USSR and Russian fast reactor operation through the example of the BN600 reactor operating experience and peculiarities of the new generation BN800 reactor power unit commissioning

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Abstract

The fast-neutron nuclear power industry development began with the BR-5/10 experimental reactors (1959) followed by BOR-60 (1969).

The power reactor evolution started with the BN350 commissioning in 1973. In 1980 the BN600 operating up to now was put into operation. In 2015 the BN800 obtained the first criticality.

BN600 fast reactor power unit No. 3 of 600 MW power has been put into operation in April 1980 and is under day-to-day operating conditions. Over the operating period the advantages of sodium-cooled fast reactor facility were highly appreciated. The complex tasks were also solved to improve safety and cost-effectiveness of the BN600 reactor facility.

Since the commissioning the BN600 reactor facility core has been upgraded three times and the main equipment lifetime has been significantly increased. The work has been carried out to extend the lifetime until 2020, as part of which it has been shown that the strength conditions in all the critical reactor components are not infringed for 45 years of operation.

After the events at Japanese Fukushima NPP the action plan aimed at greater resistance of the BN600 reactor facility against external impacts was put in practice.

Over the operating period the following were carried out at the BN600 reactor:

1. About 500 experimental fuel sub-assemblies were tested to study structural materials and designs of different types, which in particular allowed the fuel burn-up to be dramatically increased.
2. The technologies of repairs and replacement of the large reactor and steam generator components (72 heat exchangers of the steam generators, 3 low pressure cylinders, 6 feedwater pumps, 3 emergency feedwater pumps) were mastered.
3. The experience of the production of the high-specific activity isotopes was accumulated.
4. The long life tests of the large components operating in sodium were carried out.

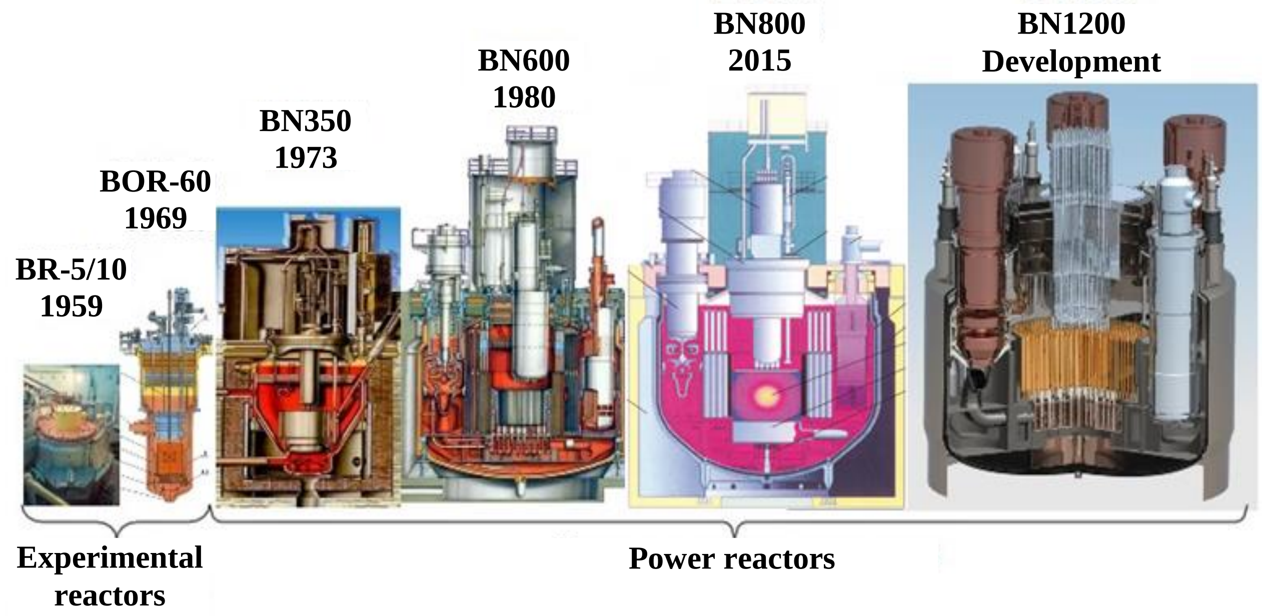
The most important outcome of the operation is a justification of the construction of the new fast-neutron reactor power units (BN800, BN1200).

For 36 years of the safe and reliable operation the main task was fulfilled, i.e. the operation of the powerful unit with the sodium cooled fast reactor and sodium steam generators was mastered.

The BN800 was designed using inherent safety principles and applying an additional reactor shutdown system based on the passive operating principle.

Key words: fast reactor, lifetime, BN600, BN800.

1. Introduction



The fast-neutron nuclear power industry development began with the BR-5/10 experimental reactors (1959) followed by BOR-60 (1969).

The power reactor evolution started with the BN350 commissioning in 1973.

In 1980 the BN600 operating up to now was put into operation.

In 2015 the BN800 obtained the first criticality. In 2016 the BN800 was put into commercial operation.

Beloyarsk NPP is one of the “clean” NPPs. The plant does not make any contribution to the natural environment radiation background, which is confirmed by the monitoring system data.

At Beloyarsk NPP the ALARA principle is consistently implemented and the certificates in the environmental management and compliance with the environmental requirements have been obtained.

2. Operation of Beloyarsk NPP power unit No. 3 with the BN600 reactor

The nuclear plant experience including both the positive and negative operating practices is the most important information source in the framework of the decision generating and making process aimed at the provision of the safe, reliable and cost-effective operation of an NPP.

Beloyarsk NPP BN600 fast reactor power unit No. 3 of 600 MW power has been put into operation in April 1980 and is under day-to-day operating conditions. The advantages of the sodium-cooled fast reactor were highly appreciated during the operating period. In addition the complex tasks of improving the BN600 reactor safety and cost-effectiveness were solved.

2.1 Core upgrade

Since the beginning of the operation the BN600 reactor core was upgraded three times and the main equipment lifetime was significantly increased. On the basis of the core upgrade results the fuel pin linear rating was decreased and the peak burnup was increased, accordingly the functioning reliability and the power unit technical and economic performance were improved. The further enhancement of the effective and efficient utilization of the nuclear fuel in the BN600 reactor is associated with the development of the innovative advanced cores. To carry out this task a number of the scientific and technical problems one of which is the development of the innovative structural materials for the fuel cladding will be needed to be solved.

Now the work is in hand to increase the burnup and test the advanced mixed nitride uranium-plutonium fuel.

2.2. Equipment upgrade and lifetime extension

During operation on the basis of the additional studies and feasibility demonstrations the specified lifetime of the following BN600 main components was extended:

- the core components: 1.5 times,
- the steam generator evaporator stages: 2.5 times, to 125 thou. hours,
- the primary sodium pump: 2.9 times, to 57 thou. hours,
- the secondary sodium pump: 2.5 times, to 125 thou. hours,
- the intermediate heat exchanger: 2.25 times, to 45 years.

On the basis of the utilization of the experience of the equipment operation, upgrade and specified lifetime extension the average capacity factor for the whole BN600 operating period without regard to bringing the unit to full power (1980, 1981) amounts to 75.55 % and the best capacity factor value for a calendar year is 87.45 %.

2.3 Lifetime extension

The positive operating experience from the BN600 power unit allowed the feasibility of the reconsideration of the 30-year service life specified by designer to be demonstrated. On the basis of the carried out work on the lifetime extension it was shown that the strength conditions in all the irreplaceable reactor components are not violated for 45 years of operation.

In the scope of the work on the lifetime extension among others the emergency shutdown cooling system based on the sodium-to-air heat exchanger was implemented, i.e. the reactor decay heat could be removed, if necessary, with the natural primary sodium flow, forced secondary sodium flow through a part of the circuit and forced air cooling of the sodium-to-air heat exchanger.

The BN600 power unit meets the requirements of the Russian Federation standing codes in the field of the nuclear power utilization.

On April 7, 2010, the license to operate Beloyarsk NPP power unit No. 3 in the extra period until 2020 was granted.

At present the work is carried out both to obtain the license to operate until 2025 and substantiate the lifetime extension after 2025.

2.4 Measures to improve safety and reliability

In the framework of the measures to improve reliability and safety the following were carried out:

- the upgraded turbine vibration monitoring system with the vibration protection function was put into operation,
- the 220 kV switchyard air circuit-breakers were replaced with the SF_6 ones,
- the oil circuit-breakers in the 6 kV switchgear were replaced with the vacuum ones,
- the work on the refueling system upgrade was carried out.

On the basis of the analysis of the events at Japanese Fukushima-Daiichi NPP the regulatory authority considered it to be necessary to perform the additional safety inspection of the operating Russian NPPs in the following areas:

- the degree of protection against the external extreme natural and man-made impacts including those with the intensity exceeding the NPP design basis as well as the degree of protection against the combinations of the external impacts,
- the preparedness for the management of the beyond-the-design-basis accidents with the loss of NPP offsite and onsite power,
- the preparedness for the management of the accidents with the loss of ultimate heat sink,
- the preparedness for the management of the severe accidents at an NPP (with the fuel damage beyond the design limits).

Within the scope of taking the measures determined on the basis of the results of the inspections and studies the plant was additionally equipped with the following:

- the mobile diesel generator sets of 2 MW, 0.4/6 kV and 0.2 MW, 0.4 kV,
- the mobile pumping units PNU 250/150, PNU 500/50, PNU 150/120.

Considering the measures taken at power unit No. 3 its resistance to the site specific impacts and the absence of necessity to extend the current design list of the beyond-the-design-basis accidents were confirmed.

2.5 Conclusion

Over the period of power unit No. 3 the following main tasks set during its creation were solved:

- the demonstration of the sustained, safe and reliable operation,
- mastering the sodium technology,
- the long run life tests of large-size equipment operating in sodium,
- the fine-tuning and refinement of the operating conditions and power unit monitoring and control systems.

In addition to the initially set tasks the following were carried out:

- the in-reactor tests and post-irradiation examinations of more than 400 experimental sub-assemblies were carried out to study the characteristics of the structural materials, different type designs and fuel compositions, which in particular allowed the burnup to be dramatically increased,
- the technologies of repairs and replacement of the large-size reactor and steam generator components were mastered,
- the experience of the production of the high-specific activity isotopes was accumulated.

During the power unit operation the following problems have been solved:

- the sodium leakages on the equipment of the primary and secondary circuits. This problem is essentially solved. There have been no sodium leakages since 1993,
- water-sodium reactions in the steam generator. There have been no steam generator tube failures since 1991,
- fuel cladding failures. There have been no power unit shutdowns because of the failures of the design fuel since 1999.

The long-term operation of the BN600 power unit and the results of research are of utmost importance for the safety and operation improvement of the running NPP and for the choice and justification both of the design and circuit solutions during the development of the next generation power units. The most important outcome of the operation is a justification of the construction of the new fast reactor power units.

3. Beloyarsk NPP BN800 reactor power unit No. 4 commissioning

The main goals of the BN800 project are as follows:

- the renewal of the experience in developing and manufacturing the large equipment (reactor, steam generator),
- the mastering of the operation of the mixed oxide fuel,
- the fine-tuning of the closed fuel cycle technologies.

The BN800 reactor power unit was designed applying the principles of the inherent safety and using the additional passive reactor shutdown system.

The main tasks to be solved using the BN800 are fine-tuning of the fuel cycle closure on the pilot and demonstration scale with involving the spent fuel of both thermal reactors and sodium-cooled fast reactors (now the spent fuel is radioactive waste) into the fuel cycle and incineration of the minor actinides in order to reduce radioactive waste activity in the longer term.

3.1Main advantages of the BN800 design against BN600

Design	The reactor is originally designed to operate the uranium-plutonium fuel of different origin and isotopic composition in the core.
Equipment	The equipment was upgraded to ensure higher reactor power with the same diameter of the reactor vessel.
Safety	1. The emergency shutdown cooling system with the sodium-to-air heat exchangers in the secondary circuit was introduced. The system is based on the heat exchanger cooling by the natural air convection. 2. The core with the sodium void reactivity effect close to zero was developed. 3. The passive hydraulically suspended scram rods were developed. 4. The corium trap for confining the molten core in case of a severe accident is installed under the plenum chamber.
Fuel handling	In the refueling system the manual operations with the fresh fuel sub-assemblies are ruled out to ensure the MOX fuel is safely handled.

3.2 Comparative characteristics of the BN600 and BN800 reactor power units

No.	Parameters	BN600	BN800
1	Reactor thermal power, MW	1470	2180
2	Unit electric power, MW	600	885
3	Main equipment configuration: • reactor, type • turbine, pcs * type • generator, pcs * type	BN600 3 * K-200-130 3 * TGV-200M	BN800 1 * K-800-130 1 * TZV-800-2
4	Reactor vessel dimensions: • diameter, m • height, m	12.86 12.60	12.96 14.82

5	Number of the heat removal loops, pcs	3	3
6	Primary coolant parameters, $T_{inlet/outlet}$, ^oC	377/550	354/590
7	Secondary coolant parameters, $T_{inlet/outlet}$, ^oC	328/518	314/505
8	Water-steam parameters, $T_{inlet/outlet}$, ^oC	240/505	210/490
9	Steam generator outlet steam pressure, MPa	13.7	14.0
10	Steam generator design	Modular staged steam generator	Modular staged steam generator
11	Steam reheating coolant circuit	Sodium	Steam
12	Reactor specific consumption of materials, t/MWe	13.0	9.7

3.3 Peculiarities of the BN800 commissioning programme

Because of the specific features of the BN800 reactor (three-circuit heat removal system, use of sodium as primary and secondary coolants) the commissioning is broken down into stages and substages.

Stage A “Precommissioning”. It includes the following substages:

A-1 – sodium reception and accumulation and cleaning of sodium in the secondary tanks,

A-2 – reactor heating with gas, reactor filling with sodium,

A-3 – filling of the secondary loops with sodium,

A-4 – commissioning of the fresh fuel storage,

A-5 – commissioning of the turbine hall systems and equipment.

Stage B “The first criticality achievement”. It includes the following substages:

B-1 – build-up of the minimum critical core charge and criticality tests,

B-2 – build-up of the starting standard core charge and criticality tests.

Stage C “The first connection to grid”. Successively bringing the power unit to 5%, 15%, 35%, 50% full power.

Stage D “Pilot operation”. Successively bringing the power unit to 67%, 85%, 100% full power.

3.4 Peculiarities of the starting charge build-up

Due to the specific feature of the sodium-cooled fast reactors related to the core refueling (under sodium) at the stage “Precommissioning adjustment activities” before sealing the reactor and filling it with sodium to adjust the in-reactor refueling system the dummy core consisting of the steel and boron shield rods, control rod guide tubes, dummy control rods and dummy fuel sub-assemblies was built up.

The first tests of the control rod drives were carried out on the dummy core.

The starting core was built up by successively replacing the dummy sub-assemblies with the fuel sub-assemblies and control and protection system rods “from the centre towards the periphery” according to the first criticality achievement programme. After a fuel batch of certain amount had been loaded the necessary measurements and calculations were performed to estimate the reactor criticality.

The minimum critical charge was obtained on June 21, 2014, with 37 MOX fuel sub-assemblies loaded into the core. The neutron tests on the core were conducted after three MOX fuel sub-assemblies had been additionally loaded into the core on June 26, 2014, to create surplus reactivity.

The tests under the critical conditions confirmed the correctness of the theoretical calculations and analyses of the critical position of the control rods.

The starting charge was obtained on July 20, 2014. The starting charge was a hybrid core, i.e. 16 % of the sub-assemblies were MOX fuel sub-assemblies (with pelletized and vibrocompacted fuel).

3.5 Peculiarities of the BN800 design and systems enhancing the safety

During the commissioning while carrying out the tests the effectiveness both of the passive hydraulically suspended scram rods and emergency shutdown cooling system with the sodium-to-air heat exchangers installed in the secondary circuits was confirmed.

In accordance with the designated purpose the passive hydraulically suspended scram rods drop into the core by gravity, inserting the negative reactivity sufficient to take the reactor subcritical from the power generating level.

The effectiveness of the emergency shutdown cooling system with the sodium-to-air heat exchangers installed in the secondary circuits was confirmed also during the loss of forced flow with scram: the reactor decay heat was removed via the sodium-to-air heat exchangers with the natural flow having established in the primary and secondary circuits.

3.6 BN800 commissioning milestones

Milestone	Date
Completion of the “First criticality achievement” stage	30.07.2015
Beginning of the “First connection to grid” stage	10.11.2015
The first connection to grid	10.12.2015
Beginning of the “Prototype operation” stage	20.02.2016
Beginning of the intermediate outage of the power unit	27.06.2016
Completion of the 15-day integral trial operation	01.09.2016
Obtaining a Rosatom state corporation’s permit for putting in commercial operation	31.10.2016

3.7 Conclusion

For the time-being Beloyarsk NPP power unit No. 4 has been successfully put in commercial operation and is under design operation.

As per the plans and approved programmes before the end of 2019 the BN800 core is planned to be changed over from the hybrid one to the core completely charged with the MOX fuel.

With the BN800 reactor being used the technology of the fuel cycle closure is planned to be fine-tuned and the operation of the reactor core with the recycled MOX fuel of different isotopic compositions is planned to be made possible.