RESULTS OF BN-1200 DESIGN ASSESSMENT FOR THE COMPLIANCE WITH THE REQUIREMENTS OF GENERATION IV AND INPRO

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Abstract. The project of a power unit with BN-1200 reactor is designed using advanced technical solutions, which define evolution of the fast breeder technology in the field of safety parameters and in the field of technical and economical indicators.

At present there was completed estimation of the BN-1200 project from the point of view of its compliance with the requirements of nuclear energy systems of Generation IV in the frames of International forum Generation IV, and comparison of the BN-1200 project with other fast breeder projects using NESA INPRO procedure, developed and verified for comparison of nuclear energy systems with PWR.

The paper presents the results of preliminary estimation by the INPRO procedure, which showed that BN-1200 has good margin of safety and economical characteristics in comparison with the previous projects; and BN-1200 meets all the basic principles in the fields of ‘safety’ and ‘economics’; and BN-1200 can ensure sustainable development of the nuclear energy system.

Estimation results of the BN-1200 concept for compliance with the requirements to Generation IV plants testify that BN-1200 project, as a whole, has good potential from the point of view of compliance with the stated requirements.

1. Introduction

The long-term energy security and sustainable development of the economy — as related to both guaranteed energy supplies to any region and to preservation of nonrenewable resources, as well as to solving the environmental issues — in many ways depend upon the scale on which the nuclear power is used.

The basic risks in the development of the nuclear power are identified by:
- specific cost of electricity generation, primarily by the high capital cost component;
- features of nuclear power station operation as a nuclear hazardous facility;
- dependence on the natural resources, the amount of which is limited;
- spent nuclear fuel (SNF) management;
- nuclear material proliferation resistance;
- need for long-term planning with account of the entire lifecycle of facilities.

At the same time, the economic characteristics and the nuclear, radiation and environmental safety characteristics become the main factor of the competitive ability. A power unit should be a competitive “product” at the promptly developing market of energy sources.

As for the SNF and radwaste management, the underlying principle of the ROSATOM's policy is to ensure the SNF reprocessing with the economically profitable and environmentally acceptable management of the recycled materials and radwaste.

The innovative power unit design with the BN-1200 reactor is being developed with the use of the new engineering solutions that determine the development of the SFR technology in terms of both safety features and technical-and-economic performance.

As of now, the BN-1200 reactor design has been assessed for its compliance with the requirements for Generation IV nuclear power systems as part of the Generation IV International Forum (GIF), and the BN-1200 design has been compared with other SFR designs with the use of the NESA-INPRO methodology developed and verified through comparing the nuclear power systems with the VVER reactors.

2. Basic Requirements for and Development Status of the BN-1200 Design

The development of the BN-1200 design ensures the evolution of the SFR technology and is based upon the use of new engineering solutions, verified R&D activities in addition to those proven by the predecessor designs.

As shown in FIG. 1, the basic design requirements [1] condition the development of the engineering solutions and the competitive ability of the BN-1200 power unit at the market of energy sources.

SAFETY:	**RELIABILITY:**	**ECONOMICS:**
• No need to evacuate or resettle the population in any accidents • The total probability of the severe core damage to be ensured below 10^{-6} per reactor-year	• Continuity in the engineering solutions for equipment and systems • The assigned service life of at least 60 years to be ensured for permanent equipment • No more than three replacements of the replaceable equipment over the service life	• Specific capital costs comparable with AES-2006 → VVER-TOI • Power factor of at least 0.9 • Specific metal content of the reactor plant of below 6.0 tonne/MWe • Specific reactor building construction volume, below 550 m^3/MWe • Pilot power unit construction

FIG. 1: Basic design requirements for the BN-1200 power unit.

As of now, the design verification R&D work has been completed; the detailed designs have been completed for the reactor plant, turbine plant; power unit design documents have been prepared with taking into account the R&D results, comments from the industry-wide and on-going design reviews, and the latest work on the improvement of the technical-and-economic performance; the BN-1200 project implementation strategy has been defined. The work results are shown in FIG.2.

2014	• The detailed design of the reactor plant is developed • The detailed design of the turbine plant is developed • The power unit design documents are developed
2015-2016	• The basic R&D work is completed to verify the BN-1200 design • The updating is completed of the reactor plant detailed design, power unit design documents according to the R&D results and comments from the review • The technical and economic studies are completed for the nuclear power generating industry system with the BN-1200 power units • The multi-criteria analysis is completed for the competitive ability of the BN-1200 power unit, including the LCOE calculation

FIG. 2. Design development phases.

3. System Analysis Methodologies

3.1 GIF Methodology

In compliance with the GIF methodology, the requirements for the Generation IV nuclear power systems are formulated as a set of 26 specific criteria/metrics shown in Table 2. The criteria are divided into 8 groups according to the goal specified as part of GIF for the Generation IV advanced reactor technologies. It their turn, the GIF goals are divided into 4 categories, each of which corresponds to the most important areas of reactor technologies, in particular:

I Sustainability of Energy Development:

1) provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilization for worldwide energy production;

2) minimize nuclear waste from the nuclear systems and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment;

II Nuclear Material Proliferation Resistance and Physical Protection:

3) increase the assurance that the nuclear systems are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism;

III Safety and Reliability:

4) excel in safety and reliability vs. the existing nuclear power systems;
5) have a very low likelihood and degree of reactor core damage
6) eliminate the need for offsite emergency response;

IV Competitive Ability (Economics):

7) provide a clear life-cycle cost advantage over other energy sources;
8) provide a level of financial risk comparable to other energy projects.

The design development cost and the design verification R&D cost are singled out as separate economic criteria.

The compliance of the specific criteria with the above-listed goals is identified according to the criterion-hierarchical structure used in this methodology.

It should be noted that the specified criteria and goals are quite general by their nature and can be used for any type of nuclear power systems, including the SFRs.

The comparison is made with the analogous basic characteristics that, as a rule, correspond to the Generation III advanced light-water reactor (LWR). The values recommended for the assessment of each of the criteria are shown in Table 2.

3.2 INPRO Methodology

The methodology to assess the capability of the nuclear power system to meet the national needs for sustainable development was developed as part of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) initiated by IAEA in 2000. In INPRO, a set of Basic Principles, User Requirements and Criteria is developed, which together with the assessment method make up a methodology to assess the nuclear power system, including its innovative components. To achieve the sustainable state, the nuclear power system should meet the basic requirements for its economics, infrastructure, waste management, proliferation resistance, physical protection, environment protection and safety.

The hierarchy of requirements for the nuclear power system design and assessment is illustrated in FIG. 3. At the top level, 14 Basic Principles are identified. The second, so-called User-Requirement level consists of 52 requirements, which identify the conditions that must be met to satisfy the Basic Principles. Each INPRO criterion includes an Indicator and an Acceptance Limit. Thus, the User Requirements identify the means to achieve the top-level goals. And finally, a set of 125 Criteria with Indicators and Acceptance Limits enable one to see the potential of the nuclear power system. The indicators may be developed based upon the calculated parameters, expert's opinion, etc.

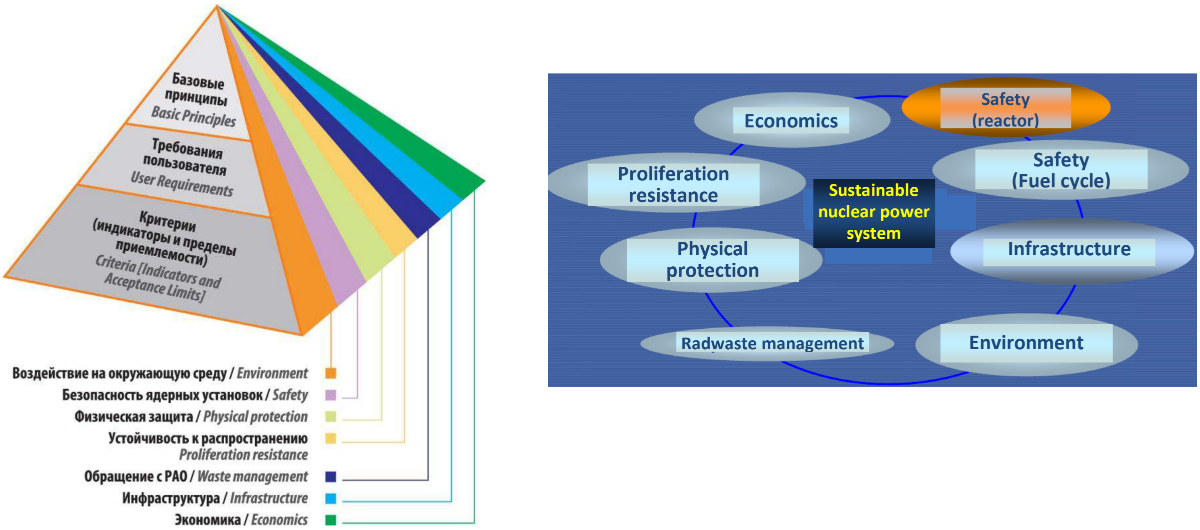

FIG. 3. Hierarchy of INPRO requirements in the area of analysis.

The Acceptance Limit of an INPRO criterion is a target, either qualitative or quantitative, against which the value of an indicator can be compared by the assessor leading to a judgement of acceptability (pass/fail, good /bad, better/poorer).

4. Design Bases to Ensure the System Analysis

Underlying the satisfaction of the system requirements are the approaches used in the design, adopted engineering solutions, which integrate the equipment design implementation, the layout solutions for the systems and for the architecture of buildings and the safety concept.

The SFR technology has been developing in Russia for more than 50 years with step-by-step perfecting of the engineering solutions on experimental, demonstration, experimental-commercial and commercial reactors. The experience and competences obtained, in particular, in the course of developing and commissioning the BN-800 reactor, operation of the BN-600 reactor, as well as the available test facilities ensured the development and representative verification of the commercial power unit design with the BN-1200 reactor.

The commercialization of the SFR technology is not only determined by the installed power increased, as a minimum, to that of the VVER level, the enhanced electricity generation efficiency but also by the attractiveness of the BN-1200 reactor in terms of operation safety and closing of the nuclear fuel cycle [1 - 12].

Table 1: Development of power unit designs.

Reactor	BN-600	BN-800	BN-1200	
Rated thermal power, MW	1,470	2,100	At least 2,800	
Electric power, gross, MW	600	880	At least 1,220	
Efficiency, gross / net, %	42.5 / 40	41.9 / 38.8	At least 43.5 / 40.7	
Fuel type	UO2	MOX (UO2 in the initial phase / MOX)	MUPN	MOX
Maximum burnup, % h.a.	11.2	11.5	7.6 / 10.9	11.8 / 14.5
Maximum damage dose, dpa	82	90	96 / 131	116 / 140
Fuel cladding material	Austenitic steel	Austenitic steel	Advanced austenitic steel / Ferrite-martensitic steel	
Fuel pin diameter, mm	6.9	6.9	9.3 / 10.5	9.3
Size across flats, mm	96	96	181	
Average core power density, MW/m3	400	450	~ 230	
FSA cycle of operation, EFPD	560	465	920 / 1,320	1,060 / 1,320
Breeding ratio	0.85	1.0	up to 1.4	up to 1.2
Integrated primary system equipment	partially	partially	completely	
Engineering solutions for safety:				
- jacketing of pipes and vessels containing radioactive Na	partial	partial	complete	
- safety systems	SCRAM	SCRAM, PAZ-G	SCRAM, PAZ-G, PAZ-T	
- emergency heat removal system	In 3rd circuit	In secondary circuit	EHRS connected to the primary circuit	
- corium confinement system (core catcher)	-	+	+	
- room to confine emergency releases	-	-	+	
Probabilities of severe accidents for SFR power units per reactor-year	1.7×10-5	2.8×10-6	5.0×10-7	
Enhancement of lifetime characteristics	30 years - design 40 years - extended	45 years	60 years	
Time in operation independent of the off-site power supply systems, h			72	

PAZ-G – hydraulically suspended safety rods
PAZ-T – temperature-actuated safety rods

The changed fuel pin and FSA designs, reactor core layout, fuel and structural materials (Table 1, FIG. 4) determined the considerable enhancement of safety features and fuel utilization characteristics.

- Larger fuel pin diameter and size across flats ⇒ reduced core power density ⇒ longer fuel cycle ⇒ reduced fuel pin consumption per year
- Effective boron shield assemblies introduced ⇒ reduced neutron fluence to the reactor vessel, reduced in-vessel steel shielding
- Larger-volume in-vessel storage with the ensured spent FSA storage time for two cycles of operation ⇒ reduced decay heat of spent FSAs ⇒ eliminated spent FSA drum
- Use of MUPN fuel / axial layer of MOX fuel ⇒ reduced burnup reactivity margin
- New temperature-actuated passive safety system (PAZ-T) introduced ⇒ enhanced safety
- Neutronic characteristics independent of the plutonium isotope composition; possible to burn minor actinides ⇒ closing of the nuclear fuel cycle

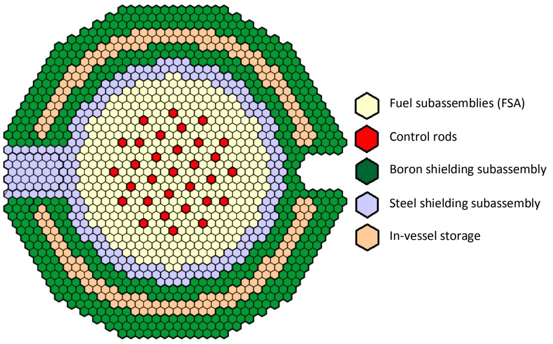

FIG. 4. Reactor core.

The primary equipment and system completely integrated in the reactor vessel, new design solutions used for the primary and secondary circuits, new structural materials used for individual reactor in-vessel internals and steam generator, optimized number of heat-transfer loops (Table 1, FIG. 5) identified the substantial enhancement of the safety features and of the technical-and-economic performance.

- All the main equipment, including primary cold traps, autonomous HX and systems placed inside the reactor vessel ⇒ all pipelines containing primary sodium eliminated
- The purification system integrated into the primary cold trap and placed inside the reactor, vertical elevator used, spent FSA drum and support systems eliminated ⇒ reduced construction volumes and metal content
- New structural material used in the reactor ⇒ longer lifetime
- Switchover from the sectional-modular steam generators to large-module steam generators ⇒ reduced material content
- New structural material used in the steam generator design ⇒ longer steam generator lifetime
- Bellows expansion joints used instead of compensatory bends in pipelines to compensate for temperature expansions ⇒ reduced pipeline length and the number of valves
- Identical secondary loops with the radially symmetrical layout ⇒ enhanced manufacturability

FIG. 5. – Reactor plant.

The engineering solutions applied in 2016 for the reactor plant design and for the power unit design considerably enhanced specific technical-and-economic characteristics (FIG. 6).

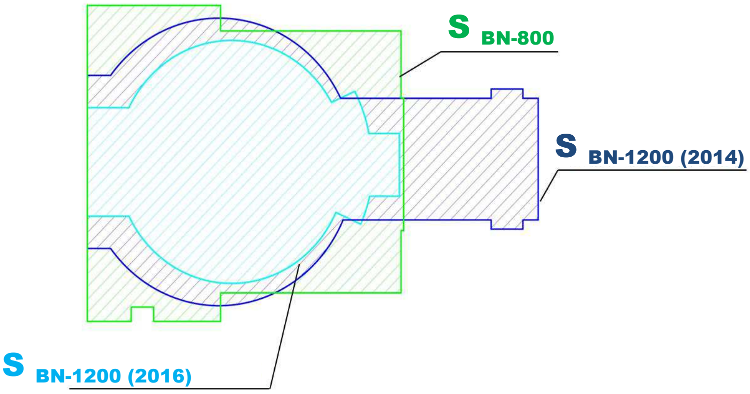

FIG.6. Overlapped BN-800 and BN-1200 reactor building footprints.

To verify the design, a large scope of computational and experimental work has been accomplished. The development work is being done with the use of state-of-the-art mathematical modeling and 3D simulation methods.

5. Results of System Analyses

5.1 Assessment Results by the GIF Methodology

The results obtained as part of GIF (Table 2) testify to the fact that generally the BN-1200 design has a good potential in terms of meeting the requirements for Generation IV nuclear power systems.

Table 2: Values of criteria for the BN-1200 reactor vs. the basic values for a LWR (preliminary assessment).

Criterion No.	Criterion	Basic value	BN-1200 (1,220 MW)
1	Fuel makeup, MTU/GWe·years	150–200	< 10
2	Radwaste mass, MT/GWe·years	15–20	5–15
3	Radwaste volume, m^3/ GWe years	15–20	5–15
4	Long-term energy generation, kW/GWe·years	1–3	< 0.1
5	Long-term radiotoxicity, MSv/GWe·years	500–1,500	< 20–100
6	Environmental impact	Equivalent =	A little better than the basic one
7	Released materials	Fuel with LEU or intensive radiation	Fuel with LEU or intensive radiation
8	SNF characteristics	Radiation level >50,000 MW·day/MT h.m.	Radiation level >50,000 MW·day/MT h.m.
9	Resistance to acts of terrorism	EHRS using the alternate source and off-site water supply	Passive systems without an active startup
10	Reliability	Failure rate comparable with advanced LWRs	Failure rate reduced by a factor of 5
11	Standard personnel irradiation	Standard irradiation risk complies with the standards	Standard irradiation considerably reduced
12	Emergency personnel/population irradiation	Emergency irradiation risk comparable with the basic one	Emergency irradiation considerably reduced
13	Reactivity control reliability	Negative temperature coefficient of reactivity and power coefficient of reactivity	Design characteristics prevent core damage
14	Heat removal reliability	Comparable with the basic EHRS	EHRS does not require any energy source

Criterion No.	Criterion	Basic value	BN-1200 (1,220 MW)
15	Uncertainty of dominating phenomena	Scaled modeling of phenomena or extrapolation	Full-scale study on phenomena in the entire range
16	Reactor thermal inertia	Reactor thermal inertia comparable with the basic one	Longer thermal inertia of fuel/coolant
17	Scale of integral experiments	Integral testing on a smaller scale	Integral testing on a prototype scale
18	Source terms	Limits of the relative release comparable with the basic one	Limits of the relative release less by a factor of 10
19	Energy release mechanisms (in core damage accidents)	Energy release comparable with the basic one	Energy release less by a factor of 2
20	Time to core damage after the initial event	Core is damaged after 1 hour after the initial event	Core is damaged after 24 hours after the initial event
21	Radioactivity confinement efficiency	Release fraction comparable with the Generation III nuclear power stations	Release fraction less by a factor of 10
22	Current specific capital costs, $/kW	1,400–1,600	1,400
23	Electricity cost, $/MW·h	14–16	16–20
24	Construction period, month	45–55	45–65
25	Design cost, $M	450–550	15–50
26	R&D cost, $M	450–550	150–350

5.2 Assessment Results by the INPRO Methodology

The assessments by the INPRO methodology were accomplished for two areas, in particular, safety and economics. In the course of this work, as part of the INPRO methodology, a safety and reliability analysis was performed for the power unit with the BN-1200 reactor thorough comparing all its project, design and operation parameters with analogous characteristics of the existing plants and plants under development [12]. All the INPRO methodology criteria were assessed in the Safety Section, in particular, 4 Basic Principles, 16 Customer Requirements, 36 Criteria and Indicators, 21 Assessed Parameters. The criterion assessment results showed that the BN-1200 reactor satisfies all the Basic Principles and Customer Requirements in the INPRO methodology in the Nuclear Reactor Safety Section.

With using the INPRO methodology, the BN-1200 reactor economic performance was also assessed. The assessment showed that the optimization of the BN-1200 reactor design that was being performed over the last few years under the *New Technological Platform* Federal Program and under the Contract with Rosenergoatom turned out to be effective and led to a considerable improvement in the economic indicators. In particular, the capital costs of BN-1200 construction turned out to be comparable, within the calculational error, with the construction costs of the VVER-TOI-1200.

6. Conclusion

The assessment results of the BN-1200 concept compliance with the requirements for Generation IV plants testify to the fact that the BN-1200 design generally has a good potential in terms of satisfying the requirements formulated both as part of the Generation IV International Forum (GIF) and with the use of the NESA-INPRO methodology.

The implementation of the BN-1200 design determines the potential for the development of the nuclear power system in the strategic perspective as related to the energy basis for the sustainable development, guaranteed fuel supplies, reduced environmental burden associated with the spent nuclear fuel and radwaste management with account of the economic competitive ability vs. the other types of electricity generation.

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