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Research Article

System features of fast sodium reactors in a two-component structure of nuclear power generating*

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Abstract

The stepwise conversion of Russian nuclear power industry to a two-component nuclear energy system (NES) with thermal and fast reactors in a single closed NFC allows a number of deferred system problems of modern power industry to be solved, such as accumulation of spent fuel from thermal reactors and spent fuel repatriated from foreign Russian-designed NPPs; inefficient use of highly limited raw uranium inventories; recycling of minor actinides and other long-lived high-level waste accumulated in the course of thermal reactors' operation. The paper examines the fundamental capabilities of two-component NES, which appear due to the availability of commercial fast neutron sodium reactors. Due to the synergistic development of thermal and fast reactors, it is expected to achieve an economic effect associated with introduction of new fuel services in the nuclear energy system, such as production of plutonium and improvement of its isotopic composition for thermal reactors, transmutation of "external" minor actinides, production of isotopes for various purposes, production of hydrogen, etc. The expansion of Russia's export opportunities is also being considered, it can be done through fuel supply for both power units built in compliance with Russian technologies and foreign power units with MOX fuel. In this approach, it is important to analyze the economy of the whole system, where fast reactors, due to their inherent surplus of neutrons, perform the functions required to the entire NES, rather than to analyze the technical and economic indicators of individual reactors. The article makes a preliminary technical and economic assessment of such system functions provided by fast sodium reactors. It is shown that fast and thermal reactors operating together in a two-component nuclear energy system, with the same electrical power and similar technical and economic indicators, can significantly reduce the necessary infrastructure costs and/or generate additional income, thereby reducing the specific levelized cost of electricity production.

Keywords

two-component nuclear energy system (NES), spent nuclear fuel (SNF), nuclear fuel cycle (NFC) closure, technical and economic assessment, additional opportunities, levelized cost of electricity production

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Capabilities of two-component nuclear energy system in addressing pending issues of the preceding stage

The basis for Russia's current nuclear energy system is formed by thermal reactors operating in an open nuclear fuel cycle (NFC). Nuclear and radiation safety of the NPPs in operation is ensured by design and engineering solutions and a vast operating experience. The solution of radiation and environmental safety issues and issues concerning high-level waste concentrated in spent nuclear fuel (SNF) has been postponed until fast reactors are introduced into the system. Until then, safety of high-level waste management is ensured by the technical requirements for SNF storage, first, on-site and then in centralized storage facilities.

In Russia, the conversion to a two-component nuclear energy system with thermal and fast reactors and a closed NFC is the strategic goal of Rosatom State Corporation for the coming decades (Alekseev et al. 2016, 2018, 2019, 2022; The White Paper of Nuclear Energy 2020; Zrodnikov et al. 2020). In this connection, the focus is currently on closing the fuel cycle based on thermal and fast reactors to form a single fuel cycle at a pilot commercial level. Apart from electricity generation, such a two-component system will make it possible to address the following system issues of Russia's nuclear power (Alekseev et al. 2016, 2018, 2022; Zrodnikov et al. 2020):

- accumulation of thermal reactor SNF;
- accumulation of SNF repatriated from foreign Russian-designed NPPs;
- inefficient use of highly limited raw uranium resources;
- accumulation of minor actinides and other long-lived high-level waste in SNF as a result of the thermal reactor operation.

Besides, switching over to a two-component structure will allow implementing large-scale innovative technological and commercial projects, such as:

- to provide long-term and reliable fuel supply for nuclear power via conversion from uranium fuel to MOX fuel;
- to implement multiple recycling of plutonium in a two-component nuclear energy system;
- to optimize the plutonium reserves in the global nuclear energy system with thermal and fast reactors;
- to extend the exporting capabilities of Rosatom State Corporation by providing foreign customers with the fuel cycle backend services (improvement of the plutonium isotope vector, burnup of minor actinides, etc.);
- to produce medical, industrial and energy isotopes, including ^{60}Co and ^{238}Pu;
- to participate in commercial production of hydrogen, etc.

Depending on their functions, fast reactors can be divided into a number of groups as it was done in Camarcat et al. 2011 for fast reactors designed for electricity generation, on the one hand, and for reactors designed for minor actinide burnup, on the other hand. In addition to these reactor types, Russia's nuclear energy system is expected to include special-purpose fast reactors for fuel breeding for fast and thermal reactors, reactors for improving ("refining") the isotopic composition of plutonium from thermal reactors (Eliseev et al. 2020; Klinov et al. 2020), reactors for production of different isotopes both in the reactor core and in blankets, and others. The designs of the above reactor types may differ in view of the specific nature of the issues addressed and respective technical requirements for fuel, the reactor core and the fuel infrastructure. It proves to be problematic in some cases to combine the above functions in a single core.

At the present time, only series-built high-power fast sodium reactors (Poplavskii et al. 2010; Alekseev et al. 2018), which along with electricity generation are capable of closing the fuel cycle together with thermal reactors, and resolving the issues in hand, can be viewed as the technology framework for such a multi-functional component of the evolving nuclear power. It should be noted that such qualities of fast sodium reactors (specifically with MOX fuel) result from their capability for nuclear fuel breeding based on plutonium of any isotopic composition used in nuclear power, in the absence of redundant reactivity margin constraints.

A synergistic interaction of two components based on thermal and fast reactors, when these reactors are partners rather than competitors, will make it possible for the system to evolve more efficiently and dynamically than the current nuclear power. By way of example, Fig. 1 shows the structure of capacities in one of the two-component NES evolution scenarios under consideration. Fig. 2 shows how a potential "refining" mission is addressed in an NFC where plutonium from all the reactors goes to the centralized warehouse after its recovery.

The efficiency of systems (Zrodnikov et al. 2020) rather than that of individual power units should be compared when the evolution scenarios are justified. This requires consideration of not only economic criteria but also the infrastructural objectives of the industry and the country, which can be achieved by a two-component energy system compared to a single-component system. The relevant solutions for infrastructure-level objectives need to be evaluated and expressed in material and cost indicators.

For example, reprocessing of spent nuclear fuel is expected to become cost effective only if its amount is sufficient for a high-capacity reprocessing facility. In this case, the entire amount of thermal reactor plutonium must be "passed through" fast reactors in advance (Tuzov et al. 2022). Short supply of plutonium for the intensively developing two-component nuclear energy system may

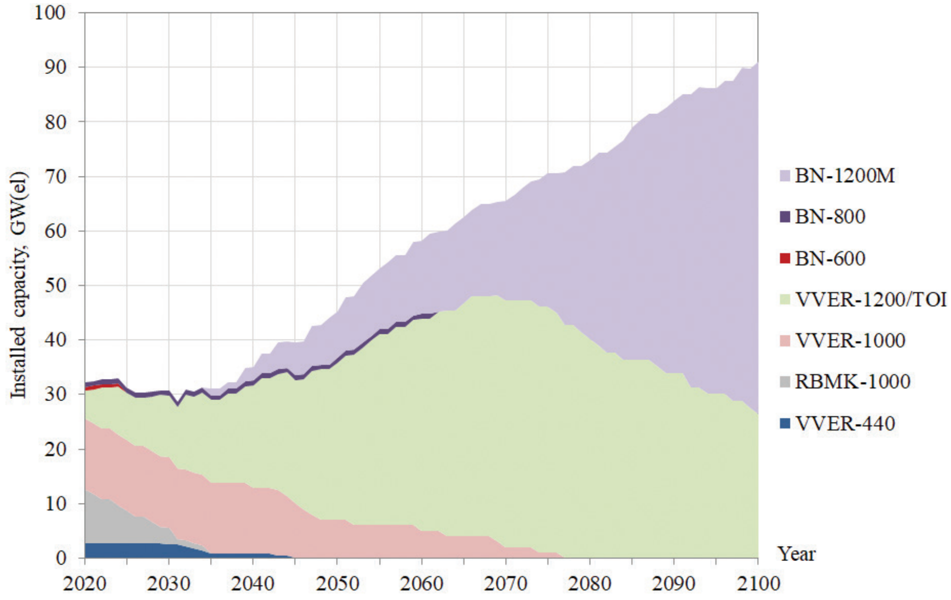

Figure 1. The structure of capacities in a two-component scenario with thermal and fast reactors.

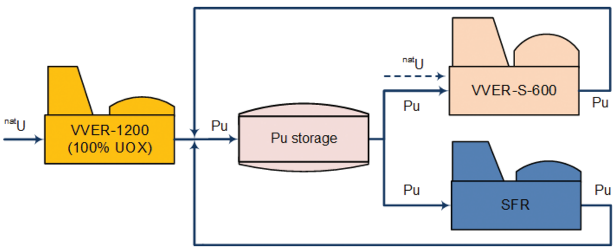

Figure 2. NFC arrangement based on multiple plutonium recycling in thermal and fast reactors (UOX – uranium oxide fuel, SFR – sodium fast reactor).

become another criterion to select the time to start the fast reactor SNF reprocessing. Fig. 3 shows the demand for the BN-800 and BN-1200M SNF reprocessing, provided that there is an adequate fuel supply in the scenario considered.

The graph takes into account 61 tons of plutonium already extracted before the 2020s, as well as the requirement to minimize its warehouse stock. It can be seen from Fig. 3 that the need for the fast reactor SNF reprocessing in the scenario under consideration arises after 2055.

Another issue to deal with here concerns the availability of lateral breeding blanket in a commercial fast reactor. Such a blanket makes it possible to produce plutonium with a low content of highest number isotopes, improve the isotopic composition of plutonium from VVER reactors (Alekseev et al. 2018, 2022) (including that from foreign PWRs based on mixed uranium-plutonium fuel), and thus, to organize the multiple plutonium recycle in a system of fast and thermal reactors. This fact will allow thermal reactors to operate in conditions with a short supply of cheap natural uranium.

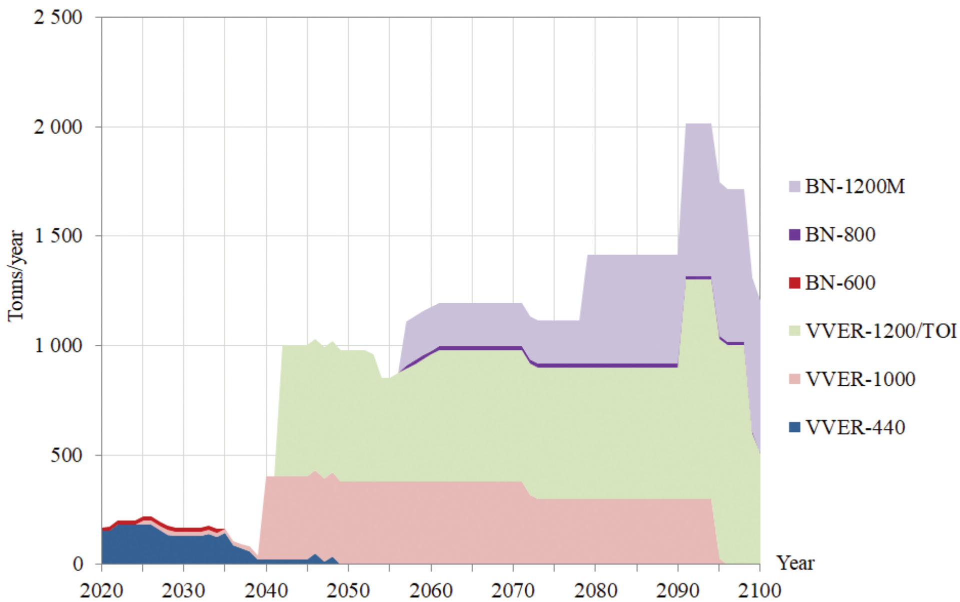

Figure 3. The structure of demand for SNF reprocessing to provide plutonium for fast reactors.

If there is no need for such options and for the purpose of plutonium balance in the system, it is possible temporary not to use the lateral breeding blanket, and replace it with a cheaper steel reflector (Tuzov et al. 2022). Besides, it is possible to use the lateral blanket for other functions, such as isotope production or minor actinide burnup (Dekusar et al. 2019; Gulevich et al. 2020).

Selecting the strategy for minor actinide handling requires R&D to be undertaken to justify technology, material testing and neutronic aspects, and nuclear and radiation safety issues. Besides, it is necessary to explore the system issues involved in spent nuclear fuel and minor actinide management in the nuclear power system as the whole, with regard to repatriated foreign SNF (Zalimskaya 2017). In this connection, it is too early to address an objective of full-scale commercial recycle for minor actinides in the first BN-1200 reactor; it is expected to be used to test and demonstrate future minor actinide transmutation technologies. At the same time, the estimates in Tuzov et al. 2023 show that it is exactly the use of the BN-1200M lateral blanket with the aim to place americium in the target assemblies with a moderator may turn out to be the most effective way for americium burnup, as compared to its homogeneous distribution in the fuel and also to its burnup in dedicated reactors.

Besides, production of medical, industrial and energy isotopes (^{238}Pu, ^{60}Co, etc.) in irradiation devices with a moderator, placed in the lateral blanket, my prove to be a commercially significant objective for BN-1200M reactors, especially under conditions of large-scale RBMK reactor decommissioning.

An objective for the future may be production of the ^{233}U isotope in the thorium lateral blanket of a fast reactor, for its further use in thermal reactors (Dekusar et al. 1999). In this case, reprocessing of assemblies containing irradiated thorium may be postponed until ^{233}U is in demand. At the same time, such a solution excludes waste of neutrons, which is typical of the proposal to replace a uranium lateral blanket with a steel reflector.

Another novel avenue for the fast reactor development is a nuclear hydrogen system (NHS). At the present time, hydrogen production is considered to be one of the key trends in decarbonization and net zero emission (NZE) programs. The total annual production of hydrogen worldwide is estimated as 55 to 70 million tons, with a cumulative annual average growth rate of 1.6% (The development of hydrogen energy as a new page of energy strategy 2023), and the only possibility for the global switchover to clean hydrogen production is to use nuclear reactor energy. The VTGR thermal reactor (Golovko et al. 2022), which is a source of high-grade heat for production of hydrogen by the steam methane reformation method, is viewed as a promising option for the NHS evolution. One more already commercialized hydrogen production technology is electrolysis of water, which requires a source of cheap electricity and superheated steam.

A large-scale hydrogen production based on nuclear energy of thermal reactors will require a substantial extra consumption of natural uranium; this fact may result in a considerable change in the nuclear power performance or may even become a constraint for its further evolution in the future. The current Nuclear Power Development Strategy does not take into account the NHS factor in its balance models. The way out consists in accelerated development of fast neutron reactors with the required secondary nuclear fuel breeding ratio and the sodium temperature increased to 700 °C and higher. It will allow extending the use of natural uranium resources and making it a source of high-grade heat for a variety of power applications (Sorokin et al. 2022). As one of the possible examples, Fig. 4 presents a diagram of a reactor facility with a fast reactor for electricity and hydrogen production based on the technology of high-temperature steam electrolysis with the use of a solid oxide electrolysis cell (Poplavskii et al. 2009).

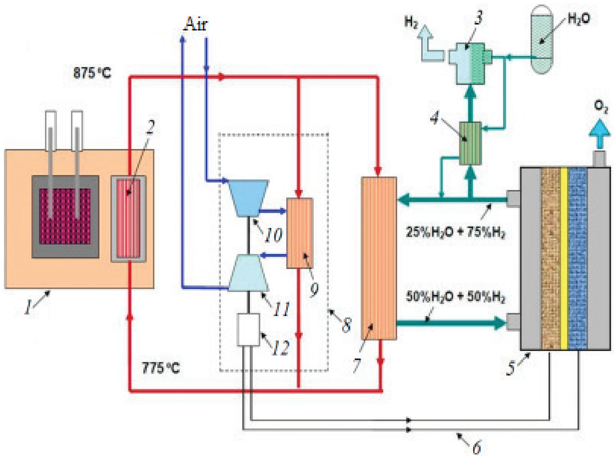

Figure 4. Reactor facility for electricity and hydrogen production based on the solid oxide water electrolysis technology: 1 — fast reactor; 2 — intermediate heat exchanger; 3 — hydrogen separator; 4 — heat exchanger; 5 — solid oxide electrolysis cell; 6 — electricity for electrolysis cell; 7 — steam generator; 8 — gas turbine plant; 9 — heat exchanger; 10 — compressor; 11 — turbine; 12 — electrical generator.

Economic estimates for some of the capabilities offered by fast reactors in a two-component system

Let us estimate some of the above-mentioned capabilities offered by fast reactors in a two-component nuclear energy system, with the advanced BN-1200M reactor as an example.

- Reduction in consumption of natural uranium by Russia's reactor fleet, with a simultaneous increase in uranium fuel export. Fig. 5 shows the natural uranium saved in the scenario under consideration due to BN-1200M reactor series commissioning after 2035. The substitution of one VVER reactor saves about 200 t of natural uranium annually. With the current natural uranium price of ~150 $/kg of heavy metal, such uranium quantity sold results in an annual income of ~$30 mln. This is equivalent to a ~12% decrease in the levelized cost of the fast reactor electricity production.
- Breeding of plutonium, the surplus of which can be used to provide fuel for thermal reactors, including

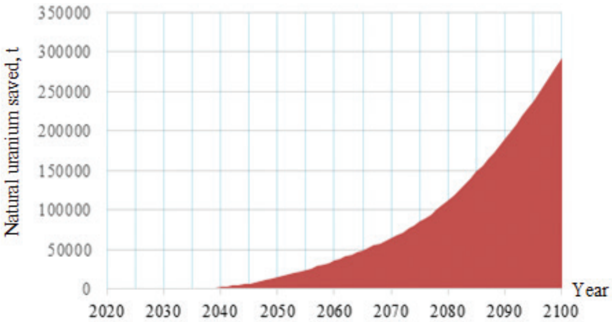

Figure 5. Natural uranium saved due to commissioning the BN-1200M reactor series after 2035.

those built abroad under Russian designs. The annual economic effect for a single fast reactor from the produced surplus plutonium when it is used in thermal reactors (VVER-S, or VVER-TOI, or VVER-SKD) is $12 to 15 mln, which is equivalent to a 0.8% to 1.2% decrease in the levelized cost of the fast reactor electricity generation. Currently, there is no business competition in the world market yet.

- Improved (refined) isotopic composition of plutonium from foreign spent MOX fuel of PWR reactors to be reused in PWRs. The economic benefit from this service consists in recovering the expenses incurred by Russia when plutonium goes through the fast reactor fuel cycle. To achieve the required isotopic composition of plutonium from PWR spent MOX fuel, double recycling of the initial plutonium is required in the fast reactor fuel cycle (with regard to plutonium production in blankets). The price of this service will amount to ~$400 thsd/kg of Pu, and the mission time will be doubled. A decrease in the levelized cost of fast reactor electricity production will be ~5%, with refining the annually produced plutonium from one PWR loaded partially with mixed uranium-plutonium fuel. No business competition at the moment.
- Burning of plutonium from PWR spent mixed uranium-plutonium fuel (commercial service for foreign NPPs). Since no plutonium isotopic composition adjustment is required in this case, a single plutonium run through the fast reactor fuel cycle is enough. The potential income will therefore amount to about $200 thsd/kg of Pu.
- Burning of americium from the SNF of foreign thermal reactors. The economic benefit from this mission consists in the recovery of the expenses incurred by Russia for burnup of 1 kg of americium. The absence of reliable performance data for the fast reactor fuel cycle with minor actinides allows for only preliminary estimates. The cost of burning of 1 kg of americium in a fast reactor is estimated to be between $70 and $700 thsd depending on the method of its arrangement inside the reactor (in an irradiation device in the lateral blanket or homogeneously distributed through the core). Burning of 23 kg of americium (from the spent nuclear fuel unloaded annually from a thermal reactor after 20 years of cooling) in the BN-1200M reactor on a commercial basis leads to up to 6% decrease in the value of the levelized cost of electricity production for a fast reactor.
- The contribution of americium heat release to the total heat release from high-level waste is substantial. Therefore, in the event of americium extraction from SNF for in-pile burning, more compact accommodation of casks is possible with HLW geological disposal. As estimated by French experts, with no americium in the fast reactor SNF high-level waste, the geological disposal area is reduced by 50% (Camarcat et al. 2011). Not only americium but also its source (^{241}Pu) can be burnt in fast reactors. To this end, fast reactor fuel needs to be made based on plutonium extracted from VVER SNF after minimum 5 years of its cooling. In this case, up to 100 kg of ^{241}Pu will be burnt, with the need for americium extraction and burning no longer relevant. No competition in americium burning.
- Production of isotopes, primarily ^{238}Pu and ^{60}Co. The annual income from isotope production is estimated as $12 mln; however, such production is competitive, which makes the project economic efficiency dependent on the global market environment.
- Deferred reprocessing of fast reactor SNF. By the time the first-of-a-kind BN-1200M power unit is commissioned, the plutonium amount accumulated will be enough not only to operate it and the BN-800, but also to start up several more series-built fast reactors. This will require VVER SNF reprocessing. The vacated storage facilities for thermal reactor SNF, after being adequately retrofitted, can be used to store fast reactor SNF. This will make it possible to dismiss the need for construction of reprocessing facilities for SNF from small-series fast reactors. The investment outlay savings will amount to some 20 bln rubles.
- Series-built BN-1200M fast reactor power units. Switching over from the commercial first-of-a-kind fast reactor to a series of power units and rejecting the need for reprocessing fast reactor SNF at the front end of NFC closing will lead to about halved fuel component in the cost of electricity (Tuzov et al. 2022), thus reducing the levelized cost of electricity production by ~10%.

Conclusions

Phased conversion of Russia's nuclear power to a two-component nuclear energy system with thermal and fast reactors in a single closed NFC cycle opens ways for solving a range of system issues involved in current nuclear power industry. A preliminary feasibility study for the capabilities offered in addition to electricity generation shows that having fast reactors in a two-component nuclear energy system is expected to bring about extra income and reduce the value of the levelized cost of electricity generation. An additional functional for sodium fast reactors is burning of minor actinides, production of artificial isotopes, recycling and refining of plutonium, etc. Apart from electricity sold, a two-component system allows producing extra products or providing services of a market value. In this case, the economic effect is expected to account for a substantial share of the fuel component in the cost of electricity generation by fast reactors.

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