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Research Article

Lead-bismuth cooled reactors: history and the potential of development. Part 2. Prospects for development*

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Abstract

The article presents the main provisions of the concept of the design of the SVBR-100 civilian reactor that meets the requirements for Generation IV nuclear technologies, which is being developed on the basis of a critically analyzed experience in developing and operating lead-bismuth-cooled reactor plants. The authors describe the current status of the project and the prospects for the use of such reactor plants in the nuclear power industry after demonstrating their reliability and safety in the operating conditions of a pilot commercial power plant.

Keywords

Lead-bismuth coolant, reactor, steam generator, safety, core, nuclear power engineering

Introduction

Based on the experience gained in the process of constructing and operating the lead-bismuth-cooled reactor plants (RP), the SVBR-100 civilian reactor is currently being developed. A characteristic feature of this reactor is a high level of inherent self-protection, which deterministically excludes the causes of the most severe accidents requiring evacuation of the population. This is due to the natural properties of the lead-bismuth coolant (LBC), its very high boiling point and chemical inertness in contact with water and air, which is possible in case of depressurization of the circuits.

As a result, there is no need to maintain high pressure in the reactor, heat removal crisis and hydrogen generation are eliminated. Due to this, it is possible not to use a number of safety systems required in traditional RPs and reduce the cost of the RPs themselves. The selected power of 100 MW(e) makes it possible to transport the reactor monoblock in factory readiness by various means of transport, in particular by rail, which reduces the construction period. On the other hand, at this power level (reactor dimensions), it becomes possible to obtain a breeding ratio in the MOX-fueled core greater than unity. At the same time, in a closed nuclear fuel cycle, the reactor will operate in the fuel self-sufficiency mode, which

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will become important when the resources of cheap natural uranium are exhausted.

On the basis of a tested reactor module, it is possible to create NPPs for various purposes with a power unit capacity divisible by 100 MW(e) without additional R&D efforts.

Development prospects for lead-bismuth-cooled reactors in the civil nuclear power industry

Commencement of works

The period of time between the completion of the operation of the NPS reactors (1996) and the start of works on the SVBR, which took about ten years, fell on the very difficult years of the collapse of the Soviet Union and was characterized by a virtual complete cessation of funding. During this time, the total number of employees working in this field decreased by more than ten times, but key specialists possessing critical knowledge survived.

The first work proposed by the SSC RF – IPPE that received real financial support was "*A Feasibility Study of the Renovation of Power Units 2, 3 and 4 at the Novovoronezh NPP after Their End of Life with Using a Nuclear Steam Generating Module an SVBR-75 Reactor (75 MW(e)) with the Lead-Bismuth Liquid Metal Coolant.*"

In 1995, by decision of the directorate of the Rosenergoatom Concern, which was headed by Ye.I. Ignatenko, five billion rubles were allocated for this work in promissory notes, which soon turned into five million rubles, and more than 90% of these funds were received by barter (including metal, gasoline, building materials), which had to be sold with a large "shrinkage" in order to obtain money. Such was the country's economy in those years. The aforementioned feasibility study for the renovation of the out-dated power units of the NvNPP was carried out by OKB Gidropress, GNIPKII Atomenergoproekt and the SSC RF – IPPE (Ignatenko et al. 2005).

The results of this work were discussed at the Scientific and Technical Council of the Rosenergoatom Concern in 1998, which, in particular, recommended "... to continue and complete in 1999 research and justification of technical and economic indicators and the amount of investment in the reconstruction of NvNPP-2, taking into account the comparative analysis of alternative options for the use of facilities and equipment of this power unit". However, this recommendation was not implemented.

Afterwards, some funds were received under the ISTC (International Science and Technology Center) project, which paid money in foreign currency directly to specialists to reduce the risk of their going abroad and letting out know-how allowing non-nuclear countries to make nuclear weapons. One of such projects, implemented by OKB Gidropress and IPPE, was aimed at creating a liquid metal (lead-bismuth alloy) target of 1 MW for a proton accelerator. Another project (a partnership agreement with a Japanese company) directly concerned the development of a modular fast reactor of the SVBR-100 type. This project participated in the fast reactor competition held in Japan after the sodium fire at the Monju fast reactor. The competition was lost as Japan headed for the restoration of this reactor. Besides that, there was a contract with the Japanese company Marubeni to perform some works on the lead-bismuth coolant.

This made it possible to preserve the qualified personnel and consolidate the funds received under the ISTC project and the Japanese contract, transferring part of them to the Atomenergoproekt Institute and OKB Gidropress and, through this, to develop a "Conceptual design of a nuclear power plant with two units of 1600 MW each, based on the RP SVBR-75/100". The Rosenergoatom Concern did not allocate funding for this work but agreed on the design specifications. The unit power was chosen at the level of 1600 MW (16 SVBR-75/100 modules) in order to be able to correctly compare economic indicators with a nuclear power plant based on two power units with VVER-1500 reactors.

When calculating the technical and economic indicators of the NPP developed in the conceptual design, GNIPKII Atomenergoproekt introduced an additional reserve of 17% for unforeseen expenses into the calculated value of capital costs for the construction of a two-unit modular SVBR NPP, against the standard reserve of 3%, which was introduced for NPPs with two VVER-1500 units. If this reserve is attributed to the cost of the 'nuclear island', it will be 60%. This approach is quite reasonable, since all other costs for the SVBR NPP (turbine, generator, cooling tower, etc.) are very close to the corresponding costs for the VVER-1500 NPP. None of the nine expert organizations commented that the accepted reserve was insufficient.

The comparison of the technical and economic indicators of these NPPs showed the advantage of NPPs with SVBR units despite the fact that the SVBR-75/100 reactor unit design was carried out with great conservatism, which predetermined a great potential for improving the project (increasing the reactor plant capacity by at least 20% due to the allowable increase in the temperature of the LBC without changing the weight, size and cost characteristics, the transition from saturated to superheated steam, etc.) (Zrodnikov et al. 2006).

The results of the conceptual project, presented in eight books, were considered at a meeting of the Scientific and Technical Research Council of the Rosenergoatom Concern on May 27, 2002 with the participation of experts from nine organizations. The Council, in particular, decided as follows: paragraph 2.1. – "To approve the development of the "Conceptual design of a nuclear power plant with two units of 1600 MW each, based on the RP SVBR-75/100", which shows the capabilities of one of the new directions for the development of nuclear power", and paragraph 2.3. – "In order to determine the feasibility of extending the service life of power units of NPPs with light water reactors by means of their renovation using alternative nuclear technologies, it is recommended that FSUE AEP, SSC RF – IPPE and OKB Gidropress conduct an Investment Rationale for the renovation NvNPP-2 based on the SVBR-75/100 reactor plant. The term is the 3rd quarter of 2003". But this decision was not implemented either.

Further, in 2003, the new minister A.Yu. Rumyantsev held a six-hour meeting. The work performed on the SVBR-75/100 reactor and instructions were given to allocate funding but, in fact, nothing significant was done.

Important decisions related to the SVBR were made in 2006, when a new team came to the leadership of the Federal Atomic Energy Agency. Scientific and Technical Research Council No. 1 recommended that work be directed to the creation of a pilot power unit, and in 2008 the Director General of the State Corporation Rosatom S.V. Kirienko and O.V. Deripaska signed the Protocol on public-private partnership in the joint development of the basic SVBR technology. These events were preceded by a letter from academicians G.I. Marchuk and V.I. Subbotin, sent at the end of 2005 to the President of the Russian Federation V.V. Putin, about the need to support this unique technology.

Later, by a joint decision of S.V. Kirienko and O.V. Deripaska, a public-private enterprise JSC AKME-engineering was formed to implement this technology.

Main provisions of the concept of the SVBR-100 RP

The concept of the SVBR-100 RP was based on the following fundamental provisions:

1. Severe accidents requiring the evacuation of the population shall be deterministically excluded.
2. The design of the RP shall be of a monoblock type.
3. The dimensions of the main RP component — the reactor monoblock — shall ensure the possibility of transporting it as an assembly with internals from the machine-building plant to the NPP site by rail.
4. A fast neutron reactor shall be used, which will make it possible to have a low reactivity margin and ensure efficient incineration of minor actinides.
5. The RP, with its design remaining unchanged, shall provide the ability to operate using various types of fuel and in various fuel cycles while complying with regulatory safety requirements.
6. When MOX fuel is used, a breeding ratio in the core (CBR) slightly greater than unity shall be ensured, which in a closed nuclear fuel cycle (NFC) will allow operation in the fuel self-sufficiency mode.
7. The RP shall be suitable for export deliveries, in particular to developing countries.

Fig. 1 shows a photograph of the leading developers of the SVBR-100 reactor.

This reactor was developed using a conservative approach. It consisted in the fact that the design of the reactor included, basically, technical solutions borrowed or scaled with small coefficients, verified by the experience of operating transport reactors and other reactor plants.

This applies to almost all the main components, assemblies and a number of equipment items of the reactor plant: fuel pellets, fuel rod claddings, fuel assemblies, absorber rods, internals, actuators of absorber rods, devices of the LBC technology system, steam generators with Field tubes, steam separators, autonomous cooling condensers, gas system condensers, refueling system equipment, etc.

Figure 1. Leading developers of the SVBR-100 reactor (2011). From left to right, sitting: V.S. (JSC OKB Gidropress), G.I. Toshinsky (SSC RF – IPPE); standing: M.P. Vakhrushin, S.N. Seroshtan (JSC OKB Gidropress), A.Ye. Rusanov, P.N. Martynov (SSC RF – IPPE), A.V. Dedul (JSC OKB Gidropress), O.G. Komlev (SSC RF – IPPE), N.N. Klimov (JSC OKB Gidropress).

The conservative approach is also characterized by the use of the mastered operating parameters for the primary and secondary circuits and the focus on the existing fuel infrastructure and technological capabilities of machine-building enterprises.

This approach makes it possible to significantly reduce technical and financial risks, potential errors and failures during the implementation of innovative nuclear technologies, as well as the scope, timing and R&D costs. The characteristic features of the SVBR-100 reactor are shown below.

Power level choice justification

The choiced reactor power at the level of 100 MW(e) or 280 MW(th), and hence the reactor size, is determined by the following reasons:

1. As calculations show, this is the minimum power level at which a CBR value greater than unity is achieved when MOX fuel is used. Due to this, it is possible to operate the reactor in a closed NFC in the fuel self-sufficiency mode without consuming natural uranium or using such reactors in a large-scale nuclear power industry.
2. On the other hand, this is the maximum power level at which the overall dimensions of the reactor monoblock allow it to be transported in factory readiness, in particular by rail, which significantly expands the choice of sites for the construction of NPPs and significantly reduces labor costs and construction terms.
3. The choiced power level provides the conditions for passive removal of the residual heat release through the reactor monoblock vessel without a dangerous increase in the temperature of the fuel elements, which fundamentally simplifies the design of the reactor plant and its safety systems.
4. The relatively small mass of the monoblock for this power level facilitates the solution of the problem of ensuring the seismic resistance of the reactor plant.
5. It becomes possible to organize large-scale (conveyor) production of reactor monoblocks (tens of pieces per year) and stable loading of machine-building plants, which significantly reduces manufacturing costs. Since the manufacture of a reactor monoblock does not require any unique machine-building equipment, as for pressure vessels of light water reactors, it becomes possible to form a competitive market for manufacturers.
6. At this power level, according to the calculations, the campaign length is ~ 50,000 eff. hours when at the first stage the developed oxide uranium fuel (CBR = 0.84) is used.

Figs 2, 3 show diagrams of the monoblock reactor and reactor unit. Their detailed description is given in the report (Dzangobegov et al. 2013, 2014).

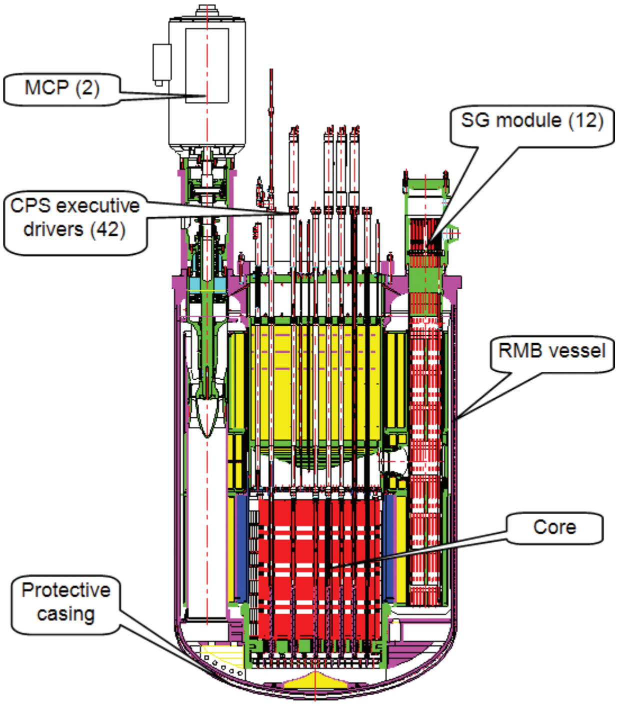

Figure 2. Scheme of the SVBR-100 reactor monoblock.

Fuel cycle and natural uranium consumption

When oxide uranium fuel with postponed latter reprocessing is used, the consumption of natural uranium will be 2–2.5 times higher than that of VVER-1000 reactors. Therefore, it is envisaged that after the first two campaigns, the reactor will be transferred to a closed nuclear fuel cycle using its own plutonium and unburnt uranium-235. The calculation results have shown that the cumulative consumption of natural uranium by one VVER-1000 reactor operating in an open fuel cycle with postponed latter reprocessing of spent nuclear fuel (SNF) and ten SVBR-100 reactors starting to operate on oxide uranium fuel with a transition to a closed NFC using own SNF after the second campaign is compared after 33 years, and over the power unit life, the integral consumption of uranium will be 30% lower than for one VVER-1000 reactor (Zrodnikov et al. 2011).

Thus, it becomes possible to develop a strategy for a closed nuclear fuel cycle that does not require preliminary expensive reprocessing of SNF from thermal reactors in order to separate plutonium from it to supply fuel to SVBR-100 reactors. This approach is also applicable to other fast reactors, if it is economically feasible, within the framework of a unified closed nuclear fuel cycle of a two-component nuclear power industry.

The flexibility of the SVBR-100 reactor with respect to the type of fuel and the fuel cycle, which is implemented in the principle "I work on the type of fuel that is the most efficient at the current stage of nuclear power development", can contribute to a timely gradual economically justified (*a posteriori*) transition to a closed nuclear fuel cycle with simultaneous solution of the problem of disposal of long-lived radioactive waste, taking into account the fact that minor actinides are efficiently burned in the fast reactors.

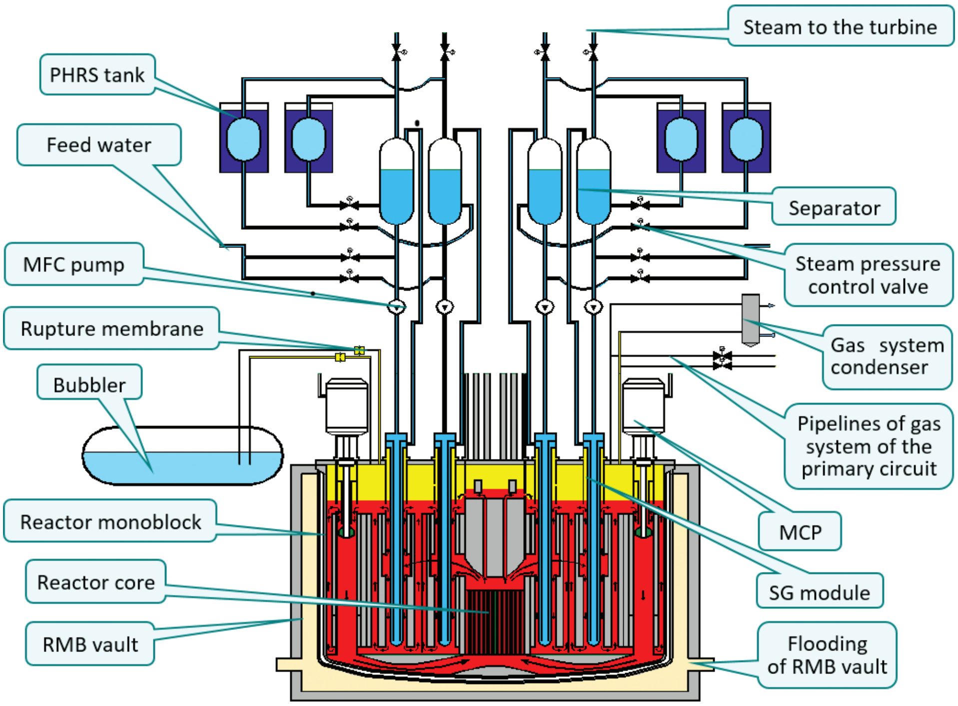

Figure 3. Basic hydraulic scheme of the SVBR-100 reactor.

For other fuel types, the following conditions are provided (Novikova et al. 2006):

- the CBR ≥ 1, when using MOX fuel and operating the reactor in a closed fuel cycle in the fuel self-sufficiency mode with a campaign length of 76000 eff. hours;
- the campaign length ~ 76000 eff. hours, when using uranium nitride fuel (CBR = 0.91) and a reactivity margin for burnup less than βeff or a campaign length of up to 150,000 eff. hours;
- the CBR ≥ 1, when using mixed nitride uranium-plutonium fuel (MNUP) and operating the reactor in the fuel self-sufficiency mode with a reactivity margin for burnup less than βeff and a campaign length of 76000 eff. hours, or operation in the expanded breeding mode with the CBR = 1.13 and a plutonium doubling time of about 45 years and a campaign length of up to 200,000 eff. hours.

Of course, the fuel reliability during such campaigns requires experimental confirmation.

Safety provisions

Inherent self-protection

Reactor self-protection against LOCA accidents

- A monoblock-type reactor is used with forced circulation of the LBC in the primary circuit, provided by two pumps with gas-tight electric motors. The vessel of the reactor monoblock (RMB) has a protective casing. There are no pipelines and fittings in the primary circuit. All this eliminates the coolant leakage.
- The natural properties of the LBC are the absence of excess pressure and chemical inertness in contact with water and air, which is possible in an accident. This, with a monoblock design of the reactor plant, eliminates the possibility of losing the LBC with the core melting, the reactor explosion and fires (there is no hydrogen release) due to internal reasons.

Compatibility of the coolant with the working fluid of the secondary circuit and with the fuel

- The reactor plant is made according to a two-circuit scheme. An intermediate circuit is not required. The SG operates with multiple forced circulation generating dry saturated steam. Compatibility of the fuel (UO_2) with the LBC eliminates the escalation of an emergency with the fuel cladding failure into an accident with the release of high radioactivity into the coolant.

Reactor self-protection against LOHS and ULOHS accidents

- Each heat-removing circuit provides the level of natural circulation of coolants, which is sufficient for residual heat removal. Heat removal through the SG is ensured by four independent channels of the passive heat removal system (PHRS) due to the evaporation of water in its tanks with steam removal to the atmosphere and a non-intervention period of 72 hours. In the event of a postulated failure of the four channels, it is envisaged that the RMB vault be flooded with water, with residual heat removed through the reactor monoblock vessel, air gap and protective casing with the generating steam removed to the atmosphere. The non-intervention period is 24 hours and can be increased if the volume of the RMB vault is increased. This accident, which is considered as beyond-design-basis one, is managed by replenishing the PHRS tanks or the RMB vault from emergency sources of water and electricity (for example, fire engines, etc.).

Self-protection against reactive accidents and UTOP accidents

- The reactor has a negative void reactivity effect and a negative temperature coefficient of reactivity.
- In addition to the emergency protection rods triggered by electrical signals, the reactor is equipped with an additional direct-acting emergency protection system (EPS), which does not have electric drives, the rods of which are triggered by an increase in the LBC temperature (fusible locks).

Self-protection against ULOF accidents

- In case of simultaneous shutdown of two pumps and failure of the main emergency protection, the RP self-protection is provided passively due to the operation of the additional EP rods, the coastdown of the pumps and the natural coolant circulation in the heat-removing circuits.

Self-protection against SGTR accidents

- To localize a steam generator tube rupture accident, steam condensers are provided in the primary gas system, and, in case of their failure, the steam-gas mixture is passively discharged through bursting discs into the bubbler when the pressure in the gas system rises above 0.3 MPa. The scheme of the LBC circulation in the RMB ensures effective gravitational separation of steam bubbles at the free level of the LBC under the MBR cover. As the experience of operating lead-bismuth-cooled reactors at nuclear-powered submarines has shown, in case of a small SG leak (up to 10 kg/h), there is no need to shut down the reactor plant.

Self-protection against unauthorized "freezing" of the LBC in the RP

- Self-protection against unauthorized "freezing" of the LBC in the reactor, when it is not operating and the residual heat release is low, is ensured by the zero change in the LBC volume during the transition from the liquid to the solid state. Maintaining the operability of the equipment during the "freezing-unfreezing" of the LBC has been confirmed not only experimentally on large-scale models, but also in the operating conditions of the NPS reactors.

Defense-in-depth barriers

The radioactivity release into the environment is excluded by a system of arranged in depth protective barriers, including the following components:

- UO_2 fuel pellet, chemically compatible with the LBC, retaining most of the accumulated fission products.
- Fuel rod cladding made of ferrite-martensite class corrosion-resistant steel in the LBC, which can withstand emergency overheating up to 900 °C for five minutes without damage. The corrosion resistance of EP-823Sh steel in the presence of a protective oxide film was confirmed by tests based on 50,000 hours (uranium oxide fuel lifetime) at a temperature of 600 °C. It has been established that the anti-corrosion oxide coating on the steel surface has a 'self-healing' effect in case of mechanical damage (provided that the required oxygen concentration in the primary coolant is maintained).
- LBC, which retains iodine, cesium and other fission products (except for gaseous ones), which can penetrate into it in case of the fuel cladding failure. Polonium-210, which is formed in the LBC upon irradiation of bismuth with neutrons, is in a very low concentration ($1\cdot10^{-6}$) and forms a thermodynamically stable intermetallic compound with lead. These factors reduce the evaporation of polonium from the LBC by a factor of $1\cdot10^{9}$ compared to pure polonium, which provides a relatively favorable radiation environment in the event of a postulated depressurization of the primary circuit or pipelines of the gas system operating without excess pressure.

Polonium determines the radiation situation in the event of depressurization of the reactor gas system and requires appropriate radiation safety measures to be taken. Such measures were developed and implemented during the operation of NPSs with lead-bismuth-cooled reactors. They turned out to be very effective, since none of the personnel (both military and civilian) who took part in the liquidation of the consequences of the accident (about 20 tons of radioactive LBC leaked into the reactor compartment of the 27/VT facility) received a dose of internal exposure to polonium exceeding the permissible one.

- Sealed the RMB vessel, equipped with a protective casing, and the gas system pipelines, excluding the radioactivity release into the reactor compartment.
- Sealed reactor compartment, protected from external impact by a reinforced concrete floor 1.5 m thick, under a slight negative pressure relative to the central hall room, created by a ventilation system with air ejected into the atmosphere via a ventilation pipe through a filter system.
- Protective reinforced concrete shell of the building 1.5 m thick, designed for additional protection against external impact (e.g., aircraft crash).

Radioecological safety

- During storage of spent nuclear fuel, the radioactivity release is excluded by the fact that the fuel assembly (FA) unloaded from the reactor is immersed in a steel canister filled with liquid lead, which is placed in a storage cell, where the residual heat release is passively removed due to the natural circulation of atmospheric air. At the same time, there are four safety barriers that prevent the radioactivity release into the environment: a fuel pellet, a fuel element cladding, solidified lead and a sealed canister.
- The long-term radioactivity of the LBC, due to the formation of a long-lived isomer ^{210m}Bi with a half-life of about 3 million years (alpha decay) during bismuth irradiation with neutrons, reaches, after a thousand years of irradiation at full power, the radioactivity of natural uranium (without taking into account the radioactivity of the decay products of its isotopes being in equilibrium). Taking into account that at the end of the reactor monoblock lifetime the LBC will be reused in new monoblocks after appropriate refining, this long-lived radioactivity will need to be taken into account in the final disposal of the LBC as solid radioactive waste.
- Practically no liquid radioactive waste is generated during operation, since the fuel is reloaded without removal of the coolant from the primary circuit and its subsequent decontamination, which produces a large amount of LRW.

Tolerance to extreme external impacts

To assess the safety potential of the SVBR-100 reactor, in 2003, a preliminary computational analysis of the consequences of a postulated severe accident (Bolhovitinov et al. 2003) was performed with a combination of such events as:

- destruction of the containment of the reactor building;
- destruction of the reinforced concrete overlapping of the reactor compartment;
- destruction of the gas system pipelines of the reactor monoblock located in the concrete vault below ground level, with direct contact of the free level of the lead-bismuth coolant under the cover of the monoblock with atmospheric air;
- complete blackout of the nuclear power plant.

Such a combination of initial events would be possible only in extreme situations: military actions, terrorist attack, extremely rare natural disasters, etc. The results of the performed computational analysis showed that even in this case, under the most unfavorable atmospheric conditions, the resettlement of the population outside the three-kilometer zone was not required.

The analysis indicates that the SVBR-100 reactor plant is not an amplifier of external influences. Therefore, the scale of damage will be determined only by the energy of the external forces. Reactors of this type provide increased stability not only in cases of single equipment failures and human errors, but also in cases of deliberate malicious acts, when all the special safety systems operating in standby mode can be deliberately disabled. Catastrophic accidents such as the Chernobyl or Fukushima nuclear disasters, as well as fires like the one that happened at the Monju reactor, are absolutely impossible here. This is especially important when nuclear power plants are construct in developing countries with a high level of terrorist threat.

When such reactors to be used in the future nuclear power industry, the post-Fukushima call of the group of international experts (NEVER AGAIN) should be realized.

Deterministic exclusion of severe accidents

Light water reactors of the VVER/PWR type, which form the basis of the nuclear power industry, operate reliably and meet modern safety requirements, the quantitative criterion of which is the probability of a severe accident requiring the evacuation of the population. However, the probabilistic safety analysis (PSA) methods do not seem to be convincing for the population experiencing a feeling of radiophobia, and they lose their meaning when the severe accident initiators are not random (equipment failures, personnel errors) but are caused by malicious actions (sabotage or terrorist attacks), when all standby safety systems can be deliberately disabled and transport gateways in the containment can be opened. Such NPPs in the hands of terrorists can become an instrument of political blackmail, which was the reason for considering this problem in the IAEA (IAEA-TECDOC-1487 2006).

The results of the safety analysis using the PSA methods, which are legalized in the regulatory documentation for severe accidents, the probability of which is very low ($1 \cdot 10^{-5}$ per reactor-year), do not have the necessary degree of persuasiveness. This is due to the great diversity and complexity of the processes occurring in a severe accident, the lack of a number of initial data necessary for the calculation, and the great uncertainty of the available data.

The aforementioned probability of a severe accident, which characterizes the average frequency of its occurrence, is socially acceptable for the existing number of power units operating in the world (about 500) and the average time of their operation. With this number of power units and a specified probability of a severe accident of $1 \cdot 10^{-5}$ per reactor-year, severe accidents can occur with a periodicity of 200 years. This is much longer than the lifespan of people in whose memory such distant events have little significance.

However, if the number of power units increases to 10,000 in the future (this number of power units is necessary for the nuclear power industry to fulfill its mission to reduce carbon emissions), the average frequency of severe accidents will already be 10 years, which is completely unacceptable.

At the same time, in the perception of the population, the possibility of catastrophic consequences of a nuclear accident is much more important than the very low probability of its realization (Forsberg and Weinberg 1990). This is where the phenomenon of radiophobia manifests itself. The importance of this aspect of nuclear power safety is also emphasized in the IAEA document (IAEA-TECDOC-1902 2020).

Nevertheless, the PSA methods have been and continue to be useful, and in many cases the only tools for quantifying safety performance. However, using them, it is impossible to substantiate the exclusion of an improbable severe accident for the existing types of reactors. This does not contribute to reducing the radiophobia of the population, in particular in a number of countries experiencing a shortage of electricity and being a potential market for the construction of NPPs. It is much easier to convince the population of the safety of NPPs without resorting to the PSA methods but relying on people's life experience: if there is no high pressure in the reactor and hydrogen is not generated, then there can be no explosions and fires fraught with radioactivity releases.

Compliance with the main requirements for generation IV innovative nuclear power systems

Efficient use of the energy potential of natural uranium. The SVBR-100 reactor satisfies this requirement, since in a closed nuclear fuel cycle, using mixed uranium-plutonium fuel, it operates in the fuel self-sufficiency mode, having a CBR slightly higher than unity.

A fundamentally higher level of safety. Using a chemically inert lead-bismuth coolant with a very high boiling point, the SVBR-100 reactor satisfies this requirement due to the high level of inherent self-protection of the reactor, which is determined by the very low value of the stored potential energy in the coolant (for comparison, the values of the potential energy accumulated in the coolant are about 20 GJ/m^3, 10 GJ/m^3, and 1 GJ/m^3 for water, sodium, and heavy liquid metal coolant (HLMC), respectively (Toshinsky et al. 2013).

Increased resistance to the proliferation of nuclear fissile materials. The SVBR-100 reactor satisfies this requirement due to the absence of breeding zones, in which weapon-grade plutonium can accumulate, the use of uranium oxide fuel with low-enriched uranium (20%), the long campaign (7–8 years) without fuel reloading, and the lack of technical possibilities for access to fuel during the campaign.

A fundamentally higher level of manufacturability. The fulfillment of this requirement is ensured due to the full prefabrication of the main component, i.e., the reactor monoblock and the possibility of its delivery to the NPP site in high readiness by rail or other modes of transport.

Acceptable technical and economic indicators. The SVBR-100 reactor satisfies this requirement due to:

- the absence of many safety systems required for traditional types of reactors due to the high potential energy stored in the primary coolant of such reactors;
- high serial production, due to the low power level of the reactor and the high demand for small- and medium-sized reactor plants;
- no need for R&D and construction of a prototype demonstration reactor due to the use of a tested unified reactor module of 100 MW(e) as part of power units of NPPs of various capacities;
- shortening the investment cycle.

Commercialization concept

The experience of operating transport lead-bismuth-cooled reactors was taken into account to the fullest extent in the development of the SVBR-100 reactor. However, the operating conditions for the equipment of transport nuclear power plants and NPP reactor plants are significantly different. The transport reactors operate mainly at low power levels and at low temperatures of the LBC, while the NPP reactors mainly operate at rated power. In addition, the requirements for the service life of NPP reactor plant equipment are significantly higher than those for transport reactors. Their technical and economic indicators also require direct confirmation.

All this makes it necessary to create a pilot power unit with the SVBR-100 reactor. It should be emphasized that the costs for the construction of the pilot (prototype) power unit are one-time, since, on the basis of the tested unified reactor module, it is possible to create nuclear power units of various capacities and purposes without additional large-scale R&D.

At the pilot power unit, which will be equipped with additional sensors and devices, the properties of reactor inherent self-protection and passive safety can be demonstrated under controlled conditions with a combination of equipment failures, human errors and simulation of deliberate malicious actions.

After testing the pilot power unit and confirming the design characteristics of the SVBR-100 reactor, it will be ready for commercialization and wide application as part of NPP power units of various capacities and purposes.

Current project status and development directions (Petrochenko et al. 2011)

Project status

The SVBR-100 project is being implemented by JSC "AKME-engineering", which is a public-private enterprise formed on a parity basis by the State Corporation Rosatom and JSC "Irkutskenergo".

At present, JSC "AKME-engineering"

- is recognized as the operating organization at the stages of deployment and construction of the experimental-industrial power unit (EIPU) with the SVBR-100 reactor;
- is entitled to own nuclear materials and nuclear power facilities;
- is licensed by "Rostekhnadzor" (Regulator Body) to perform work and provide services to the operating organization during the construction of nuclear power plants;
- is licensed by "Rostekhnadzor" to deploy a nuclear power facility in the city of Dimitrovgrad, Ulyanovsk Region.

The main objectives of the current stage of the project are to identify opportunities to attract an additional financial partner (possibly foreign), as well as to optimize the EIPU solutions in order to reduce costs. In addition, it is necessary to determine the appearance of serial small- and medium-sized NPPs with SVBR reactors in accordance with the recommendations of industry experts and STC No. 8 of the State Corporation "Rosatom" dated September 15, 2015, which should ensure their competitiveness and investment attractiveness.

The design documentation is developed to the required extent. As part of the project documentation, 12 sections were developed, including 210 volumes and describing the architectural, construction, design, technological and other solutions of the EIPU. As part of the preparation for the licensing of the EIPU, the initial versions of the preliminary safety analysis report and the first level probabilistic safety analysis were developed.

The analysis of the developed project documentation revealed the main areas of optimization: reducing the cost of EIPU equipment, reducing specific indicators (site size, volume of the main buildings of the nuclear island, mass of thermal-mechanical equipment to installed capacity) and the cost of construction and installation works, reducing the number of personnel and increasing the installed electrical capacity.

The technology for managing fresh and spent nuclear fuel had a significant impact on the design decisions. Thus, for example, the height dimensions of the reactor building are determined by the dimensions of the refueling equipment, and the dimensions of the reactor building in plan view are determined by the needs of transport and technological operations for the storage of fresh fuel assemblies, spent fuel assemblies and the arrangement of reloading equipment. For the serial NPPs, the technical solutions adopted for the EIPU will be optimized.

Main directions for further improvement of the project

The main system opportunities for improving the technical and economic characteristics of the serial NPPs include as follows:

- the possibility of increasing the reactor capacity by removing excessive conservatism and using a number of technical solutions;
- a high level of factory readiness of the reactor, which eliminates the need for labor-intensive installation work on the primary circuit, which makes it possible to significantly reduce the construction time of the serial NPPs;
- the effect of modularity (NPP capacity range with a capacity multiple of 100 MW(e) based on a single module, the use of unit and plant equipment for all the reactor modules that are part of a nuclear steam supplying system (NSSS));
- the economy of production scale (serialization, "learning curve");
- the multi-purpose use of reactor plants (production of electricity, heat, fresh water, renovation of VVER-440 NPP units, and, possibly, VVER-1000, the reactors of which have reached the end of their service life).

Conclusion

1. On the basis of the critically analyzed operating experience, the design of a civil-purpose reactor plant (SVBR-100), a modular type, that meets the requirements of Generation IV, is currently being developed.
2. The SVBR-100 reactor plant can operate in a closed NFC in the fuel self-sufficiency mode. Using it, it is impossible to obtain a short plutonium doubling time, as in the developed sodium-cooled FRs, but, due to the natural properties of the LBC, it can provide a higher level of safety and improve technical and economic indicators.
3. The SVBR-100 reactor plant, with its design remaining unchanged, can use different fuel types in different fuel cycles, providing a gradual economically justified transition to a closed NFC with a corresponding increase in the cost of natural uranium and the cost of storing SNF from thermal reactors.
4. The SVBR-100 reactor plant, like other HLM-cooled reactors, has the smallest reserve of potential power accumulated in the coolant, which makes it possible to realize the properties of inherent self-protection and passive safety to the fullest extent, eliminate the causes and mitigate the consequences of severe accidents requiring evacuation of the population. Reactor plant of this type will have robust properties that ensure their increased stability not only in cases of single equipment failures and personnel errors (human factor impact) but also in cases of deliberate malicious actions. These qualities of the HLM-cooled reactors should make it possible to overcome the radiophobia of the population, which again intensified after the Fukushima nuclear disaster, which is very important for the sustainable development of nuclear power. The safety chain of the future nuclear power industry should not have weak links. As the third IAEA Director General,

Hans Blix, said, "An accident is somewhere is an accident everywhere".

5. The modular structure of the NSSS of the power unit makes it possible to switch to advanced technologies for the generic design of power units of various capacities based on serially manufactured "standard" reactor modules and in-line methods for performing construction and installation works. Due to this, it will be possible to significantly reduce the NPP construction time as well as to switch to the maintenance of the reactor modules on a service basis to reduce the number of operating personnel and related costs.
6. The conservative approach adopted in the development of the reactor for the pilot power unit (EIPU) predetermined the high potential for further improvement of the reactor plant (transition to superheated steam, etc.). The implementation of the planned measures, which requires appropriate R&D, will bring the specific capital costs in the construction of a modular NPP and construction time closer to the values typical for combined-cycle thermal power plants. This will increase the competitiveness of these NPPs in the investment market and, with the widespread introduction of this nuclear power technology, will keep electricity prices down. The costs for the construction of the EIPU are one-time, since, on the basis of the tested "standard" reactor module, nuclear power units of various capacities and purposes can be created without large-scale additional R&D efforts.
7. The SVBR technology, which is not burdened with high safety costs due to the high level of its inherent self-protection, has the advantages of modularity, provides higher steam parameters compared to water-cooled reactors (for serial NPPs) and hence higher efficiency, and is more likely to achieve the required LCOE values compared to other nuclear power technologies.
8. The SVBR-100 reactor plants, like other innovative reactors, require a stage of their development, including the acquisition of real operating experience as part of the EIPU. After the necessary experience is acquired, the SVBR-100 reactor plants can be used to create modular small- and medium-sized NPPs, operating in local or regional power systems in the load following mode and generating heat energy along with electricity, and thus making it possible to replace coal-fired fossil power plants (FPPs), which are the main environmental pollutants. These reactors are expected to be widely introduced in the nuclear power industry after the confirmation of their technical and economic characteristics at the EIPU on the horizon of 2035.

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