Experience Gained in Russia on Sodium Cooled Fast Reactors and Prospects of Their Further Development

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Lifetime of SFR operation (as of 31.10.2009)

No	Reactor (Country)	First criticality date	Date of shutdown	Operation lifetime, year
		Research facilities with SFR		
1.	EBR-I (USA)	24.08.1951	30.12.1963	12.4
2.	BR-5/BR-10 (Russia)	26.01.1959	06.12.2002	43.9
3.	DFR (UK)	14.11.1959	23.03.1977	17.4
4.	EBR-II (USA)	11.11.1963	09.1994	30.9
5.	EFFBR (USA)	08.1963	1972	9.3
6.	Rapsodie (France)	28.01.1967	15.04.1983	16.2
7.	SEFOR (USA)	1969	1972	~3
8.	BOR-60 (Russia)	14.12.1969	-	39.9
9.	JOYO (Japan)	24.04.1977	-	32.5
10.	KNK-II (Germany)	10.10.1977	23.08.1991	13.9
11.	FFTF (USA)	09.02.1980	18.03.1992	12.1
12.	FBTR (India)	18.10.1985	-	24.1
	Total (research facilities with SFR)			255.6 years
		Power generating reactor facilities with SFR		
1.	BN-350 (Russia/Kazakhstan)	29.11.1972	22.04.1999	26.4
2.	Phenix (France)	31.	-	36.2
3.	PFR (UK)	01.03.1974	31.03.1994	20.1
4.	BN-600 (Russia)	26.02.1980	-	29.7
5.	Super-Phenix (France)	07.09.1985	02.02.1998	12.4
6.	MONJU (Japan)	05.04.1994	-	15.6
	Total (power reactor facilities with SFR)			140.4
	Total (research and power facilities with SFR)			396.0

Lifetime of SFR operation in different countries, years (as of 31.10.2009)

No	Country	Lifetime of research SFR operation	Lifetime of power SFR operation	Total lifetime of SFR operation
1.	Russia/Kazakhstan	83.8 (32.8%)	56.1 (40%)	139.9 (35.3%)
2.	USA	67.7 (26.5%)	-	67.7 (17.1%)
3.	France	16.2 (6.4%)	48.6 (34.6%)	64.8 (16.4%)
4.	Japan	32.5 (12.7%)	15.6 (11.1%)	48.1 (12.1%)
5.	United Kingdom	17.4 (6.8%)	20.1 (14.3%)	37.5 (9.5%)
6.	India	24.1 (9.4%)	-	24.1 (6.1%)
7.	Germany	13.9 (5.4%)	-	13.9 (3.5%)
	All countries	255.6 (100%)	140.4 (100%)	396.0 (100%)

Chronology of Russian experience on SFR

R&D works on SFR were initiated in the USSR in the 2nd half of the 20th century, and they have been underway continuously for over fifty years already.

The real results of these activities are as follows:

- ***Research fast reactor BR-5/BR-10 (IPPE, Obninsk);***
- ***Experimental fast reactor BOR-60 (RIAR, Melekess/Dimitrovgrad);***
- ***Prototype reactor facility (RF) with BN-350 reactor (Mangyshlack power combine, Shevchenko/Aktau, Republic of Kazakhstan);***
- ***Industrial power unit with BN-600 reactor (BelNPP, Zarechny);***
- ***Design of industrial power unit with BN-800 reactor (its construction is underway in Zarechny, at the BelNPP site).***

Successful functioning of SFR facilities operated and currently operating in Russia, where elements of SFR technology were tested and upgraded, confirms a high level of industrial mastering SFR technology in our country.

Main phases of mastering SFR technology

The history of SFR development in Russia testifies to a regular and consecutive (step-wise, i.e. phase) character of mastering this reactor technology.

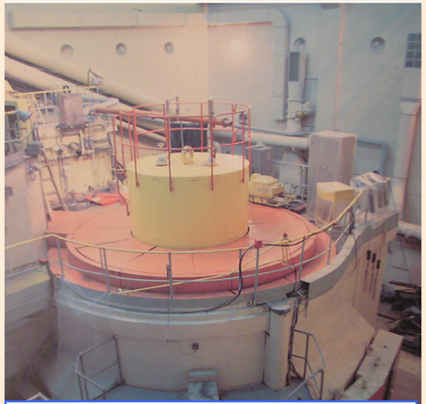
The following major phases can be defined in creation and mastering SFR technology in Russia:

- ***Initial phase – justification of SFR feasibility (based on BR-5 experience);***
- ***Phase of confirming SFR viability at industrial level (by example of prototype BN-350 RF);***
- ***Research and choice of principal design and technical proposals for demo industrial facility within the framework of development of BN-600 RF design (considering experience with operation of BOR-60 and BN-350 facilities);***
- ***Justification of reliability and safety of SFR technology (operation of industrial power unit with BN-600 reactor as an example).***

The following phases could be defined in accordance with further tasks of SFR technology development and upgrading:

- ***Demonstration of the closed fuel cycle of SFR (on the basis of BN-800 reactor);***
- ***Phase of SFR technology commercialization (design development and construction of the commercial reactor BN-K);***
- ***Phase of an extended deployment of SFR technology (construction of a small series of commercial power units with BN-K reactor).***

Initial phases of development and mastering SFR technology
BR-5/BR-10



BR-5/10
(1959-2002, Obninsk)

The main goals of BR-5 included the following:

- *Experimental demonstration of feasibility of creation and operation of sodium cooled fast reactor with parameters corresponding to the parameters of power facilities;*
- *Confirmation of the feasibility of practical implementation of fuel breeding in SFR;*
- *Mastering sodium technology and basic elements of SFR technology within a separate facility;*
- *Fulfilment of tests with different types of fuel compositions and structural materials;*
- *Substantiation of fuel pins' and fuel compositions' serviceability to acceptable burn-up levels (maximum achieved burn-up made 14.1% h.a. – for plutonium dioxide, 6.1% h.a. – for uranium monocarbide, 9% h.a. – for uranium mononitride).*

Initial phases of development and mastering SFR technology

BR-5/BR-10

It is also necessary to note reconstruction of BR-5 reactor into BR-10 in 1971-73, and then reconstruction in 1979-83.

A series of investigations on mastering SFR technology elements has been done in subsequent periods of BR-5/BR-10 reactor operation:

- *Experiments with operation of failed fuel pins and substantiation of a cladding tightness monitoring system based on indication of delayed neutrons in coolant;*
- *Detailed study of mass transfer and distribution of different impurities and nuclides (Mn, Co, Cs and others) over the primary circuit and development of methods for control of fission and corrosion products' activity in coolant and on the walls of the primary circuit pipelines;*
- *Development of technology for purification of coolant from oxides and radioactive cesium;*
- *Development of technologies for removal of non-drainable sodium residues from the circuit by vacuum distillation, washing (steam, steam-gas mixture) internal circuit surfaces from sodium and their decontamination, etc.*

Nowadays BR-10 reactor is under preparation for decommissioning, and it is used for development of technological processes proposed for SFR decommissioning.

An extensive operation experience has been gained at BR-5/BR-10 reactor, including that on sodium leaks, operation with failed fuel pins, determining lifetime of structural materials under irradiation and corrosion effects of sodium coolant, etc.

This experience is used for continued upgrading SFR technology and improvement of its technical and economic performance.

Initial phases of development and mastering SFR technology

BOR-60

BOR-60
(1969, Dimitrovgrad)

The scheme of BOR-60 RF models, in a full scope, design of NPP with SFR. This gave an opportunity to test all basic elements of NPP with SFR at BOR-60. High neutron-physical and thermal characteristics of BOR-60 reactor make it possible to perform in-pile testing fuel pins, fuel compositions, and structural materials for SFR under conditions corresponding to those of power reactors.

Thus, BOR-60 has played an important role in justification of various design and technical proposals for power SFR and adjusting different systems and technologies.

The following works contributed to SFR technology development and upgrading:

- ***Tests of various fuel compositions, structural materials and absorbing materials, including fuel pins with vibropacked MOX fuel;***
- ***Tests of different types of steam generators (SG), including section of the modular BN-600 SG and reverse SG (RSG) of micromodular and modular design;***
- ***Experiments for study of processes of water-sodium interaction under small (up to 0.2 g/s) and large (to 0.25 kg/s) water leaks, checking various methods for leak indication and confirmation of serviceability and reliability of SG protection systems;***
- ***Implementation of complex studies on technology of sodium and sodium equipment, including justification of serviceability of systems for sodium purification from impurities and cesium, regeneration of oxide cold traps, decontamination of equipment in contact with sodium, etc.***

Initial phases of development and mastering SFR technology

BOR-60

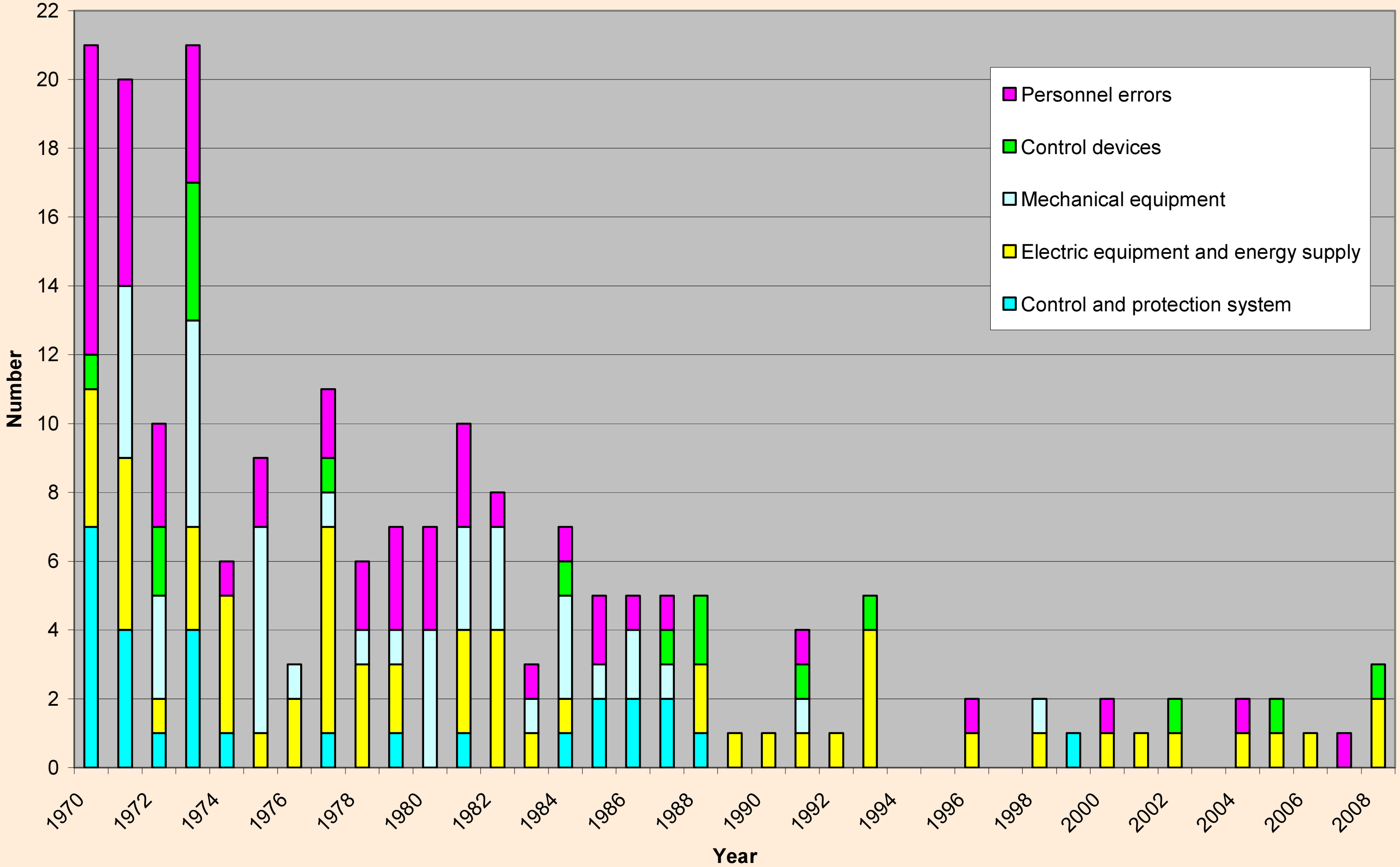
Design operation time of BOR-60 reactor is ending late this year, and now the works are carried out on its lifetime extension for period till 2015.

During operation period of BOR-60 reactor (more than 225 000 hours in critical condition), considerable experience was gained on faults of some RF elements, their inspection and repair, on operation time achieved for non-replaceable RF elements under irradiation, on lifetime achieved for main equipment, etc., which can be used in further upgrading SFR technology.

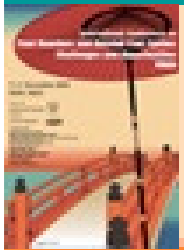
In particular, unique experience has been obtained with long-term operation of RSG without any leaks (29-year operation of RSG-1 and 19-year operation of RSG-2).

Initial phases of development and mastering SFR technology

BOR-60

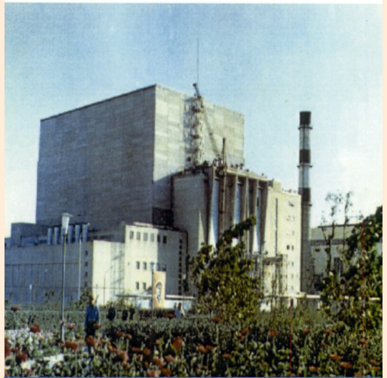


Distribution of unscheduled BOR-60 shutdowns on initial events and years



Initial phases of development and mastering SFR technology

BN-350



BN-350
(1972-1999, Aktau)

BN-350 RF operation on the whole has shown correctness of principal solutions accepted in its design, demonstrated stability and easiness of SFR control, their sufficient reliability and safety.

Though the problem of ensuring SG reliability was indicated at the initial period of BN-350 operation owing to numerous leaks appearing because of insufficient manufacturing quality of heat exchange Fild's tubes applied in SG evaporators:

- ***During the first two years (1973-75) 8 leaks had occurred, including three "large" ones;***
- ***12 leaks altogether occurred in SG with Fild's tubes for entire operation period.***

A fast self-development of small SG leaks into large ones was revealed. This required improvement of SG protection systems against leaks and increasing their response speed.

The experience concerning leaks in BN-350 SG influenced subsequently transition from vessel-type SG (BN-350 SG with Fild's tubes, BOR-60 vessel coil-type SG) to sectional-modular SG (BN-600 and BN-800 sectional-modular SG, BN-350 micromodular SG "Nadezhnost", BOR-60 micromodular and modular SG).

Summarizing BN-350 operation experience, we can say that it has confirmed the possibility of implementation of this reactor technology at the level of an industrial power unit.

The knowledge gained during BN-350 operation has provided a reliable basis for development and upgrading BN-600, BN-800 designs, designs of advanced SFR and for further upgrading SFR technology.

Phase of justification of reliability and safety of SFR technology

BN-600

BN-600
(1980, Zarechny)

Principal difference of BN-600 from previous SFR designs is an integral configuration of the primary circuit.

The correctness of decisions accepted in BN-600 design was confirmed subsequently by its successful operation for nearly 30 years.

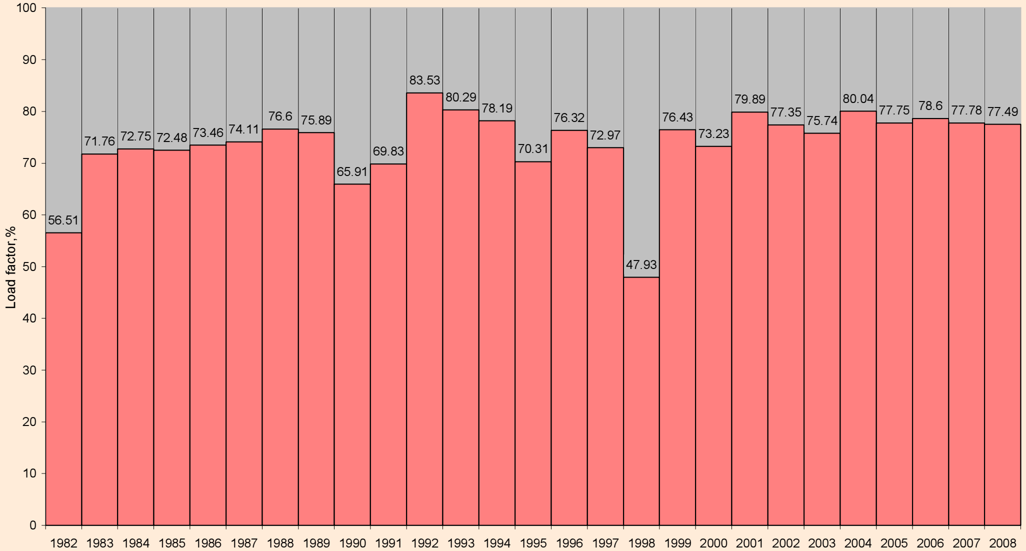
BN-600 was connected to the grid on April 8, 1980; design power level was reached in December 1981.

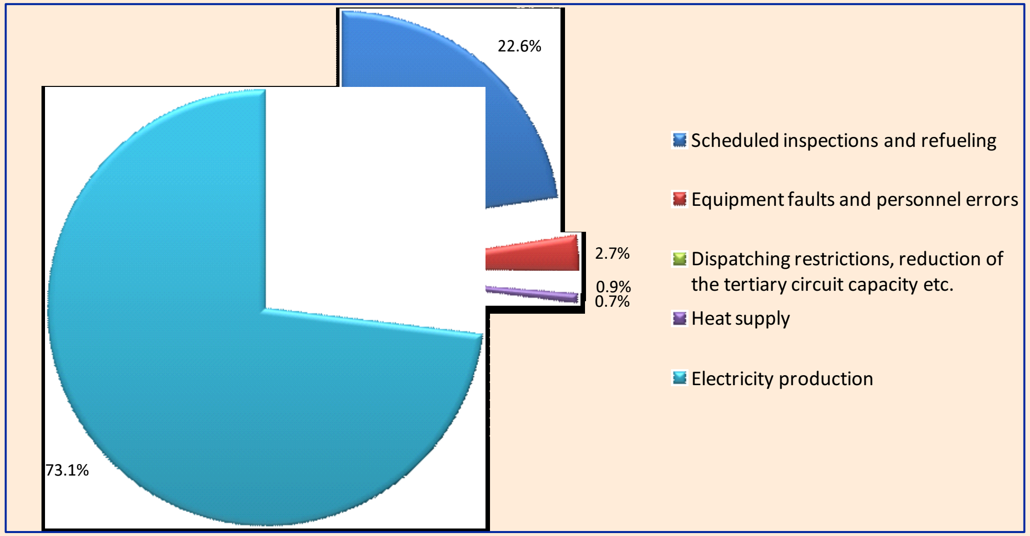
Beginning from 1982, power unit No.3 of Beloyarsk NPP with BN-600 reactor operates as a commercial power unit. Average load factor during this period (1982-2008) is equal to 73.82%.

For the whole period of its operation (about 205 000 h in critical condition), BN-600 produced more than 110 billion kW·h of electric power.

Phase of justification of reliability and safety of SFR technology

BN-600 load factor



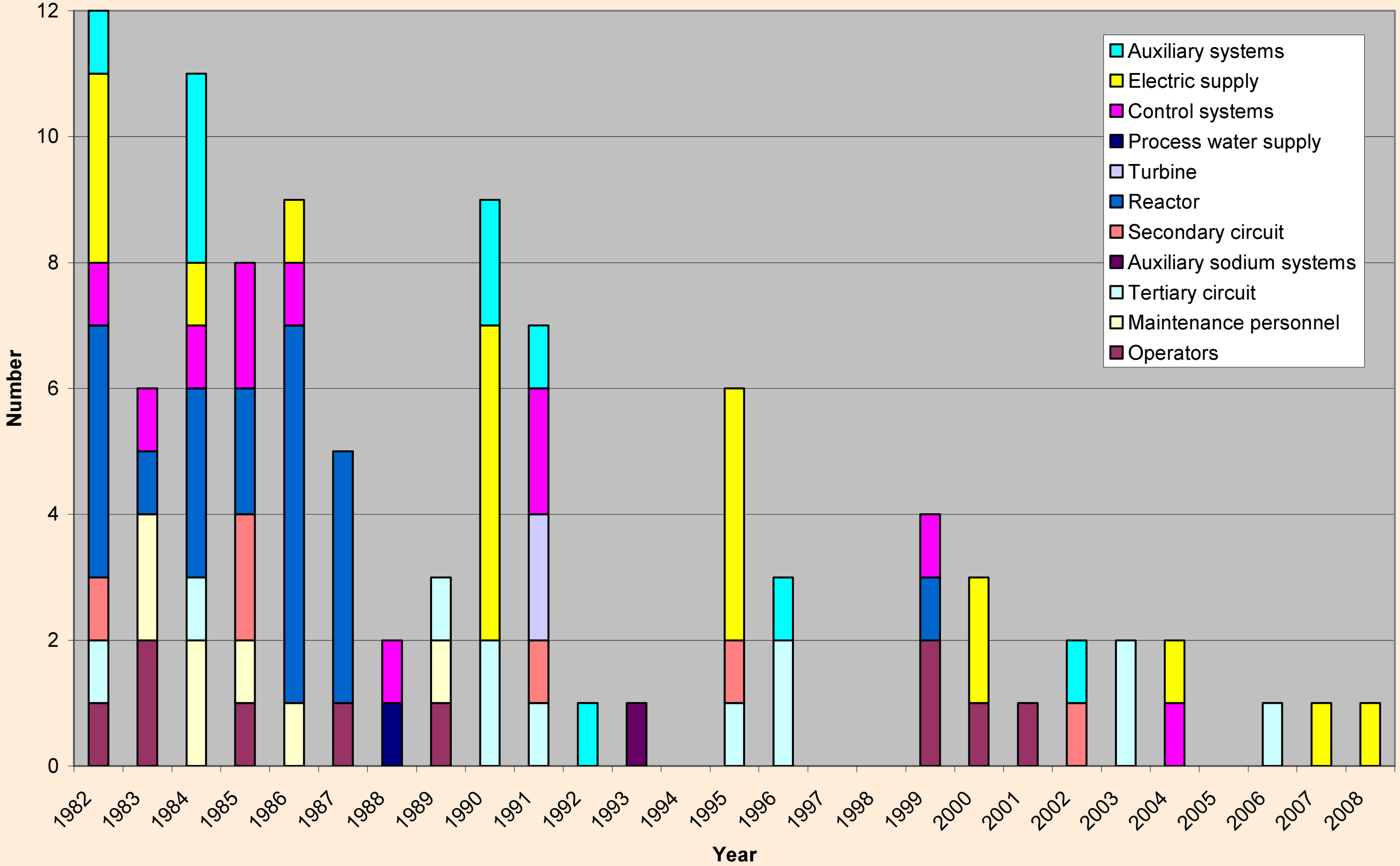


Change of load factor during BN-600 power unit commercial operation

Distribution of causes of decrease of the BN-600 power unit's load factor

Phase of justification of reliability and safety of SFR technology

BN-600



Time distribution of equipment faults and personnel errors during BN-600 power unit commercial operation

Phase of justification of reliability and safety of SFR technology

BN-600 operational experience

The main results of BN-600 reactor operation are as follows:

- *Long-duration tests of large-size sodium components;*
- *Mastering sodium technology in industrial scale;*
- *Development and optimization of operation modes;*
- *Achievement of acceptable level of fuel burn-up;*
- *Mastering technology of replacement and repair of sodium components including the main equipment (pumps, steam generators, intermediate heat exchangers, rotating plugs).*

Replacement of the following main equipment of BN-600 power unit was performed during its operation:

- *4 sets of the primary sodium main circulating pumps;*
- *1 set of the secondary sodium main circulating pumps;*
- *1 set of mechanisms of the control and protection system (CPS);*
- *3 sets of guide tubes of CPS rods;*
- *Nearly complete set of SG modules + 1 set of evaporator SG modules;*
- *1 intermediate heat exchanger.*

Unique repair of the small rotating plug has been fulfilled.

Phase of justification of reliability and safety of SFR technology

BN-600 reactor core designs evolution

Parameter	Reactor core type			
	01	01M	01M1	01M2
Period of the core type operation	1980-1986	1987-1991	1993-2004	since 2005
Active core height, mm	750	1000	1030	1030
Axial blankets height, mm				
- upper	400	300	300	300
- lower	400	380	350	350
Number of fuel enrichment zones	2	3	3	3
Fuel pin gas plenum length, mm	808	653	653	653
Core structural materials:				
- fuel pin cladding	EI-847	EI-847	ChS-68cw	ChS-68cw
- FSA wrapper	Cr16Ni11Mo3	Cr16Ni11Mo3Ti	EP-450	EP-450
Fuel pin maximum linear heat rating, kW/m	54.0	47.2	≤48.0	≤48.0
Maximum fuel burnup, % h.a.	7.2	8.3	10	11.1
Maximum radiation dose to cladding, dpa	43.5	53.9	75.0	82.0
Fuel operating life, fpd	200/300	300/495	480	560/720
Core fuel cycle, fpd	100	165	160	120/160
Fuel inventory in core, kg	8260	11630	12090	12090
Average fuel burnup, MW·d/kg U	42.5	44.5	60.0	70.0

Phase of justification of reliability and safety of SFR technology

Sodium technology experience

Operation time and lifetime of SFR equipment without overhaul

Type of equipment	BR-5/BR-10	BOR-60	BN-350	BN-600
Non-replaceable equipment:				
Reactor vessel	150 000	225 000	170 000	205 000
Primary pipings	300 000	225 000	170 000	205 000
Sodium pumps	170 000 electromagnetic	260 000 mechanical	100 000 mechanical	105 000 mechanical
Intermediate heat exchangers	300 000	225 000	170 000	205 000
Steam generators	-	155 000 reverse SG	150 000	125 000 evaporators

The data presented testify to a good compatibility of sodium coolant with structural materials used and its low corrosion activity in mastered range of SFR parameters.

Phase of justification of reliability and safety of SFR technology

BN-600 operational experience

Altogether, there were 27 outside sodium leaks and 12 leaks in SG during BN-600 operation.

The experience gained on outside sodium leaks showed sufficient efficiency of protection systems for localizing leaks' consequences:

- ***All outside sodium leaks were detected in due time by detection systems or by operating personnel.***
- ***Powders were used for localization and extinguishing non-radioactive sodium fires.***
- ***There was the only case with radioactive sodium leak from auxiliary pipeline of the primary circuit when design algorithm of confinement of sodium fire consequences was implemented successfully (radioactivity release was much lower than permissible limit).***

Sectional-modular SG used in BN-600 power unit have demonstrated high performance for the whole period of operation:

- ***Half of 12 SG leaks occurred in the first year of operation, they were caused by development of latent manufacture defects.***
- ***Intercircuit leaks took place mainly in the superheaters (6 events) and reheaters (5 events), whereas only one leak occurred in the evaporator.***
- ***All SG leaks were suppressed by regular means, and they did not result in emergencies.***

Evaluating all abnormal events occurred during BN-600 operation, including those associated with sodium leaks, we should specially emphasize that none of them ever resulted in radiation impact on the population and environment – all of them are below International Nuclear Event Scale range by "off-site impact" criterion, i.e., they are insignificant.

Phase of justification of reliability and safety of SFR technology

BN-600 operational experience

To date, BN-600 power unit has operated practically full design lifetime equal to 30 years. The following facts should be mentioned in this connection:

- ***The last outside sodium leak occurred at BN-600 more than fifteen years ago – in May 1994.***
- ***As for leaks in SG, during recent 24 years of BN-600 operation there was only one small leak in SG in January 1991. SG have operated without any intercircuit leaks for nearly 19 years, in spite of numerous replacements of SG modules made in this period according to the regulations and SG lifetime.***
- ***As it was mentioned above, faults that occurred in recent years were mainly related to technological equipment of the tertiary circuit and electric power supply systems, but not to sodium systems.***

Thus, BN-600 reactor has demonstrated high safety and reliability indices during its commercial operation, and, therefore, allowed a successful solution of the task set – justification of safety and reliability of SFR technology at industrial level, in particular, sodium coolant technology.

Phase of justification of reliability and safety of SFR technology

Lifetime extension of BN-600

Successful operation of BN-600 power unit served as the basis for organizing activities for extending its design lifetime from 30 years to 45 years.

These activities are carried out in the following areas:

- ***Justification of serviceability of non-replaceable elements of reactor plant for additional period of operation;***
- ***Inspection and lifetime extension of elements not planned to replacement;***
- ***Replacement of equipment;***
- ***Implementation of stipulated measures on enhancement of power unit's safety;***
- ***Development of the Report on Profound Safety Estimation of the power unit and a complete set of substantiation documentation for reception of a new license on operation.***

The most important results implemented within the frame of BN-600 lifetime extension are as follows:

- ***Confirmation of serviceability of non-replaceable elements for 45-year lifetime;***
- ***Equipping the power unit with the second complete set of emergency protection system and redundant control room;***
- ***Installation of additional decay heat removal system using air heat exchanger;***
- ***Replacement of SG modules (49 of 72 modules have been replaced);***
- ***Increase of seismic stability of power unit's systems and equipment.***

Thus, extension of BN-600 power unit lifetime till 2025 as anticipated would promote:

- ***Further mastering SFR technology;***
- ***Succession of SFR development via training of the personnel for new SFR power units.***

Prospects of SFR development in Russia

BN-800

Successful experience with BN-600 operation has created good prerequisites for the further SFR development in Russia.

Nowadays power unit No.4 with BN-800 reactor is under construction at the site of Beloyarsk NPP with commissioning scheduled in 2012.

One of the major tasks to be resolved in the course of BN-800 operation is demonstration of closed nuclear fuel cycle (CNFC).

The implementation of CNFC with SFR will mean the mastering of full complex of SFR technology. This will give an opportunity to resolve problem of both extension of fuel base for nuclear power industry, and utilization of spent nuclear fuel, including minor actinides.

Prospects of SFR development in Russia

FTP on new technological platform for nuclear power

The Federal Target Programme (FTP) "Nuclear power technologies of a new generation for period of 2010-2015 and with outlook to 2020" has been developed.

In accordance with this Programme, a further development of SFR is stipulated in Russia within the framework of creation of the new technological platform for nuclear power based on transition to the CNFC with the 4^{th} generation fast reactors.

The development of advanced commercial BN-K reactor design with installed electric power of 1200 MW (BN-1200) is planned as SFR of the 4th generation.

It is supposed that this design will ensure economic characteristics comparable with those of thermal NPP and achieve safety level meeting the requirements defined for the 4th generation reactors.

Thus, designing and construction of BN-1200 reactor will be carried out within the SFR technology commercialization phase.

Possibilities of construction of a pilot NPP with BN-1200 reactor by 2020 and small series of BN-1200 by 2030 that will correspond to the phase of deployment of SFR technology, are under discussion.

In order to provide R&D necessary for development of the 4th generation innovation fast reactors, FTP stipulates modernization of related experimental base.

In particular, construction of a multifunctional research fast reactor MBIR with sodium coolant is scheduled after 2015.

CONCLUSIONS

- **The review of SFR development in Russia gives evidences of their systematic progressive evolution during the whole period of activities in this area (more than 50 years).**
- **The analysis of experience gained in Russia on SFR in recent 30 years, primarily the results of successful and stable operation of power unit No.3 of the BelNPP with BN-600 reactor, gives grounds to draw a conclusion about industrial mastering SFR technology, in particular, sodium technology.**
- **The SFR operating indices achieved provide good prerequisites for their further commercialization and enhancement of safety.**
- **The Federal Target Programme “Nuclear power technologies of a new generation for period of 2010-2015 and with outlook to 2020” suggests further development of SFR in Russia in the framework of creating the new technological platform for nuclear power based on transition to closed nuclear fuel cycle with the 4th generation fast reactors.**

Thank you for your attention !