Modern Approaches to Safety Assurance of Sodium Fast Reactors of a New Generation

I.M. Ashurko[a], A.A. Kamayev[a], V.M. Poplavsky[a], B.A. Vasilyev[b], S.L. Osipov[b], A.I. Staroverov[b], S.F Shepelev[b]

[a]FSUE "SSC RF – Institute for Physics and Power Engineering", Obninsk, Russian Federation

[b]JSC "OKBM Afrikantov", Nizhny Novgorod, Russian Federation

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Contents

New generation of reactors and safety requirements to them

Sustainable development of nuclear power in the future can only be provided by means of fast reactors (FR).

The following 4th generation advanced reactors are considered as candidates:

- *Sodium-cooled fast reactors (SFRs)*
- *Fast reactors with heavy liquid metal coolants (HLMC)*
- *Gas-cooled fast reactors*
- *Supercritical water-cooled reactors*
- *Molten-salt reactors.*

SFRs are the most developed and mastered as compared to others.

The following general safety goals which should be achieved in the 4th generation NES designs have been formulated within the GIF framework:

- *Safety and reliability should exceed their level in existing NES*
- *Probability and degree of reactor core damage should be minimized up to very low value*
- *Need for any off-site emergency response should be eliminated.*

But now all specialists agreed that specific safety design criteria should be developed for each type of the 4th generation NES.

BN-1200 as advanced reactor of new generation

BN-1200 design is developed within the framework of the Federal Target-oriented Program (FTP): “Nuclear Power Technologies of a New Generation for Period of 2010-2015 and with Outlook to 2020”.

It is considered as integral part of the “Breakthrough” Project aimed at the creation of a new technological platform for future nuclear power in Russia based on fast neutron reactors and closed nuclear fuel cycle.

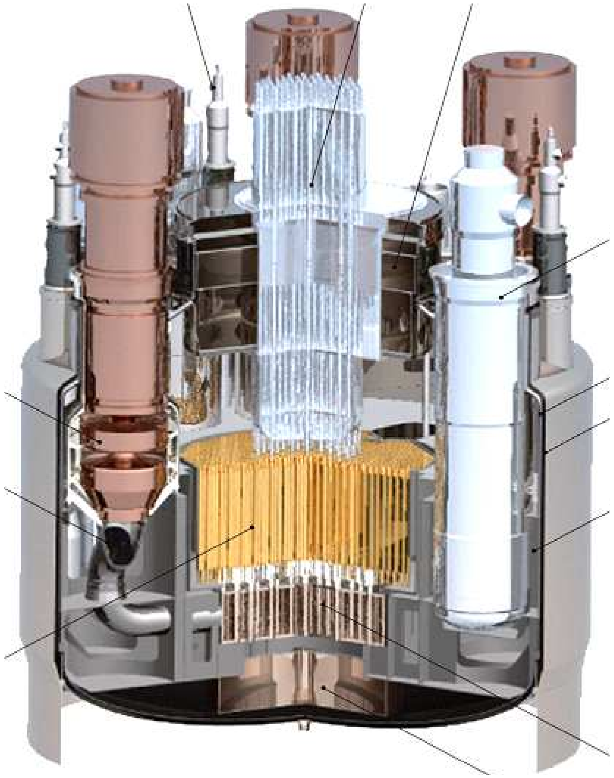
Natural safety philosophy formulated in the “Breakthrough” Project postulates deterministic elimination of severe accidents that require evacuation of the population from the area adjacent to the NPP by application of inherent safety features and passive safety systems.

BN-1200 design as advanced reactor of a new generation should meet these safety requirements that are strongly correlated with safety requirements for the 4^{th} generation reactors.

Thus, modern approach for safety substantiation of the advanced SFRs of the new generation can be illustrated by means of analysis of approach applied for safety justification of the BN-1200 design.

In particular, it is interesting to indicate changes in modern safety approach in comparison with safety approach used for substantiation of the previous Russian SFRs.

Main BN-1200 parameters



Parameter	Value
Rated thermal power, MW	2800
Electric power, MW	1220
Load factor, %	90
NPP efficiency, %: –gross –net	 43.5 40.7
Number of heat removal loops	4
Primary and secondary circuit coolant	Sodium
Working medium in the tertiary circuit	Water/steam
Design lifetime, year	60
Flowrate of the primary sodium, kg/s	15784
Flowrate of the secondary sodium, kg/s	12776
Primary sodium temperature (IHX outlet/inlet), °C	410/550
Secondary sodium temperature (SG outlet/inlet), °C	355/527
Tertiary circuit parameters: –live steam pressure, MPa –live steam temperature, °C –feedwater temperature, °C –steam reheating option	 17.0 510 275 Steam
Fuel	Nitride, MOX

Fundamental for development of the BN-1200 design

Development of the BN-1200 design, in particular, design solutions on safety systems and approach to safety substantiation of the power unit in the whole, is based on:

- *Experience gained in SFR designing, constructing and operating (BR-5/10, BOR-60, BN-350, BN-600 and BN-800)*
- *Fundamental SFR features*
- *Requirements of acting national safety regulatory documents*
- *Specific requirements to the BN-1200 formulated within the framework of the “Breakthrough” Project*

Russian SFR experience

4 SFRs have been successfully operated in the USSR and in the Russian Federation:

- *Experimental reactor BR-5/10 in Obninsk*
  - *(start-up on 26 January 1959, finally shut down on 6 December 2002)*
- *Research reactor BOR-60 in Dimitrovgrad (Melekess)*
  - *(start-up on 14 December 1969, by now its lifetime has been extended till 31.12.2014)*
- *Prototype power reactor BN-350 in Aktau (Shevchenko)*
  - *(first criticality gained on 29 November 1972, finally shut down on 22 April 1999)*
- *Commercial power unit No. 3 of Beloyarsk NPP with BN-600 reactor*
  - *(first criticality gained on 26 February 1980, 30 years design lifetime has been extended up to 40 years - till 31 March 2020).*

So, as of December 2012, the total SFR operation experience in the USSR and Russia exceeded147 reactor-years, i.e. more than 34% of the worldwide SFR operation experience (over 427 reactor-years).

Fundamental SFR features

- Chemical activity of sodium coolant with respect to air and water
- Sodium activation (formation of radioactive isotope Na^{24} with ~15 h half-life)
- Possibility of realization of a positive sodium void reactivity effect (SVRE) in case of sodium boiling onset in the core
- Fair thermal physical characteristics of sodium coolant, which are qualified as inherent safety characteristics:
  - *High thermal conductivity of sodium would assure high heat transfer in both forced and natural coolant flow modes and, hence, the relatively small-size reactor core with the stable, easy-to-control power profile can be used*
  - *Low melting point (98°C) making it possible to easily maintain liquid coolant condition*
  - *High boiling temperature (880-960°C) assures high level of working temperatures (500-550°C) with high margin (over 300°C) for sodium boiling temperature*
  - *Large thermal capacity of the sodium circuits would facilitate smoothing of transients under conditions of Unprotected Loss of Heat Sink Accident*
  - *Possibility of providing effective natural circulation of sodium coolant in the heat removal circuits assures self-protection against the accidents with loss of power supply*
  - *Possibility of stable effective heat removal from the fuel pins in the coolant boiling mode*
- Good sodium compatibility with structural materials and its low corrosiveness
- Low pressure in the sodium circuits (close to atmospheric pressure value)
- Negative temperature and power reactivity effects assuring stable negative power and temperature reactivity feedback.

Requirements of acting national safety regulatory documents

Existing national safety regulatory documents, such as NP-001-97 (OPB-88/97), NP-082-07 (PBYa RU AS-89) etc, contain safety design criteria not only for NPPs with specific type of reactor, but for NPPs with various types of reactors operated in Russia.

These regulatory documents define key principles, criteria and approaches for safety analysis and safety substantiation, in particular Defense in-Depth (DiD) concept.

NPP design should provide for the required technical means and organizational measures aimed for prevention of exceeding safe operation limits and conditions, including prevention of DBAs and minimization of their consequences and ensuring safety in case of any single initial event considered in the design with superposition of independent failure of:

- *One element of safety systems – active or passive one having mechanical moving elements*
- *Or one personnel error independent on the initiating event.*

Value of probability of the core disruptive accident (CDA) should not exceed 10^{-5} per reactor year.

For avoiding the necessity to evacuate the population efforts should be made in design to ensure that probability of limiting emergency radioactivity release beyond established boundaries will not exceed 10^{-7} per reactor year.

Safety requirements to the BN-1200 design

BN-1200 design should provide elimination of severe accidents that require evacuation of the population from the area adjacent to the NPP by means of maximal application of *inherent safety features* and *passive safety systems*.

These measures should provide under any *possible realistic accident*:

- *Reactor shutdown with maintaining core components temperature at acceptable level*
- *Decay heat removal from the reactor without any damage of its structures*
- *Confinement of the major part of radioactive products released from the reactor under possible accident conditions within reactor building.*

Term "*possible realistic accident*" means any initial event, even with very low probability, accompanied by superposition on the initial event of:

- *Failures of all active safety systems*
- *Single failures of elements of passive safety systems (having mechanical moving parts) provided by the design for restriction of consequences of the given initial event*
- *Failures of active safety-related systems of normal operation*
- *And erroneous actions of the personnel.*

BN-1200 design should meet the following requirements:

- *Total probability of severe BDBAs that can lead to significant damage or meltdown of the reactor core should not exceed 10^{-6} 1/reactor-year, and all damaged structural elements of the core should be kept within the reactor vessel*
- *Value of radioactivity release into environment under any possible realistic accident should not exceed radiation dose for population outside of the NPP site boundaries, specified by the regulatory documents, that requires evacuation of residents.*

Safety design solutions for the BN-1200 design (1/2)

Based on positive experience gained in SFR area in Russia, the following mastered safety-related solutions are used in the BN-1200 design:

- *Traditional three-circuit design with steam-water tertiary circuit excluding interaction of radioactive sodium with water and overpressure of the primary circuit in case of SG leaks*
- *Reactor guard vessel preventing radioactivity release from the reactor even in case of failure of main reactor vessel*
- *Sodium plenum above the core for decreasing SVRE*
- *Core catcher made of refractory metal for confinement and cooling of corium in case of postulated CDA*
- *Passive shutdown systems (PSS) with hydraulically suspended absorber rods operating in case of decrease of coolant flow rate through core (PSS-H)*

Safety design solutions for the BN-1200 design (2/2)

New design solutions used in the BN-1200 as compared to those applied in the previous Russian SFR designs are as follows:

- *Pool design of the primary circuit with location of all sodium systems (including cold traps, neutronics and chemical-engineering control systems) in the reactor vessel practically eliminating leaks of the radioactive primary sodium*
- *Passive decay heat removal system (DHRS) using independent loops connected directly to the reactor vessel*
- *Design measures on elimination or minimization of non-radioactive sodium leaks from the secondary loops and intermediate DHRS loops*
  - *In particular, minimization of surface area of SG sodium components by transition from sectional-modular SG design to integral one*
- *Additional PSS with absorber rods operating in case of increase of the core outlet coolant temperature above the certain value (PSS-T)*
- *Gas-tight compartment above the reactor used for radioactivity confinement under severe accident condition.*

Approach to the BN-1200 safety analysis

- Meeting all requirements of acting national regulatory documents
  - *Implementation of the DiD concept*
  - *Application of deterministic and probabilistic methods for safety analysis*
- Consideration of all possible realistic accidents in the BN-1200 design and application of appropriate inherent safety features and passive safety systems to meet design safety criteria and limits
- Evaluation of self-protection of the BN-1200 against severe accidents not included into list of realistic BDBAs, in particular ULOF accident with failure of all active and passive shutdown systems

Safety potential of the BN-1200

- For evaluation of the BN-1200 self-protection against severe beyond design basis accident, exceeding possible realistic accident, analysis of ULOF accident with postulated failure of all active and passive reactor shutdown systems including all PSS-H and PSS-T rods was made:
  - *Preliminary results of this analysis show the possibility to avoid melting of fuel pin claddings and fuel even in case of sodium boiling onset in the core*
    - *This is provided by the use of special design of the BN-1200 reactor core with sodium plenum at the core outlet*
    - *Besides, alternative core design options, such as axial layer of depleted uranium, layer with moderator, etc. are studied in order to decrease SVRE value*
- Chosen passive DHRS design increases fundamentally resistance of the BN-1200 power unit against the accidents similar to those occurred in Fukushima-1 NPP, since it does not require any additional power source for its operation.
- Chosen arrangement of the primary circuit of the BN-1200 allowed practical elimination of any radiological consequences of sodium leaks in the system.

Conclusion

- Analysis of approaches to safety assurance for advanced SFR designs of the next generation made with regard to the BN-1200 design shows the possibility of meeting all safety requirements imposed to the 4^{th} generation NES.
- This makes it possible to consider SFR as the real basis for achieving the goal of sustainable and safe development of nuclear power even in the nearest future.
- It is important to provide development of the common safety design criteria for SFR of the 4^{th} generation.

Thank you

for your attention !