# SVBR-100 PROJECT: KEY FEATURES AND CURRENT STATE

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**Annotation**

The SVBR-100 reactor facility (power ∼ 100 MW electrical) with a fast neutron reactor, an integral layout of the primary circuit and a lead-bismuth coolant in the primary circuit is being developed as one of the main components of NOAK NPPs of a modular structure in the average power range from 100 to 600 MW (e.). The main design provisions of the SVBR-100 reactor, presented in the paper, are aimed at simplifying the design of reactor equipment and systems, using the inherent safety characteristics and passive systems to increase the resistance of the reactor to potential hazards. Due to the developed property of internal self-protection, the number and complexity of safety systems are significantly reduced in comparison with traditional reactors. Key technical solutions used in the design of the reactor are based on materials and technologies mastered by industry, the most important of which are protected by approximately 60 patent families. To test the technology, the development of a design for the SVBR-100 reactor for a FOAK NPP is underway.

## INTRODUCTION

Identifying small and medium modular reactors (SMR) as a special class of reactors, the IAEA usually divides them into small and/or modular reactors with a power of up to 300 MW(e) and medium power reactors with a power of 300-700 MW(e) [1] . Interest in SMRs is growing worldwide due to their benefits such as flexible power generation options, a wide range of applications, increased safety due to their inherent passive safety features [2], reduced initial capital investment, and opportunities for cogeneration and non-electric applications.

Achieving competitive economic performance of the SMRs is the most important factor in choosing the characteristics and parameters of the reactor plant. In practice, this factor causes the greatest difficulties for SMRs. Perhaps that is why, out of almost a hundred projects being developed according to IAEA data [3], an extremely limited number of projects have been brought to practical implementation, and data revealing the actual cost of construction and operation of such facilities are practically unavailable.

Certain, but not quite obvious solutions can be obtained through SMRs modularity. However, the large-scale factor associated with the improvement of specific economic characteristics with an increase in unit capacity also works for the case of low power. However, the technical solutions used in the field of small and medium-sized capacities, apparently, should differ from solutions for large capacity.

The paper is based on materials from the design of the FOAK NPP with a fast neutron reactor with lead-bismuth coolant (LBC) SVBR-100, developed for placement at the site in Dimitrovgrad. Below is a brief description of the main technical solutions adopted in the SVBR-100 design and prerequisites for improving the economic indicators of the Project.

## Basic Design Provisions

### Design concept and design solutions

The historical background for choosing a lead-bismuth coolant, operating experience and lessons learned from this experience are described in more detail in a number of publications, for example [4, 5]. Below are the key features that are important in terms of the impact of the scaling factor to design, mentioned in the introduction above.

The following main design provisions were embodied in the SVBR-100 reactor plant project:

* uranium oxide fuel was used as the main type of fuel for the initial stage of operation;
* for the first stage of operation, a maximum local burnup depth of no more than 10% was adopted;
* the core is designed based on the fulfillment of non-proliferation conditions, namely, the use of depleted uranium as a reflector is excluded, and the maximum enrichment in U -235 is less than 20%;
* a two-circuit heat-removal system and a modular steam generator (SG) producing saturated steam with an external steam separator, a heat exchange surface in the form of coaxial tubes and multiple forced circulation of the coolant along the SG-separator path are used;
* the natural circulation in the primary and secondary circuits is sufficient for decay heat removal from the rated power level without dangerous overheating of the core;
* proven solutions have been used for the heat removal through the passive heat removal system (PHRS) from the SG independently from the turbine system;
* simultaneous loading of a fresh core and assembly-by-assembly unloading of spent fuel from the reactor at the end of the core lifetime are provided;
* the main components of the reactor monoblock and the reactor facility are made in the form of separate modules, and the possibility of their replacement and repair is provided;
* The reactor monoblock has such weight and size characteristics that allow it to be completely manufactured at the plant and delivered to the NPP site or removed from the NPP site by water, road or rail.

The main technical characteristics and parameters of the SVBR-100 reactor in nominal mode are presented below in Table 1. The specified characteristics may vary depending on the use case of the SVBR-100 reactor as well as for NOAK NPPs with several power units.

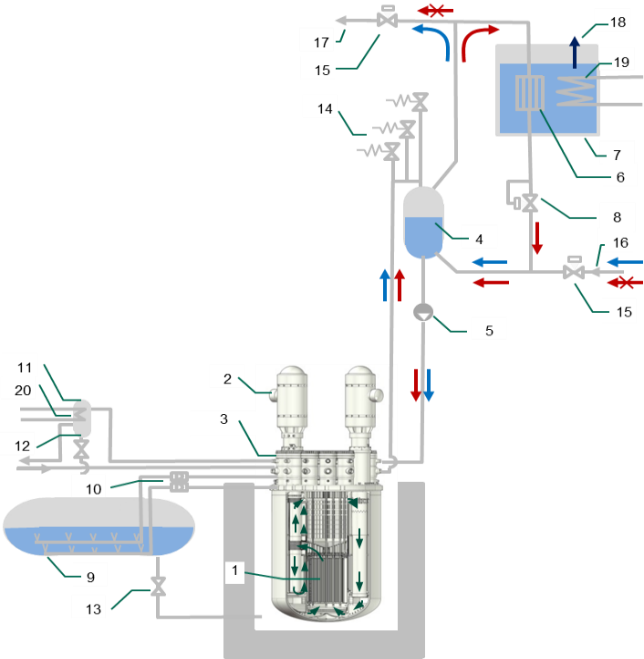
TABLE 1 Main technical characteristics and parameters of the SVBR-100

|  |  |
| --- | --- |
| Parameter | Value |
| Thermal power, MW | 280 |
| Pressure of generated saturated steam, MPa | 7 |
| Steam capacity, t / h | 580 |
| Temperature of the primary coolant, at core inlet / outlet °C | 335 / 477 |
| Maximum local damaging dose, dpa | 97 |
| Fuel: type  average U-235 enrichment,%  maximum U-235 enrichment,% | UО2  16,7  19,5 |
| Core life time, thousand eff. h. | 50 |
| Core discharge burnup, MW·d/kg h.a. | 65 |
| Maximum local burnup, % h.a. | 9,9 |
| Refuelling cycle, years (simultaneous loading of a fresh core) | 6-7 |
| Dimensions of reactor monoblock (diameter/height), m | 4,40 / 6,53 |

### Basic hydraulic diagram of the NSSS SVBR-100

Figure 1 shows basic hydraulic diagram of the NSSS SVBR-100.

The result of the adopted basic approaches was the simplification of the scheme and the practical exclusion or minimization of the number of safety systems. The most significant feature of the adopted scheme is the connection of a passive heat removal system from the steam generator (SG PHRS) [6]. In case of loss of process water for cooling the SG PHRS, heat removal is carried out by boiling the water reserve in the PHRS tanks. At the same time, the water supply is sufficient for autonomous cooling without the participation of any control actions for 72 hours (the non-intervention time accepted for FOAK NPP can be increased for NOAK NPP). These functions are also performed in case of accidents with total blackout of the plant. The blue arrows in the diagram (Fig. 1) show the direction of flow of the secondary circuit coolant when operating at power, and the red arrows when operating in autonomous modes without communication with the turbine systems.



Direction of secondary coolant flow:

- normal operation;

- in case of cooldown through SG PHRS

Direction of primary coolant flow:

1 – Core

2 – Main circulation pump

3 – SG module

4 – Separator

5 – Multiple forced circulation pump

6 – PHRS heat exchanger

7 – PHRS tank

8 – Passive regulator (by pressure in circuit)

9 – Bubbler

10 – Bursting membrane

11 – Condenser of gas system

12 – Level indicator

13 – Valve of reactor shaft fluding

14 – Safety valves (vented to

atmosphere, condenser, box)

15 – High-speed shut-off valves

16 – Feedwater inlet

17 – Saturated steam outlet

18 – To atmosphere

19 – PHRS cooler, cooled

by technical water

20 – Cooler - condenser

*FIG. 1. The basic hydraulic diagram of the NSSS SVBR-100*

All primary circuit equipment is located in the reactor vessel (reactor monoblock), hydraulic circuit are formed without the use of pipelines and fittings [7].

The condenser included in it is designed to indicate a small SG leak and condensation of steam entering the gas system. In case of a large leak the steam-gas mixture is discharged through a bursting membrane into the bubbler tank of the steam and steam-gas mixture receiving system.

The water reserve in the bubbler tank can be used as a means of minimizing the consequences of a beyond design accident with the simultaneous breakdown of all four SG PHRS channels that provide decay heat removal, or boiling off of water reserve in the SG PHRS tanks during a long-term de-energization of the plant. Discharge of water from the bubbler tank into the reactor shaft ensures cooling of the reactor without damaging the reactor vessel and core.

### Reactor facility layout

The main equipment of the SVBR-100 reactor facility is located in a sealed concrete box. The number and configuration of boxes may vary depending on the number of SVBR-100 reactor modules installed at the NPP site, but the layout of equipment in the box does not change.

Above the reactor in the upper part of the box, reactor facility equipment is located, which is not structurally part of the reactor monoblock, including four steam separators.

The adopted layout solutions, together with the design solutions of the heat exchange equipment, ensure the cooling of the reactor under any initial events, including total blackout of the plant, in the natural circulation mode of the primary and secondary circuits.

## MAIN REACTOR EQUIPMENT DESIGN

### Reactor monoblock

An integral layout of the reactor was chosen, in which pipelines with primary coolant are completely excluded, reactor vessel in the part in contact with the primary coolant is surrounded by a protective cover.

Electromechanical pumps with a gas-tight electric drive are used as LBC circulators. The lower radial bearing operates in a lead-bismuth coolant.

In the central part of the reactor monoblock there is a removable block with the core and control rods of the protection system, which is surrounded by internal radiation protection with SG modules located in it (12 pcs.), as well as main circulation pumps (2 pcs.) The protective plug is installed above the active zone. The control and protection system rods drives are installed on the cover of the protective plug [8].

Hydraulic coolant connections between the primary circuit equipment are completely formed within the reactor vessel by elements of internal devices, without the use of pipelines and fittings.

The adopted circulation scheme with the presence of free coolant levels ensures the separation of the steam-water mixture from the coolant in the event of a leak in the pipe system of the SG modules.

### Core

The consequence of the adopted approaches, taking into account the fulfillment of the reactor compensability restrictions necessary from the point of view of nuclear safety, was the duration of the core lifetime increased to 6-7 years and the relatively low energy intensity of the core. The analysis of the possibility of using alternative fuels showed [9, 10] that the use of mixed uranium-plutonium oxide or nitride fuel only improves the physical characteristics of the core, increasing the breeding factor, which in the case of mixed nitride fuel approaches unity, thereby minimizing run-out reactivity and reducing the risk of reactivity accidents.

The core composition includes: fuel assemblies (FA) [11], control rods (the absorbing material is boron carbide), side reflector elements, and neutron sources.

A fuel assembly is a metal structure consisting of a set of fuel elements located between the upper, intermediate and lower grids. The fuel elements in the FA are located in the nodes of a regular triangular lattice [12]. All fuel assemblies are identical in design and differ only in enrichment (5 zones of different enrichment).

The fuel element cladding is a four-fin tube [13], which ensures the spacing of fuel elements in the fuel assembly along the ribs.

### Mail circulaton pump

Main circulation pump is a pumping unit consisting of an axial submersible pump and an adjustable sealed electric motor, the shafts of which are connected by a splined coupling [14]. The internal free cavities of the pump and electric motor are filled with inert gas. The use of oil in bearing units is excluded. The decisions taken exclude both the entry of any radioactive elements from the primary circuit into the reactor box and any contamination of the coolant that is dangerous from the point of view of violating the quality of the LBE and circuit purity.

### Steam generator modules

The reactor monoblock includes 12 SG modules, connected by pipelines into four independent heat removal loops, including a separator and a multiple forced circulation pump on each loop.

The heat transfer surface of the SG module is made from coaxial tubes. The tubes in the bundle are arranged in a triangular lattice. Displacers [15] and spacer grids [16] are installed in the SG module shaft. To diagnose the heat exchange tubes of the SG module, as well as to repair them, the module design provides for the possibility of dismantling the central tube.

## MAIN RESULTS OF THE SVBR-100 REACTOR DESIGN DEVELOPMENT

The design of the reactor facility and main equipment has been developed.

R&D and tests were carried out on the reactor vessel sealing unit (main connector), the control rod fastening unit, the additional emergency protection rod fastening unit, and the fuel assembly fixing unit [17].

Technical design documentation of the refueling equipment complex has been released. Tests of prototypes and mock-ups of units and elements of refueling equipment were carried out, including tests simulating the operation of the load-handling element in the LBC and simulating the operation of the lifting mechanism under the action of the buoyancy force of the LBC [18].

Technical design documentation of the main circulation pump (MCP) was released. Tests of the model flow part of the MCP on a scale of 2 to 1 were carried out on water, pressure and flow characteristics were obtained in four quadrants. The first stage of a large hydraulic test bench (BGS) was built on CDBMB JSC Sosnovoborsk site for testing models of the bearing assembly of the MCP in lead-bismuth, and the performance of the model was experimentally tested.

A set of works on technological development of the production of the reactor vessel, internal equipment and steam generators was completed. A set of design documentation for a reactor monoblock with internal equipment and steam generator modules was reviewed by ZIOMAR JSC (Podolsk), based on the results of assessing the manufacturability of the reactor design, proposals for its improvement were formulated. Also, other enterprises have confirmed their readiness to supply the reactor monoblock. The main semi-finished products necessary for the manufacture of equipment were put into production with receipt of specifications.

R&D related to the development and validation of core elements was carried out at a faster pace due to the need to conduct long-term reactor tests. Technical design documentation released for fuel element, absorbing elements of control rods, secondary neutron source [19], primary neutron source. Industrial production of fuel element, neutron source claddings was mastered in 2014.

Irradiation tests carried out at BOR-60 research reactor confirmed that the radiation swelling of the steel of the fuel element cladding, at least up to 80 dpa, does not exceed 1% in the entire operating temperature range of operation of the core elements. The high corrosion resistance of steel in a lead-bismuth coolant has been confirmed by bench tests at IPPE JSC on a basis of 53,000 hours.

A pilot batch of full-scale fuel elements of a standard design was manufactured at the Central Scientific Research Laboratory of MSZ JSC and delivered to IPPE JSC in 2014.

In 2015, IPPE JSC completed the production of a full-size fuel assembly for hydraulic and vibration tests at the stands of OKB GIDROPRESS JSC. All structural materials and components for fuel assemblies, including hexagonal tubes, are manufactured by industry according to newly developed specifications.

Reactor tests of fuel element mock-ups were carried out as part of a seven-element assembly in the BOR-60 reactor. During 3 years of testing, no depressurization of fuel elements was registered. Reactor tests of neutron source prototypes have been successfully completed. In 2014, reactor tests of absorbing elements prototypes with boron carbide cores of standard geometry, enrichment and density began.

In terms of justification of the coolant technology system (CTS), the work to justify the design of the CTS has been largely completed:

* designs of CTS devices located in a reactor monoblock and a gas process loop have been developed;
* a set of calculation works was completed to justify the designs of CTS elements adopted in the project;
* design documentation was developed and full-scale prototypes of CTS elements were manufactured;
* full-scale prototypes of CTS equipment were tested to justify their technical characteristics;
* comprehensive tests of CTS elements were carried out;
* technical designs of individual elements of the STT and the system as a whole were released;
* operating regulations for CTS have been developed.

A full range of experimental substantiation of the physical characteristics of the core was carried out at the large physical test bench (BFS) at IPPE JSC. Certification reports were prepared for the full range of physical codes used to justify the core design. Preliminary materials have been prepared for the verification of system thermal-hydraulic codes for safety justification. Further work requires testing of steam generator models.

Rostechnadzor reviewed the program for developing new and adjusting existing regulatory documents to substantiate the nuclear and radiation safety of FOAK with SVBR-100 reactor, and formulated recommendations for its adjustment and addition.

The project has created a system for identifying protectable IP (inventions, know-how). In total, the current patent portfolio of AKME-engineering JSC amounts to 58 key inventions, 38 of which are additionally patented in more than 30 countries, including China, the USA, the European Union, countries of Southeast Asia, etc. (in total more than 600 patent applications). The SVBR trademark is registered in 14 foreign jurisdictions, including China, Korea, Kazakhstan, the USA, Singapore and the European Union.

## PREREQUISITES FOR INCREASING ECONOMIC COMPETITIVENESS

Design and estimate documentation was developed by ATOMPROEKT JSC in accordance with Decree of the Government of the Russian Federation dated February 16, 2008 No. 87 “On the composition of sections of design documentation and requirements for their content.”

In 2019, the cost of constructing the FOAK NPP was clarified on the basis of the assessment of construction costs for the 4th class carried out by Rosatom OCKS in accordance with the TCM NC methodology (Total Cost Management Nuclear Construction - an industry-wide system for integrated management of the cost and timing of the construction of nuclear energy facilities) [20].

The cost of the reactor facility main equipment makes a significant contribution to the total cost of the FOAK NPP construction.

In accordance with the noted features, the key areas for further optimization are:

* reducing construction volumes due to more optimal layout solutions and improving the refueling system;
* reduction of construction volumes by the placement of several SVBR-100 reactor facilities in one reactor hall;
* reducing the cost of main equipment due to the Learning Curve and Economies of Scale;
* increasing reactor power by reducing the conservatism of design solutions;
* consistent increase in fuel burnup up to the levels adopted in BN-1200 95-116-137 MW day/kg [21].

## Conclusion

The adopted design approaches to the creation of the SVBR-100 reactor, based on solutions tested by industrial experience in the use of lead-bismuth coolant, lead to a high level of self-protection of the reactor without the use of a large number of safety systems. This, in turn, determines the potential for further improvement of the technical characteristics of NPPs with SVBR-100 reactor and increasing the economic competitiveness of such NPPs by removing the conservatism of the decisions made.

A number of key experimental and technological works were carried out to substantiate the project, including the first stage of reactor tests of fuel elements, neutron source, absorbing elements; full-size standard fuel elements were manufactured; critical experiments on core models necessary for certification of calculation codes were carried out; full-scale models of the CTS were manufactured and their comprehensive testing was carried out in laboratory conditions.

A complete set of design documentation for FOAK NPP was also released. Based on the results of consideration of materials to justify the license, in 2015 Rostechnadzor issued a license for placement (it is currently required to be renewed).

The main directions of planned further R&D for the creation of an FOAK NPP with SVBR-100 reactor include work on finalizing regulatory documents on justification of nuclear and radiation safety, certification of structural materials and calculation codes, conducting reactor tests of fuel, and safety justification on large-scale thermal-hydraulic stands.

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