BREST-OD-300 – Demonstration of Natural Safety Technologies

Vadim Lemehov and Valeriy Rachkov

Introduction The article discusses the need to update the strategy for the development of nuclear power, various approaches to the development of large-scale nuclear power. The current state of fast reactor technologies development is examined through the example of the BREST-OD-300 reactor plant and the closed nuclear fuel cycle (CNFC) in Russia with highlighting the main problems. The problems of choosing solutions for fast reactors and organization of the nuclear fuel cycle are discussed within the article as well.

Evaluation of prospects for the development of the nuclear power industry in Russia and other countries shows the presence of two trends [1]:

1. Focusing on the development of the nuclear power industry on the basis of the existing and improved types of thermal reactors with an open nuclear fuel cycle that use mainly U-235. This also includes possibilities of using a limited additional fuel resource in the form of mixed oxide uranium-plutonium fuel (MOX-fuel). It is obtained by single recycling of spent nuclear fuel (SNF) from these reactors, separation of accumulated plutonium, and mixing it with depleted uranium. Despite a long history, the share of MOX fuel in the world's nuclear fuel production for thermal reactors has never exceeded 5 %, and its production at some plants (Belgium, UK) is ceasing.
2. Focusing on the development of the closed nuclear fuel cycle (NFC) with the introduction of reactors ensuring simple nuclear fuel conversion or nuclear fuel breeding (BR ≥ 1). These could be conventional fast neutron reactors (FNRs) or the light water hard spectrum reactors (LWRs) previously discussed in the 1970s and newly proposed in the United States and Russia. Nuclear fuel breeding provides full-scale involvement of natural uranium (with 99.3 % U-238) in the plutonium-uranium breeder producing fissionable plutonium from U-238 and fissionable U-233 from natural Th-232 in the breeder reactor.

The first approach involves ever-growing quantities of natural uranium that is used less than 1 % energy-wise, and the amount of accumulated SNF constantly increases. In the conditions of modern energy markets, this approach is recognized as economically justified. A concept of further development of this approach has spread in the Unites States, which has the largest nuclear power industry in the world, and has been promoted by leading nuclear power plant (NPP) designers in emerging countries, where nuclear power engineering is in progress. According to American experts, the world‘s known uranium resources make it possible to stay on this track for a long time.

It is obvious that large-scale nuclear power engineering can be implemented only under the second approach. But development strategies under this approach are conceptually different in different countries, depending on the expected role of fast-neutron reactor (FNR) in the structure of the nuclear power industry. There are three strategies for the formation of large-scale nuclear power engineering, which can be conditionally distinguished: [1].

"AS USUAL" Strategy. The United States in the foreseeable future will rely on thermal light water reactors (LWRs) with the open NFC, and provision is made for the transition to SNF reprocessing from LWR (being accumulated in a temporary storage facility for 100 years) in order to reduce the amount of high level waste (HLW) subject to final disposal by means of burning of minor actinides (MA) from HLW in an FNR. At the same time, FNRs themselves are considered as noncompetitive energy generators and possible "cleaners" for the dominant LWRs. For such FNRs, a breeding ratio (BR < 1) is adopted, and their NFCs remain open, since it requires a constant external (not from the NFC) makeup by fissile nuclides. A possibility of using FNRs with BR ~ 1 and BR > 1 is under consideration, but their mission remains fundamentally the same.

Closed NFC with thermal reactors (TRs). France and Japan, which do not have their own uranium deposits, have traditionally built their development strategies providing for the transition from LWRs with the open NFC to sodium-cooled FNRs with the closed NFC and a BR much larger than 1, ensuring LWR makeup fuel supply. A similar strategy was considered and has still been proposed bv a team of specialists in Russia.

Closed NFC with FNR. The Russian Strategy Guidelines formulated in the "Strategy for the Development of Russia's Nuclear Power Industry in the First Half of the 21st Century" [2] and worked out in detail in [3] is based on the concept of large-scale nuclear power engineering, which can be used to solve its main tasks by means of FNRs of moderate power rate without surplus plutonium production remaining in the structure of previously built NPPs with thermal reactors. In this case, the complete inner plutonium breeding (IBR » 1) with dense nitride fuel of equilibrium composition is important.

Scenarios for the formation of FNRs with the closed NFC should be based on the actually established structure of the nuclear power industry. In this regard, it is important to understand the difference between temporary two-component nuclear power engineering ensuring a gradual transition from thermal reactors to FNRs, and basic two-component nuclear power engineering, where thermal reactors play a key role and fast breeder reactors only feed them with fuel and burn HLW.

The idea of the basic two-component nuclear energetics was developed in the second half of the last century under the influence of the following factors:

- Development of uranium enriched thermal reactors for military purposes and their further modernization for the civilian power engineering;
- Understanding of the necessity of FNRs for the development of nuclear power industry;
- Economic uncompetitiveness of fast reactors reactors built in different countries with their specific features determined by the

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requirements of a large BR: high power density, use of a sodium coolant, production of weapon-grade plutonium in the blanket.

With the development of the uranium enrichment technology, thermal reactors became the basis of modern nuclear power engineering, and, for more expensive FNRs with a large BR, they could be used for thermal reactors' makeup fuel supply (with plutonium produced by FNRs) in case of cheap natural uranium depletion. In such a two-component nuclear power industry, a large-scale SNF and MOX fuel circulation is required between fast and thermal reactors and centralized nuclear fuel recycling plants.

The "Strategy for the Development of Russia's Nuclear Power Industry in the First Half of the 21st Century" [1] considers two-component nuclear power as a Stage of a gradual transition from thermal to fast neutron reactors, which forms the basis of the future large-scale power industry.

The main large-scale development factors of the nuclear power industry in Russia and the world remain safety and economic competitiveness with other types of energy generation. Russia's nuclear power processing datum surface on the basis water-water energetic reactors (VVER) reactors is sufficient for the scale of NPP construction and volume of exports forecasted by the ES-2030. [4] However, its long- term strategic potential is limited by the inconsistency of a safety level with requirements for large-scale nuclear power engineering, limited natural uranium resources, SNF accumulation, and falling competitiveness due to increased safety measures.

The "Strategy for the Development of Russia's Nuclear Power Industry in the First Half of the 21st Century" [2] defined main conditions for natural safety of a large-scale nuclear power industry:

- Elimination of accidents requiring evacuation, and especially resettlement of the population and withdrawal of significant areas from economic use;
- Effective use of energy potential of the extracted fuel raw materials;
- Circulation of nuclear materials in the fuel cycle without significant violation of the natural radiation balance[1];
- Technological support of the nonproliferation of nuclear weapons;
- Ensuring the competitiveness of nuclear power engineering in comparison with other types of energy generation.

The abandonment of the thermal reactor plutonium makeup from the SNF solves the problem of choosing between a large or small FNR BR in favor of the inner BR (IBR) close to 1. It should be noted again that the small-scale nuclear energy system (NES) component is an imperative associated with acceptable safety of the large-scale nuclear power engineering, while the choice between the hybrid NFC (with the enriched uranium makeup) and a closed NFC (with the plutonium makeup from the FNR SNF) is a matter of economic feasibility.

Sometimes fears are expressed that in the case of a FNR BR close to one, it is impossible to increase the power of the nuclear power plant in a short time (if necessary). But, firstly, today even the most optimistic forecasts do not

1 Preservation of the natural radiation balance assumes that, after a certain historically short period of time, the total radioactivity and radiotoxicity of the waste generated as a result of the NPP operation, reprocessing of irradiated fuel and land-buried waste will not exceed the total radioactivity and radiotoxicity of the uranium isotopes extracted from the earth's crust to supply NPPs with fuel.

discern such a scenario for the development of nuclear power. Secondly, if such a scenario turns out to be in demand, then, without going beyond the natural safety, it can be implemented by quickly putting in any rationally required amount of FNR capacity with fuel from enriched uranium or using a blanket, the presence of which in the countries of the "nuclear club" meets non-proliferation requirements.

At present, it can be considered theoretically proven and computationally experimentally substantiated that such **three additional requirements for FNR**, as IBR close to 1 [5], lead coolant [6] and dense nitride uranium-plutonium fuel (MNIT-fuel) [7], **make it possible to significantly increase the safety level of FNR** that meet these requirements, in comparison with FNR with IBR, significantly less than one (larger only when using a blanket), with sodium coolant and MOX fuel mastered in Russia. Thus, for a large-scale component of nuclear power, an FNR with a IBR close to unity, with lead coolant and dense uranium-plutonium fuel is required.

1. In connection...

with the requirement to increase the level of safety, in relation to the reactor installations of NPPs, **six main technical solutions can be distinguished** that ensure the satisfaction of the natural safety requirements of large-scale nuclear power, which are demonstrated in the BREST-OD-300 reactor plant: **The equilibrium active zone of FNR**

The equilibrium FNR core allows minimizing the reactivity margin for nuclear fuel burnout and virtually eliminating instantaneous neutron acceleration **(Figure 1)**.

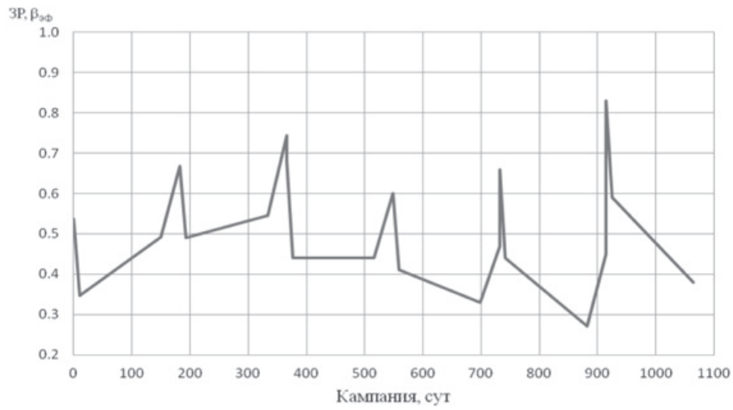


Figure 1
Reactivity reserve for the campaign of the BREST-OD-300.

2. Dense fuel

Among the fundamental properties of dense fuel, three play a significant role in terms of influencing the basic characteristics of the active zones and safety: density, thermal conductivity, and the specific amount of scattering light elements (oxygen, carbon, and nitrogen).

A higher fuel density and a smaller number of light elements contributes to an increase in the reproduction coefficient in the reactor core (IBR) and the integral BR for the reactor plant (RP). Special unique properties are acquired by active zones with the so-called "equilibrium" fuel, in which the burning of the fissile material is completely compensated by its reproduction.

Dense fuel allows realizing an equilibrium core **(Figure 2)** with a IBR of about one **(Table 1)**, that provide:

- complete reproduction of fissile nuclides, which is a sufficient condition for the practical use of the energy resource U-238;
- work without a uranium blanket, which eliminates the production of low-background radiation with a quality close to weapons-grade;
- the absence of the need to separate plutonium from SNF and the possibility of using technologies without separating uranium and plutonium, which together with the previous advantage provide technological support for the non-proliferation regime;
- minimization of the burnout reactivity margin, which reduces the maximum reactivity margin of the reactor vessel and increases the nuclear safety of the reactor vessel;
- unique stability of fuel rods and fuel assemblies heat release during their operation.

Currently, more than 1,500 fuel rods have been tested in the BOR-60 and BN-600 rector plants, including up to a burn-up depth of 9.3 % t. a.

3. Wide core grid

The wide grid of the core allows having a level of natural circulation sufficient to remove the residual heat and reduce the power consumption for pumping the coolant.

4. Integrated layout of the reactor plant

The integrated layout of the reactor plant **(Figure 3)** allows excluding the loss of core cooling.

All primary circuit equipment required for organizing the circulation circuit and transferring energy to the heat conversion circuit is located in a single reactor block.

5. Heavy liquid metal coolant

The choice of lead as a coolant for the BREST-OD-300 reactor plant stems from:

- the presence of a well-founded lead coolant technology, i.e. a set of measures and means to ensure the required quality of the coolant and the cleanliness of the primary circuit during operation;
- low potential energy associated with possible chemical reactions involving lead;
- negligible moderating ability of lead nuclei, which, on the one hand, eliminates the problem of the positive void effect of coolant reactivity, and on the other hand,

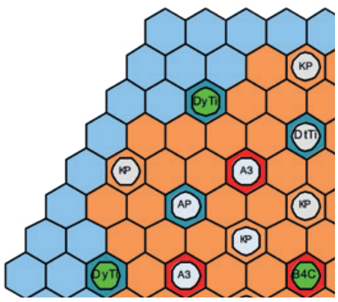
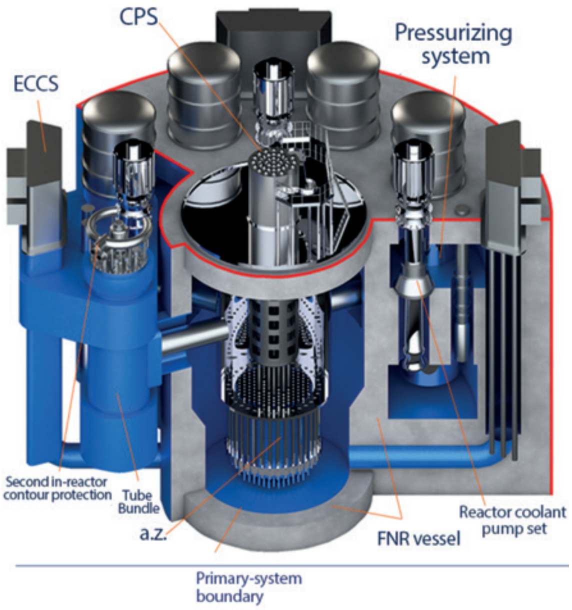


Figure 2
Cartogram a.z. reactor plant BREST-OD-300.

Number of fuel assemblies in the core	169
Core height, mm	1,100
MNIT fuel density, g/cm^3	12.3
Full load of MNIT fuel, t	20.8
Max. burn-up depth in the discharged fuel (at the initial stage), % t. a.	9.3 (6.0)
Average ST temperature at the inlet/outlet of the core, °C	420/535
Average energy intensity of a.z., MWth/m^3	140
Maximum linear power over the core, W/cm	420
Reproduction rate (blanket is missing)	1.05

Table 1
Index a.z. reactor plant BREST-OD-300.



| **Figure 3**
The view of BREST-OD-300 reactor plant.

allows the use of a wide lattice in the core, thereby providing an effective mode of natural circulation of the coolant in the core with a simultaneous decrease in coolant velocity (almost twice as compared with sodium coolants in a sodium-cooled fast breeder reactor (BN-reactor) reactor) and hydraulic resistance of the circulation loop and, as a consequence, with a reduction in the power consumption for pumping the coolant;

- low availability of lead nuclei in the neutron flux, which makes it possible to switch from a vessel structure to a pool structure, characterized by a high heat capacity, and place the equipment in a concrete shaft lined with steel or cast iron compatible with lead, with a decrease in the cost of a reactor installation and an increase in reactor safety in transient and emergency processes due to the thermal inertia of the circuit;
- high boiling point (~ 1745 °C) of the lead coolant, which excludes accidents associated with the crisis of heat exchange (in the reactor, due to the higher pressure in the core, the boiling point of lead can reach 2300 °C).

The above benefits are illustrated in **Figures 4 and 5.**

The figures are given for the worst conditions of heat removal from the reactor core – complete blackout. There is a shutdown of four reactor coolant pumps (RCPs) and a cessation of feed water supply during operation at the initial nominal power. The removal of the residual energy release is carried out by two of the four emergency core cooling systems (ECCSs) loops (the failure of the other two ECCS loops and the failure of the ECCS is postulated).

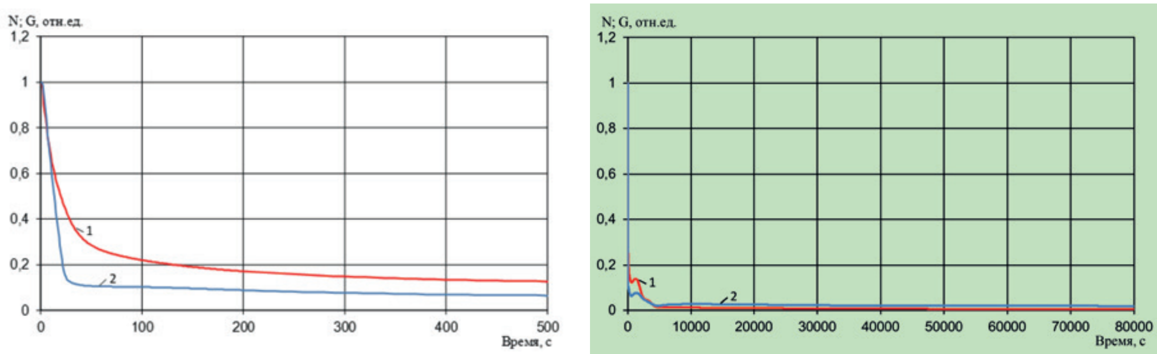
Result: for all standardized radionuclides, emissions into the atmosphere do not reach the control level per day.

6. Using ambient air as an aftercooler

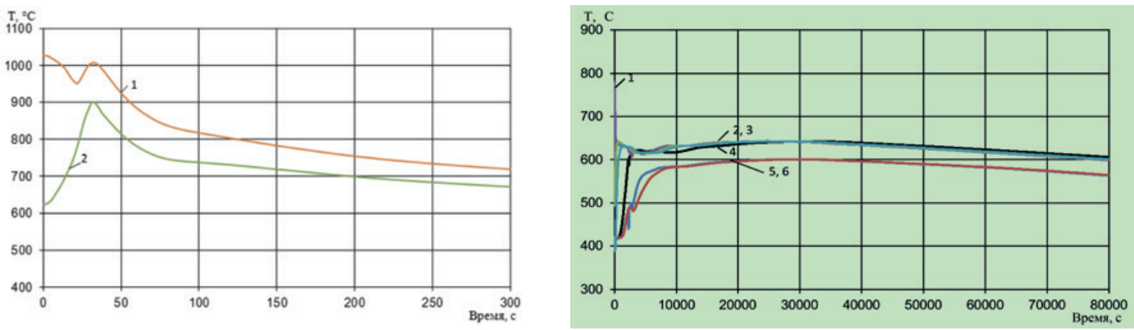
Use of atmospheric air as a final cooler without intermediate circuits in the case of natural circulation removal of residual heat in a high-power reactor plant **(Figure 6)**.

In addition to the safety requirements for nuclear power plants, there are a number of requirements for closed NFC technologies, which are implemented at the Industrial pilot facility with a power complex with the BREST OD-300 reactor, a plant for the production of nuclear fuel from the products of reprocessing of spent nuclear fuel and a plant for reprocessing spent nuclear fuel:

- low-waste reprocessing spent nuclear fuel from FNR;
- involvement of SNF reprocessing products from thermal reactors into the nuclear reactor fuel cycle;
- reduction of the duration the spent nuclear fuel spends on the nuclear reactor before its reprocessing to 1–2 years;
- ensuring the radiation balance between the extracted fuel raw materials and the buried radioactive waste (RW);
- technological support for the nonproliferation regime.



| **Figure 4**
Change in power (1) and flow through the reactor (2).



| **Figure 5**
Temperature change of fuel (1) and fuel element cladding (2).

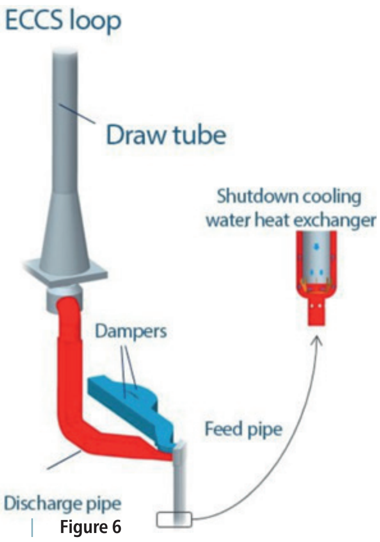


Figure 6
ECCS plan.

In connection with the requirements for the technologies of the closed NFC, **three technical solutions can be distinguished:**

- **"dry" reprocessing of spent nuclear fuel from FNR** to reduce the duration of spent nuclear fuel holding before reprocessing and to exclude the separation of pure plutonium during reprocessing;
- **transmutation of minor actinides in FNR** to ensure a balance between the extracted fuel raw material and the disposed radioactive waste;
- **abandonment of the blanket in FNR** to exclude the production of weapon-grade plutonium (when exporting technologies).

The question remaining is competitiveness of NPPs in general and on the basis of FNR in particular. Obviously, without norms and standards corresponding with the new technological nuclear power platform the solution of this question is difficult. The first approach to the answer about the feasibility of competitive CNFC power engineering based on fast neutron reactors will be given by conceptual projects of industrial power facilities with reactor plants BN-1200 and BR-1200.

Conclusions

1. A large-scale element of two-component nuclear power engineering, i.e. a closed nuclear fuel cycle FNR, requires an FNR with the inner breeding rate close to 1 with a lead coolant and dense uranium-plutonium fuel to ensure the necessary safety level.
2. Low-waste "dry" SNF reprocessing (mainly to reduce a duration of the SNF conditioning before its reprocessing) and minor actinide transmutation (to ensure a radiation balance between the extracted fuel raw material and buried RAW) are preferable for the large-scale nuclear power engineering in general.
3. To prove the advantages of reactors with lead coolant, a pilot demonstration power complex is being created at the site of JSC Siberian Chemical Combine (SKhK).
4. Answers to the questions related to the industrial production and application of MNIT fuel for the IPF on the BN-1200 and BR-1200 basis can be given only in case of its pilot application in the BREST-OD-300 reactor plant of the industrial pilot facility.
5. Answers to the questions related to the industrial reprocessing of MNIT-SNF for the isotope production facilities (IPF) can be given only in the operation of the processing module on the pilot demonstration facility.
6. Technological support of the non-proliferation regime in the export version of natural safety technologies is not a complete solution to the nonproliferation problem but only an important addition to institutional tools of its solution.
7. For a radical solution to the CO_2 problem, it is possible to develop a large-scale nuclear power industry by the end of this century, which means a gradual transition to FNRs with closed NFC in the nearest future.
8. The main requirement for the development of the nuclear power industry is its competitiveness, primarily with the generation based on organic fuels and with renewable energy sources in terms of exports. Preliminary calculations for industrial power complexes with fast reactors operating in a closed fuel cycle show the possibility of achieving parity with other types of generation.

Abbreviations

BN	Sodium-Cooled Fast Breeder Reactor
BR	Breeding Ratio
CFC	Closed fuel cycle
ECCS	Emergency Core Cooling Systems
FNR	Fast-Neutron Reactor
HLW	High Level Waste
IBR	Inner Breeding Ratio
IPF	Isotope Production Facilities
LWR	Light Water Reactor
MA	Minor Actinides
MNIT	Mixed Uranium-Plutonium Nitride Fuel
NES	Nuclear energy system
NFC	Nuclear Fuel Cycle
NPP	Nuclear Power Plant
RCP	Reactor Coolant Pump
RP	Reactor Plant
RW	Radioactive Waste
SNF	Spent Nuclear Fuel
TR	Thermal Reactor
VVER	Water-Water Energetic Reactor

Preferences

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