Fast reactors: Experience in design, construction, and operation. Prospects for further development

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FAST REACTORS: EXPERIENCE IN DESIGN, CONSTRUCTION, AND OPERATION. PROSPECTS FOR FURTHER DEVELOPMENT

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Experience in Operating Fast Reactors. Experience in operating fast reactors. The development of fast reactors started in our country forty years ago at the initiative and under the leadership of A. I. Leipunskii. We have now accumulated more than 90 reactor·years in operating fast reactors (BR-10, BOR-60, BN-350, and BN-600). Worldwide operating experience with fast reactors now exceeds 200 reactor·years.

Experience in operating the reactors has confirmed that these reactors are safe [1-3]. Negative temperature and power coefficients of reactivity guarantee that the reactors are self-regulatable. The heat-release field in the core is stable, and the excess reactivity is low. The reactor is simple to control. Heat removal by sodium is efficient, and the margin up to boiling in the core during operation is not less than 300°C. The low sodium pressure and the absence of appreciable corrosion phenomena in sodium ensure that the loops remain completely sealed. Methods for containing leaks of radioactive sodium are well developed. A high degree of reliability has been achieved. The main sodium equipment has operated in a stable fashion. The operating time of the main circulation pumps between repairs has exceeded 70,000 h; the analogous period for steam generators is 100,000 h; the structural elements of the reactor and the sodium loops operate unremarkably from reactor startup.

The power utilization factor of fast reactors is as follows (%):

	1988	1989	1990	1991	1992
BN-600	77	76	66	70	84
BBÉR-440	79,4	79,7	79,6	69,3	73,2
BBÉR-1000	65,5	59,1	58,7	63,7	67,7
RBMK-1000	69,7	77,4	68,9	69,3	64,7

The decrease in the power utilization factor of the BN-600 reactor is mainly attributable to refueling operations. In 1993 it equalled 80%. The radiation effect of fast reactors on the environment is minimal. In the case of the BN-60 reactors, the emission of radioactivity into the atmosphere, averaged over the operating period, is less than 10 Ci/day, the admissable level being 500 Ci/day according to modern standards.

Extensive experience in operating fast reactors has been accumulated in France, Great Britain, and the USA.

Safety of Fast Reactors in Connection with the Requirements Imposed on Next-Generation Units [4, 5]. Fast reactors have the required prerequisites for implementing the requirements formulated for the next-generation power-generating units of nuclear power plants. This is achieved by the unique qualities of fast reactors and the technical designs adopted:

stable negative feedback during power and temperature perturbations; the deficiency, well known for traditional cores of fast reactors, associated with a positive void effect of reactivity for sodium during off-design accidents, can be substantially reduced or eliminated (as has been done, for example, in the BN-800 design);

possibility of achieving an internal fuel breeding ratio close to one in the core;

absence of any effects such as xenon poisoning of the reactor followed by positive reactivity;

high stability of neutron fields;

impossibility of local formation of a critical mass in the core, even during strong perturbations of the neutron fields;

low coolant pressure, determined by the hydraulic resistance of the loop;

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high heat-storage capacity of the sodium loops of a reactor with integrated equipment, making nonstationary processes during disruptions of heat removal very slow;

high heat of vaporization of sodium and large margins up to boiling;

retainment by the sodium and trapping by cold traps of a large fraction of radioactive fission fragments in the case when the fission fragments escape from the fuel elements into the coolant;

low corrosion activity of sodium with respect to the structural materials, which increases the reliability of the hermetically sealed shielding barriers;

passive reactor shutdown system, which transfers the reactor into and maintains it in a subcritical state, including during prolonged cooldown;

passive loop cooldown systems, allowing for removal of residual heat without exceeding the limits of safe operation.

In spite of the well-known negative property of sodium to burn when it comes into contact with air, operating experience confirms that power-generating units are safe when such leaks do occur.

Experimental investigations have shown that sodium ignites at temperatures above 180°C. A burning layer of sodium releases approximately 15 times less heat than a layer of petroleum products of equal area.

Various means for eliminating this deficiency have been developed and implemented, and they have proved to be highly efficient: Indicators indicating a break (electric circuits, fire alarms, filters for discovering radioactive aerosols, and others), passive means for putting out a sodium fire (different powder compositions), passive barriers (backup cladding on the vessels and pipes), and so on. Several tens of cases of sodium leaks have occurred in operating reactors, including a leak, occurring in October 1993 and lasting for many hours, from the loop of a BN-600 reactor (about 1 tonne of sodium leaked out). In no case was the situation classified as an accident according to the international scale of events, and in no case were the personnel or population irradiated.

The BN-800 reactor, being constructed at the Southern Ural nuclear power plant, has all of these qualities, including passive means for affecting the reactivity, systems of emergency cooldown through air exchangers, and a tray for collecting the melted fuel mass. This made it possible for the BN-800 reactor to meet the corresponding safety requirements for the new-generation reactors.

Possibilities for Improving the Economic Indicators. The principal methods for reaching this goal are as follows [6]:

increasing burnup, which determines the economic efficiency of the fuel cycle;

improvement of technological processes for fuel reprocessing and manufacturing fuel elements;

simplification and curtailment of auxiliary systems and emergency power-supply systems;

improvement, optimization, and enlargement of the main equipment, reducing to a minimum the number of heat-removing loops, length of sodium pipes in the second loop, and simplification of the transport and technological channel for loading and unloading fuel assemblies;

reduction of construction volumes and material intensiveness of the power-generating unit by implementation of the second and third measures as well as by using improved configurations;

increase of the service life of the reactor (taking into account obsolescence), for which favorable possibilities exist, taking into account the low corrosion activity of sodium; and,

switching to batch construction.

Comparative analysis has shown that the metal intensiveness of the improved BN-600 M unit can be reduced by 40% with respect to BN-600M and by 25% with respect to BN-800.

The combined efforts of the western European countries have led to the design of a fast reactor (European fast reactor) with an electric power of 1500 MW(e), in which, thanks to many improvements, the amount of metal employed was substantially decreased. As a result, the specific capital investments should be 45% lower than for "Superphoenix-1" (France), and it can be lowered by an additional 22% by switching to batch production.

Estimates show [7] that the specific capital investment equals 1800-2000 US dollars for batch-produced fast reactors and 1500 US dollars for thermal light-water reactors. The average ratio of these indicators is 1.26. In our country, where new types of light-water thermal reactors have been produced, the difference of the specific capital investments between thermal and fast reactors is smaller.

TABLE 1. Construction Costs of Several Nuclear Power Plants, Millions of Rubles (according to prices during the fourth quarter of 1992)

Nuclear power plant, unit	Power, MW	Estimated cost, millions of rubles	Specific costs, rubles/kW
Southern-Ural nuclear power plant,	800	56694	70860
pilot unit BN-800,	1600	55770	
2nd line, two BN-800	2400	112464	46860
Beloyarsk nuclear power plant, fourth unit, BN-800	800	44949	56186
Kola nuclear power plant, third line, fifth, sixth, and seventh units	1890	92400	48888
Sosnovyi bor, pilot unit NP-500	630	36795	58404
Primor'e nuclear power plant (or the nuclear power plant in Dimitrovgrad), pilot unit NP-600	1200	70950	59125

As a result of the increased safety requirements, the economic indicators of fast reactors are approaching those of thermal reactors, since in fast reactors the safety goals are achieved by simpler means. The construction costs for several pilot and batch-produced units of the new-generation nuclear power plants are presented in Table 1 [6].

We can give one more example of a calculation of the economic characteristics of three alternative power-generating units, to be constructed at the same site. This concerns the power plant for the Kaluga oblast'. Nuclear power plants with three V-407 thermal reactors, three BN-600M fast reactors, and coal-burning heat and electric plants were considered. Since the calculations were performed several years ago, the relative and not the absolute costs are of interest: the thermal and fast reactors are equally economic and much more economic than the coal-burning heat and electric plant.

Ecological Problems and the Role of Fast Reactors in Their Solution. Power-generating units of any type have a radiation and thermal effect on the environment. The most acute problem associated with the operation of nuclear power plants is the accumulation of high-level wastes in the form of fission products and minor actinides – neptunium, americium, and curium. Over the long term the latter radionuclides, which have a half-life of a thousand years, are most dangerous. This is the main obstacle to the storage of high-level wastes. In this connection, the possibility of lowering the activity of wastes by transmutation, i.e., by irradiating long-lived radioactive nuclides in order to transform them into short-lived or stable nuclides, is under consideration [1, 6]. In a fast reactor these actinides are subjected to fission by high-energy neutrons, i.e., they can be used as fuel. This will make it possible to burn out efficiently neptunium, americium, and curium in fast reactors by adding these radionuclides to the main fuel. By introducing into BN-800 fuel 3.5% additives in the form of oxides, it is possible to burnout 100 kg/yr (the difference between the amount of actinides loaded and unloaded). Three VVÉR-1000 reactors can be "serviced" in this manner. Even greater burnout of neptunium, americium, and curium is possible in a specialized fast reactor (or a specialized core).

Besides these actinides, plutonium presents a great potential danger to the environment. Storage of plutonium increases its radiological toxicity, since the long-lived α-emitters ^{241}Am (half-life of 433 years) and ^{237}Np (half-life exceeding 2 million years) accumulate as a result of the decay of ^{241}Pu.

This question is especially acute for the so-called high-background plutonium. This type of plutonium is generated in thermal reactors. By 1993 more than 25 tonnes of it had accumulated. It has been proved that it is best to burn high-background plutonium in fast reactors. The BN-800 reactor is capable of converting 200 kg of high-background plutonium per year into low-background plutonium; this will reduce considerably the accumulation of the most dangerous radioactive substance. Thermal reactors are in principle incapable of converting high-background plutonium into low-background plutonium; in any case, only high-background plutonium accumulates in such reactors.

One other important feature of fast reactors should be noted: the possibility of accumulation of quite pure ^{233}U in the breeding zones. The schemes by which this isotope accumulates are diverse, and they can be combined with burnup of actinides. It is best to use the produced ^{233}U in thermal reactors, whose safety will thereby be increased.

In the case of extensive construction of nuclear power plants, the question of decreasing their thermal effect on the environment becomes important. Fast reactors have indisputable advantages here, since they are capable of providing a gross efficiency of 40-42%. This will reduce thermal emissions by approximately 40% compared to thermal reactors with the same electric power.

Creation of a Closed Fuel Cycle [6]. The first BN-350 and -600 reactors have been brought on-line and are still operating in the converter mode, because the production of uranium-plutonium oxide fuel has still not been perfected. This solution would make it possible to accelerate the construction of these reactors and is justified because of our well-developed uranium production and enrichment industry.

The efficiency of pellet mixed oxide fuel has been confirmed by irradiation of experimental fuel assemblies in BOR-60, BN-350, and BN-600 reactors. The fuel elements for these fuel assemblies are fabricated on an experimental setup at the Industrial Association "Mayak." Fuel assemblies with vibrationally compacted mixed fuel, test production of which was instituted at the Scientific-Research Institute of Nuclear Reactors, are also being conducted.

Fast reactors will initially operate on plutonium accumulated as a result of the reprocessing of uranium fuel from thermal reactors as well as BN-350 and BN-600 reactors. We note that in our country plutonium is still not used in thermal reactors.

Another possible source of plutonium is conversion of nuclear weapons.

The Industrial Association "Mayak" has unique capabilities for the creation of a closed cycle:

the RT plant, which produces a uranium and plutonium regenerate, is in operation;

Complex 300, which will fabricate fuel assemblies from uranium–plutonium fuel, is under construction (work corresponding to ~50% of the total expenditures has been performed);

a complex of radioactive-waste reprocessing plants is in operation; and,

spent BN-800 reactor fuel can be reprocessed in improved technological divisions of the RT plant.

In summary, if the Southern Ural nuclear power plant with BN-800 power-generating units and Complex 300 are brought on line, a closed fuel cycle will be realized. This cycle will make it possible to concentrate in one location the entire production process, including the extraction and burnup of the most dangerous fissioning plutonium material, and to avoid transporting this material to other parts of the country. The experience gained will form the basis for further extensive development of elements of the nuclear fuel cycle.

Utilization of Weapons Plutonium. The effective and safe use of weapons plutonium is part of the problem of reuse of fuel in nuclear power, and implementation of a safe and ecologically acceptable closed fuel cycle.

Fast reactors are best suited for use of uranium–plutonium fuel, including fuel based on weapons plutonium. The BN-600 reactor, currently burning enriched uranium, is capable of utilizing up to 0.6 tonnes of plutonium per year. One BN-800 unit is designed to use 2.3 tonnes of plutonium for the initial load and 1.6 tonnes for yearly replenishment. The loading of the entire fuel cycle (including the external fuel cycle) will constitute ~10 tonnes of weapons plutonium. Up to now, more than 2000 fuel elements based on mixed fuel have been tested in BN-350 and BN-600 reactors. Not one tested fuel element ruptured with burnup up to 10% at. wt., heat power density rate of 490 W(t)/cm, and cladding temperature of 690°C.

In summary, the fast reactors which are under construction and which are currently operating make it possible to solve quite effectively the problem of utilization of weapons plutonium.

International Collaboration. Since 1955, the results of work performed on fast reactors in different countries have become an object of extensive international exchange. The combined experience of different countries has been incorporated in each national program, especially in the solutions to engineering problems, though the target plants and the strategic role of fast reactors in power production have been treated differently during this period [8-10].

The following considerations can be offered in support of expanding international cooperation:

The new-generation plants must meet international safety standards.

In all countries the sodium-coolant variant has been adopted as the main concept of a fast reactor. An enormous volume of experimental investigations has been performed on test stands and under real conditions for studying the behavior of the core during severe accidents, accompanied by boiling of sodium and melting of the fuel. A large number of complex codes has been developed for calculating the flow of accident processes. These works require large resources, and for this reason they have been performed, as a rule, on the basis of international cooperation. This trend became especially noticeable in the mid-1980s. A graphic example of this is the fact that the leading European countries have joined together to develop a common design of a fast reactor instead of developing national programs in parallel.

The Russian Federation has adequate potential for participating as an equal and worthy partner with foreign countries.

Unification with foreign designs is necessary with respect to the most important structural elements.

Cooperation with foreign partners is necessary for solving problems of radiochemistry and treatment of radioactive wastes. This certainly is of mutual interest.

Conclusions. From the standpoint of domestic and worldwide experience accumulated up to the 40th anniversary of the development of nuclear power, it is obvious that new aspects of the potential of fast reactors are opening up. The possibilities of achieving a high degree of safety, acceptable economy, and a base for implementing the utilization of plutonium from both power production and from weapons, as well as important ecological advantages are now added to what has been well known for a long time – breeding and unlimited expansion of the raw material base. Concentrating the further development efforts in these directions will make it possible to introduce into nuclear power a competitive type of reactor even before large-scale breeding will become necessary.

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