEVEL IN RUSSIA

Today an absolute majority of power units under construction worldwide are light-water thermal reactors . When expanding the nuclear fleet the customers are interested in increasing the competitiveness of power units in terms of capital and operating costs taking into account spent fuel and radioactive waste management. It appears that optimization of spent fuel and radioactive waste management can become one of the areas to improve the competitiveness of fast reactors in terms of economy compared to technologies like, for example, pressurized water reactors.

It should also be taken into account that an increase in nuclear capacity in the future will inevitably lead to an increase in the cost of natural uranium and will require increased efficiency of uranium burn-up.

Under these conditions, the two-component system becomes increasingly attractive owing to the fact that the plutonium and minor actinides separated during light-water reactors spent nuclear fuel reprocessing are sent to a fast reactor for burning.

As part of a two-component system, a fast reactor addresses a number of issues:

* electric power generation;
* production of nuclear material for fuel fabrication, including fuel for self-supply and for VVER/PWR;
* transmutation of minor actinides which do not leave the fuel cycle in the given system.

Russia has reference experience in the development and operation of fast-neutron reactors: BN-600 has been in commercial operation for more than 30 years, the power start-up of BN-800 took place in 2015. In January 2020, the first 18 commercial-scale fuel assemblies with uranium-plutonium fuel were loaded into BN-800 in power unit No. 4 at Beloyarsk NPP; and in February 2021, another 160 fuel assemblies were loaded. Thus, the one-third of the BN-800 core is now loaded with innovative fuel. From now on, only uranium-plutonium fuel will be loaded into the reactor, which makes it possible to take another step closer to implementing the strategy in nuclear industry development aimed at establishing a new technological platform based on the closed nuclear fuel cycle. The use of uranium-plutonium fuel will make it possible to involve the uranium-238 isotope, which is not currently used, in production, i.e. it will increase tenfold the nuclear industry fuel potential. In addition, the BN-800 reactor can reuse spent nuclear fuel from other nuclear power plants and minimize radioactive waste by “burning out” long-lived isotopes present in them. [4]

JSC “Afrikantov OKBM” is the chief designer of BN-type reactors. In 2014, JSC “Afrikantov OKBM” developed the basic design of the BN-1200 reactor, as well as the basic design of the turbine unit and the key materials of the power unit design. Currently, the design upgrading activities are underway.

Thus, as for today, ROSATOM has the BN-800 reactor, a reference commercial product, and the BN-1200 reactor design with new technical solutions which have been experimentally justified. In view of the fact that a number of foreign countries are interested in BN reactors, the fast reactor commercialization capabilities in the international market shall be analyzed.

## OPTIONS OF THE BN TECHNOLOGY COMMERCIALIZATION AT THE INTERNATIONAL MARKET

As described above, it can be claimed that the basis for developing nuclear industry is fast reactors with expanded breeding ratio in a closed fuel cycle which use plutonium as fissile material, among other ones. When implementing fast reactor designs, it seems possible to consider several export scenarios.

Similar to the export of thermal neutron reactors, the construction of nuclear power plants based on fast reactors abroad can be considered as a base scenario. Of course, the market for this commercialization scenario is limited to a narrow range of countries due to the high requirements for the competencies of the operating personnel and nonproliferation requirements, and the market is essentially limited to the Treaty on the Non-Proliferation of Nuclear Weapons member states.

The business relations on fast reactor technology can also include delivery of individual equipment, rendering of services related to operation, expert review, and personnel training. However, this market is also extremely limited, since the cooperation participants can be countries that have their own fast reactor technologies or a long-term programme for the development of fast reactor technologies aimed at closing the nuclear fuel cycle.

The BN unique characteristics contribute to alternative business solutions associated with spent fuel reprocessing.

In particular, a possible option for the BN technology commercialization would be rendering of spent fuel reprocessing services in a BN reactor. This will significantly expand the market, and offer the possibility, for example, of taking the spent fuel from newcomer countries which do not have their own infrastructure for the spent fuel storage or reprocessing. This would relieve newcomer countries of the high capital costs associated with construction of the relevant infrastructure.

Apart from that, most of the countries that use thermal-neutron reactors in the open nuclear fuel cycle defer the final solution to the back-end stage problems to a distant future. The spent fuel reprocessing and waste compacting under acceptable economic conditions would be an attractive option for them.

The competencies in the following areas or associated costs will be required to support the spent fuel reprocessing business:

* establishing an uranium-plutonium fuel production;
* constructing a VVER/PWR uranium fuel reprocessing plant;
* developing additional volume of R&D;
* construction costs of power units with fast reactors.

TABLE 1. BUSINESS DEVELOPMENT OPTIONS IN THE INTERNATIONAL ARENA FOR THE IMPLEMENTATION OF A TWO-COMPONENT NUCLEAR ENERGY SYSTEM (BN/ VVER-BASED CLOSED NUCLEAR FUEL CYCLE)

|  |  |
| --- | --- |
| Business Options | Products |
| Turnkey construction of power units abroad | Constructed power unit, fuel supply, spent nuclear fuel return, using a spent fuel as BN fuel |
| Production of uranium fuel | Uranium fuel (including enrichment) |
| Production of uranium-plutonium fuel | uranium-plutonium fuel for VVER/PWR |
| Reprocessing of “foreign” spent fuel | Spent fuel reprocessing services |

The necessary condition for transition to a balanced two-component nuclear energy system is a demonstrative verification of the declared technological and economic characteristics of the BN reactor and nuclear fuel cycle facilities.

Using the new opportunities which are viable only in case of a two-component nuclear power system implementation with a closed nuclear fuel cycle, the product package offered by ROSATOM to the international market can be expanded by a set of services, including: storage and reprocessing of spent fuel of foreign NPPs and uranium-plutonium fuel production, as well as a comprehensive service including fuel “leasing”, the return of spent fuel and further use of spent fuel in fresh fuel fabrication for the BN reactors.

At the same time spent fuel reprocessing is interesting not only to foreign, but also to domestic market. The annual rate of spent fuel return to Russia from foreign NPPs of Russian design under the relevant contracts may be from 500 to 1000 tonnes per year. [5] Under these conditions, spent fuel reprocessing in the framework of a two-component nuclear energy system will:

* reduce the costs of spent fuel handling and storage;
* decrease the dependence on stockpile reduction and increase of uranium cost using unlimited potential of waste and natural uranium in the fuel cycle of thermal and BN reactors;
* reduce radioactive waste management costs by significant reduction in their activity and volumes by burning the long-lived minor actinides in the BN reactor;
* reduce the environmental burden.

It is already today that measures shall be taken to resolve the problems related to spent fuel transportation from foreign NPPs and spent fuel acceptance in Russia through planning, development and construction of new facilities in Russia intended for process storage and reprocessing of such spent fuel. Nowadays Russian proposals on the construction of nuclear power plants abroad in many cases include fresh fuel provision to these nuclear power plants with the spent fuel return to Russia.

## ANALYSIS OF ECONOMIC ASPECTS OF FAST REACTOR TECHNOLOGY AND OPTIONS FOR IMPROVING THE COMPETITIVENESS

“Russian Nuclear Power Development Strategy till 2050 and prospects up to 2100” [6] declares that economic characteristics of the BN-1200 reactor unit will be close to those of a VVER reactor, while the BN-1200 design can be 15% cheaper than that of a VVER reactor. The activities aimed at justification and optimization of technical and economic characteristics of a power unit design with BN-1200 reactors is currently underway.

As for the technical characteristics of the BN-1200 reactor plant, the following should be noted. The reactor plant generates 2868 MW of heat and 1250 MW of electrical power. The service life of the main equipment is 60 years. Breeding factor is 1.2. New technical solutions lead, among other things, to positive dynamics of changes in technical and economic parameters of the reactor plant and of the balance-of-plant equipment.

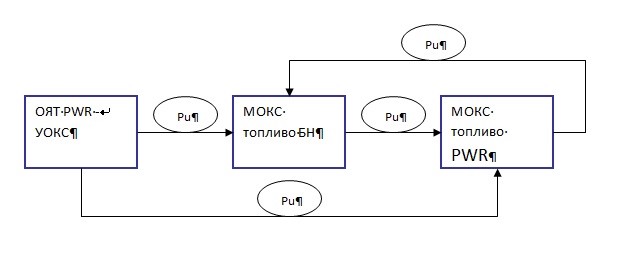
In calculations, in order to make them generalized for the Russian and international markets, the characteristics of PWR units are taken into account. Speaking of pressurized water reactors, we can focus on the French experience, which consist in implementing thermal reactor in nuclear energy system with a single-phase plutonium recycling. The nuclear energy system includes two types of PWR reactors: with UOX fuel loaded into the core with partial loading of uranium-plutonium fuel. There are no BN reactors in this system, the spent UOX fuel is reprocessed and the separated plutonium is used in fabrication of fresh uranium-plutonium fuel, while the spent uranium-plutonium fuel is not reprocessed. Such a scheme imposes restrictions on the ratio of reactors determined based on the condition that the amount of plutonium separated from fuel assemblies with UOX fuel is equal to the amount of plutonium in fuel assemblies with uranium-plutonium fuel. The advantage of such a scheme is the reduced amount of accumulated spent fuel (by approximately 10-20%), but the economic characteristics deteriorate due to the growth of the fuel component (LCOE is increased by approximately 9% (an expert assessment)).

To improve the competitiveness of power units with BN-1200 reactor in the business structure, it is proposed to consider a nuclear energy system consisting of PWR reactors with partial loading of uranium-plutonium fuel and BN-1200 fast reactors with complete loading of uranium-plutonium fuel (the breeding ratio varies from 1 to 1.2).

The uranium-plutonium fuel of the both types of reactors is reprocessed. The PWR spent UOX fuel is reprocessed and the separated Pu is used for fabrication of:

* fresh uranium-plutonium fuel for BN-1200;
* fresh uranium-plutonium fuel for PWR.

The plutonium separated from the BN fuel is used to make fresh uranium-plutonium fuel for PWR reactors. The plutonium separated from PWR uranium-plutonium fuel is used to make fresh uranium-plutonium fuel for BN reactors. The Schematic of the scenario under consideration is shown in Figure 1.



**PWR   
uranium-plutonium fuel**

**BN   
 uranium-plutonium fuel**

**PWR   
 UOX fuel**

*Figure 1 Schematic diagram of using Pu separated from spent fuel produced by PWR operating with UOX and URANIUM-PLUTONIUM fuel and by BN operating with URANIUM-PLUTONIUM fuel*

The role of fast reactors in a two-component nuclear energy system is extremely important: they increase the breeding ratio in the system and “correct” the isotopic composition of the plutonium that has passed through the thermal reactors in the fuel. An unlimited number of fuel recycles is possible in fast reactors; this is because their plutonium isotope composition always seeks a certain equilibrium ratio. This ratio (balance) can be maintained by using 11 PWRs and 2 BN-type units and increasing them by multiplication. The two BN-type units will be able to consume the entire energy-grade plutonium separated from the spent fuel of 11 PWR units (with uranium-plutonium fuel loading of approximately 1/3), transforming it into effective feedstock of plutonium when reprocessing the BN spent fuel to be used as part of uranium-plutonium fuel for PWR.

If we consider the Levelized Cost of Electricity (LCOE) as the key economic indicator, then the calculation for the system with closed NFC can be written as follows:

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*EQUATION 1 CALCULATION FOR THE SYSTEM WITH CLOSED NFC*

where the profit from the closed nuclear fuel cycle PWR (fuel) =

= annual costs for maintaining the system without closed nuclear fuel cycle – annual costs for the system with closed nuclear fuel cycle (in terms of fuel).

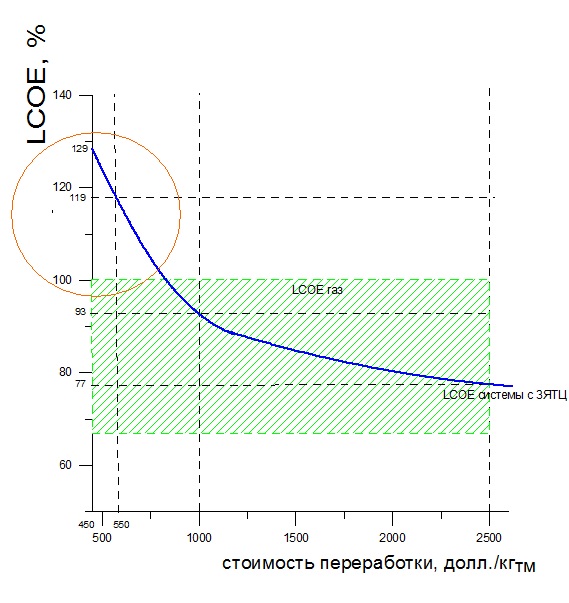
LCOE of BN in the two-component power industry, taking into account PWR spent fuel reprocessing (at the world price of $1000/kgof heavy metals) and sales of uranium-plutonium fuel for PWR at a price 2 times lower than the world market price of UOX fuel, is improved up to 30% as compared with LCOE in the one-component system, implying power generation and self-sufficiency in fuel. As the reprocessing price increases, it appears that theoretically the economic characteristics, including the additional net income, will increase exponentially. It should be noted that in simplified calculation, arithmetically this dependence will be linear, but the cost of spent fuel reprocessing depends on the demand and supply, and is regulated by market mechanisms, among others. Thus, while recognizing the absolute importance of solving the environmental problem of spent fuel disposal on a long-term horizon, the NPP-operators shall ensure profitability of business taking into account spent fuel reprocessing. Similar processes of searching for a balanced cost of reprocessing are now taking place in the market of household waste recycling, where the trend is to include the cost of recycling into the cost of the final product.

A more correct estimate of annual income requires calculations in a dynamic model, taking into account, in particular, the natural uranium-saving effect and UOX fuel enrichment services. Spent fuel reprocessing within a two-component nuclear energy system contributes to reducing dependence on stockpile reductions and increased uranium cost by utilizing the unlimited potential of waste and natural uranium within the BN and PWR fuel cycles.

The additional revenue provides freedom of market maneuver to meet the demands of electricity consumers (reduced tariff), as well as the requirements of the investor (reduced payback period in relation to BN units compared to alternative power units).

The economic indicators of an NPP with the BN-1200 reactor has advantages over the alternative power units, including gas-fired generation, over the entire range of additional revenue use ($450-2500 $/kgof heavy metals) while recovering the costs of spent fuel handling and energy-grade plutonium separation.

**LCOE of closed NFC system**



**Cost of reprocessing, $/kgof heavy metals**

**LCOE of closed NFC system**

**Gas LCOE**

*Figure 2 Change in LCOE as a function of Spent fuel reprocessing costs*

An integrated marketing proposal related to the back end of the nuclear fuel cycle, with the construction of a BN on the territory of a nuclear-weapon partner country, while the spent fuel reprocessing proposal extended to all countries, is unique and makes it possible to significantly expand the market for the technology commercialization.

## OPTIONS for potential cooperation of world leaders in fast reactor development

In view of the global nature of the spent fuel reprocessing problem, the reprocessing market could be forcibly formed upon emergence of international initiative similar to the Kyoto Protocol. Particularly the market-based principles of the 1997 Kyoto Protocol, which is a complement to the 1992 UN Framework Convention on Climate Change, may be adopted as a mechanism to implement international arrangements for spent nuclear fuel reprocessing: Cooperating member countries would set targets for spent nuclear fuel reprocessing for the medium and long term. Achievement of the targets will be monitored by designated collective bodies or by the IAEA. Such an initiative would provide a solution to the global problem of spent nuclear fuel in the long term while significantly reducing the risks of nuclear proliferation.

Most countries actively developing and using nuclear power have already accumulated a large amount of spent fuel, including, according to data for 2020, the Russian Federation, which has more than 23 thousand tonnes of spent fuel, the United States have more than 100 thousand tonnes of spent fuel, France has more than 54 thousand tonnes of spent fuel, Japan has more than 21 thousand tonnes of spent fuel, the Republic of Korea has more than 24 thousand tonnes of spent fuel, the UK has more than 12 thousand tons of spent fuel, China has more than 11 thousand tonnes of spent fuel. At the end of 2016, the amount of spent fuel in the world was 260,000 tonnes; as of September 2020, about 400,000 tonnes of spent fuel had been unloaded from commercial power reactors, of which about 30% was reprocessed. [7] Reprocessing of such amount of spent fuel would require the commissioning of a significant number of fast reactors. If we consider the technologies developed as part of the BN-1200 project, up to 40 BN units will be needed worldwide to reprocess the accumulated spent fuel by 2100. It must be taken into account that reprocessing of large volumes of spent fuel is a multi-year process. A nuclear power plant with the BN-1200 reactor unit will be able to reprocess about 13 thousand tonnes of spent fuel in 60 years, not counting the start-up load.

While nuclear-weapon states can solve the problems associated with the reprocessing and storage of spent fuel, due to the availability of appropriate nuclear infrastructure, non-nuclear-weapon states face certain financial and technological difficulties in solving this problem, and are forced to focus on the strategy of long-term disposal.

In this regard, it is worth considering the following commercialization scenario, which is alternative to the approaches taken in the commercialization of thermal neutron reactors. Countries that possess fast neutron technology may provide spent nuclear fuel reprocessing services to countries that do not possess the appropriate technology. In this case fast reactors and reprocessing facilities will be located on the territories of states possessing nuclear weapons, and export of the technology itself will be limited to the product of fast reactor operation and production facilities, namely fresh nuclear fuel for thermal neutron reactors.

Diversification of storage facilities, including their construction in each country possessing a nuclear reactor, is not possible. Creation of international repositories, the use of which is possible under an intergovernmental agreement, is a temporary solution, since without spent fuel reprocessing the fast filling of these repositories seems most likely. In this regard, the use of fast reactors for reprocessing spent fuel and other types of nuclear material seems relevant nowadays.

Several countries have research and development programs for advanced fast reactors. In France, for example, there is a scenario in which half of the current nuclear capacity will be replaced by fast reactors by 2050 (the first half will be replaced by EPR units). [8]

Currently, the main goal of fast reactor programs is to the closed nuclear fuel cycle to ensure national interests by securing fuel and energy independence. The development of the fast reactor programs is mainly carried out by the countries themselves. International cooperation is carried out only with regard to certain equipment and solutions.

Having fast reactors and uranium-plutonium fuel technologies, it is possible to cooperate in the plutonium “enriching” area, i.e. improving its isotopic composition and reducing the share of fertile isotopes to a level that allows reusing this plutonium in thermal reactors. This will facilitate the transition to a new stage in the development of the global nuclear industry – the formation of its two-component structure, which is based on the synergistic merge of Russian BN technologies with European uranium-plutonium-fuel technologies. [9]

In solving the issue of closing the nuclear fuel cycle within one country, we come to the initiative of centralized reprocessing of spent fuel by involving as many countries as possible. The best possible solution in terms of maintaining the non-proliferation regime seems to be the creation of international centers for spent fuel reprocessing (fast reactors and closed nuclear fuel cycle facilities) on the territory of the country that possesses nuclear weapons. To achieve the required scale of business and create a market for consumers of closed nuclear fuel cycle products and render closed nuclear fuel cycle services, an appropriate international support is required to promote this initiative. Incentives at the national level to use the service of reprocessing spent fuel abroad and obtaining fresh nuclear fuel fabricated based on spent fuel contributes to speeding up the implementation of this international initiative and solving the problem of spent nuclear fuel at large.

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