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SMALL SIZE MODULAR FAST REACTORS IN LARGE SCALE NUCLEAR POWER

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ABSTRACT

The report presents an innovative nuclear power technology (NPT) based on usage of modular type fast reactors (FR) (SVBR-75/100) with heavy liquid metal coolant (HLMC) i. e. eutectic lead-bismuth alloy mastered for Russian nuclear submarines’ (NS) reactors.

Use of this NPT makes it possible to eliminate a conflict between safety and economic requirements peculiar to the traditional reactors.

Physical features of FRs, an integral design of the reactor and its small power (100 MWe), as well as natural properties of lead-bismuth coolant assured realization of the inherent safety properties. This made it possible to eliminate a lot of safety systems necessary for the reactor installations (RI) of operating NPPs and to design the modular NPP which technical and economical parameters are competitive not only with those of the NPP based on light water reactors (LWR) but with those of the steam-gas electric power plant.

Multipurpose usage of transportable reactor modules SVBR-75/100 of entirely factory manufacture assures their production in large quantities that reduces their fabrication costs.

The proposed NPT provides economically expedient change over to the closed nuclear fuel cycle (NFC). When the uranium-plutonium fuel is used, the breeding ratio is over one.

Use of proposed NPT makes it possible to considerably increase the investment attractiveness of nuclear power (NP) with fast neutron reactors even today at low costs of natural uranium.

Keywords: Lead-Bismuth Coolant, Small Power, Fast Reactor.

1. INTRODUCTION

After the severe accidents happened at the nuclear power plants (NPP) in TMI-2 and Chernobyl, the safety requirements have increased very much. To meet these requirements, the NPPs have been equipped with a lot of safety systems, accidents localizing systems, disposed in depth multi-barrier protection system. As a result, the capital cost of the NPP construction and the cost of the produced electricity have increased considerably.

In order to improve these parameters, considerable increase of reactor unit capacity up to 1500 MWe and over was needed in the new NPP projects. However, this will cause increases of the total capital cost of the NPP and in the schedule of NPP construction, which will decrease the investment attractiveness of such projects in market conditions.

This is caused by the fact that the inherent conflict between the economic and safety requirements is typical to the evolutionary type reactors (PWR, BWR, FBR) and impedes development of the nuclear power (NP).

This conflict can be overcome if an innovative nuclear power technology (NPT) based on the use of small power modular fast reactors (FR) cooled by lead-bismuth coolant (LBC) is used.

Prima facie, as for the economic parameters, the power unit with a large power unit reactor seems to have an advantage over the same power unit with a corresponding number of the small power reactors (the modular structure of the nuclear steam supplying system) due to the influence of the scale factor. However, this does not refer to the LBC cooled FRs which have the developed inherent self-protection and passive safety properties that make it possible to eliminate all safety systems operating in the waiting mode (except for the reactor's emergency protection system) and entrust realization of the safety functions to the normal operating systems.

The economical parameters can be also improved due to high serial production of the “standard” reactor modules in high factory readiness.

LBC was mastered in Russia in conditions of operating the nuclear submarines' (NS) reactors (Gromov, Toshinsky, Stepanov, 1997). For that reason, the proposed innovative NPT does not need carrying out large scale R&D prior to implementing.

The proposed NPT also meets the requirements for nonproliferation of nuclear fissile materials (NFM) as uranium enriched in low than 20 % is used as fuel and at operating in the closed fuel cycle, the reprocessing technology provides non-fissioning of plutonium and minor actinides.

The Report presents the basic results of experience of operating the LBC cooled reactor installations (RI) at the NSs, the concept and design of modular RI SVBR-75/100 (Lead-Bismuth Fast-Neutron Reactor that delivers 75 – 100 MWe electric power, depending on the parameters of the associated steam generation system), the concept of providing RI safety and other issues concerning the use of the proposed innovative NPT.

2. USE OF THE PROPOSED NPT – ASSURING THE NP COMPETITIVENESS IN MARKET CONDITIONS

Even if the cost of natural uranium increases greatly, the operating NPPs with thermal-neutron reactors will be very competitive with thermal electric power plants (TEPP) in the electricity market. This is caused by the fact that the economic situation of the expected escalation of prices of NP fuel (natural uranium) and that of thermal electric power (natural gas) favors NP.

The latter is conditioned by the fact that the contribution of nuclear fuel cost to the cost of produced electricity by NPPs is only about 20 – 25 % (the share of the natural uranium cost is only about 7%), as compared to TEPPs that use natural gas, where the contribution of the cost of gas to the cost of gas-produced electricity is about 70 %.

The main difficulty that should be overcome is lack of the NP competitiveness with the modern steam-gas TEPPs at the investment market that has been caused by the higher capital costs and the longer investment cycle of the NPP. The competitiveness of the NP based on the proposed NPT will be ensured due to the following features:

1.1 A high level of the inherent self-protection safety and passive safety properties of the RI that makes it possible to implement the stringent safety requirements when the special safety systems being in a waiting mode are eliminated (except the emergency protection system of the reactor). The turbine installation is not the system important for safety and can be designed and fabricated in compliance with the common industrial standards. All these will diminish considerably the specific capital cost and almost eliminate a scale loss when changing over from the large power reactor to the small power one.

1.2 The option for 100 MWe reactor will assure its production in quantities, the entire reactor module will be fabricated at the factory and it will be an opportunity to transport it to the NPP site not only by road and sea but by railway as well. These will diminish considerably the cost of RI fabrication, increase quality, reduce the assembly schedule due to the high factory readiness of the reactor module, broaden the areas of the NPP possible location.

1.3 An opportunity to construct the large, medium, and small power units for the different purposes including nuclear heat electric power plants (NHEPP) and desalinating power complexes on the basis of a unified reactor module. Compactness of the SVBR-75/100 modules makes it possible to use them for renovation of the NPP units with light water reactors (LWR) which expired their lifetime. The reactor modules should be installed in the original steam-generators (SG) and main circulation pumps' (MCP) compartments with total replacement of the LWR power capacities. In this, the existing buildings, constructions and infrastructure of the power unit should be used, the lifetime of the unit will be extended to 40 years. Such a renovation would reduce the specific capital cost by a factor of two, as compared to the construction of a new power unit that replaces the removed power capacity.

All these accounting the higher safety level, which deterministically eliminates the severe accidents, will assure forming of the stable market for these reactor modules to be sold in many regions of the world.

1.4 A modular structure of the power unit's NSSS will make it possible to use the methods of standard designing the different power units and in-line methods of organizing the construction and assembly works. Along with production of RIs in large quantities, these will make it possible to form a competitive market of the RI producers, to reduce the schedule and cost of the power units construction to the values compared with those parameters of the modern steam-gas TEPPs at the considerably lower cost of produced electricity.

1.5 The modular structure of the power unit's NSSS will make it possible to put the power unit in operating phase-by-phase with gradual raising of power capacities as the assembly and starting-adjustment works have been completed for the group of modules. These enables to diminish the pay-back term of the capital investments at the expense of earlier production output and earlier beginning of repaying a credit as compared with a power unit based on the large unit capacity reactor.

1.6 On expiring the reactor module's lifetime (50…60 years) and after extracting the spent nuclear fuel (SNF) and LBC, the reactor module should be decommissioned and placed in the repository of solid radioactive waste (SRW). The new reactor module should be installed instead. In this, the NPP lifetime will increase up to 100…120 years and the capital cost will be reduced by a factor of two, as compared to the construction of a new power unit. After the power unit has been totally withdrawn from operating, practically no radioactive materials will remain in the NSSS building after the reactor modules have been decommissioned. This considerably reduces the cost of withdrawing the power unit from operating.

1.7 An opportunity for the reactor to operate by using different types of fuel and in different fuel cycles under long lifetime (7…8 years) enables to respond flexibly to the change of prices at the uranium market and ensure the timely economically effective changeover to the closed NFC with use of LWRs' SNF as make-up fuel without separating uranium, plutonium, fission products and minor actinides (MA) (Zrodnikov, Toshinsky, Stepanov, Mayorshin, 2003).

1.8 A conservative approach adopted for designing the SVBR-75/100 RI was shown in

- closeness of the scale factors of RI SVBR-75/100 and operating RIs with LBC;
- use to the maximal possible extent the mastered and proved technical solutions both for the equipment design and for the operating modes, refueling technology, etc.;
- orientation towards the existing fuel infrastructure and abilities of the engineering enterprises

enables to reduce considerably technical and financial risks, to diminish a probability of mistakes and failures which are typical in the event of implementing the innovative nuclear technologies, to reduce considerably the scope, execution schedule and cost of the R&D.

1.9 With due account of the small power of the RI, the cost of constructing the experimental-industrial one is comparatively low and is only once as well as the R&D cost to justify the RI. On the basis of the RI, which was tested once and received the conformance certificate, it will be possible to construct the different power units with a minimal investment risk.

1.10 The conservative approach adopted for designing the RI predetermined a high potential of heightening the technical and economical parameters of the RI in the process of the project's evolutionary improvement. It can be realized when changing over to the next generations' RI of the given type after carrying out the required R&D.

First of all, these improvements are as follows:

- use of a once-through SG, producing super-heated steam, makes it possible to increase the thermodynamic cycle efficiency and the electric power of the NPP by 10 – 15 % at unchangeable thermal power and the same cost of the RI;
- increasing the LBC temperature at the reactor outlet at a predictable opportunity to increase the maximum temperature of the fuel element cladding from 600 to 650 °C. This provides an increase of the reactor’s thermal power (and, correspondingly, electric power) by 10 – 15 %, without changing the RI design and cost in the case of using both saturated and super-heated steam.

3. EXPEDIENCE AND OPPORTUNITY TO USE LEAD-BISMUTH EUTECTIC ALLOY AS FAST REACTOR COOLANT

In 1950 lead-bismuth coolant in fast reactors was first examined by A.I. Leypunsky, in a paper (Leypunsky, 1990) that estimated the opportunity to construct a breeder reactor. However, the heat-transfer properties of that coolant being low, as compared to those of sodium, did not allow obtaining sufficiently high power density in the core, together with a short doubling time in breeding plutonium, even at a breeding ratio (BR) that considerably exceeded 1. For that reason, when the fast breeder reactor was further developed, sodium was selected as the coolant.

Due to reasons highlighted in the above, now and in the foreseeable future, for the task of further developing NP, it is not realistic to have a considerable number of FR-based NPPs that provide a short plutonium doubling time, together with a high pace of NP development without consuming natural uranium. For that reason, it has become possible now to consider the opportunity of using LBC in FRs, uniquely taking into consideration the experience of its use in nuclear submarines' reactors.

The high boiling point of the coolant heightens the reliability of heat removal from the core, and provides safety due to the lack of crisis of heat transfer. Also, being coupled with the reactor's casing, the loss of coolant accident (LOCA) is eliminated.

The low pressure in the primary circuit reduces the risk of the casing’s failure and makes it possible to reduce the thickness of the reactor vessel walls. It also reduces the limitations imposed on the rate of temperature changes, in compliance with thermal-cycling strength conditions.

LBC is chemically inert. It reacts very slightly with water and air. Development of the processes caused by the primary circuit's tightness loss and the steam generator’s (SG) inter-circuit leaks will occur without the release of hydrogen and without any exothermic reactions. There are no materials within the core and reactor installation that release hydrogen, as a result of thermal and radiation effects and chemical reactions with the coolant. Therefore, the likelihood of chemical explosions and fires as internal events is virtually eliminated.

When speaking about wide use of lead-bismuth-cooled RIs in NP, it is necessary to consider certain specific issues concerning the use of bismuth in the coolant. These concern the radiation hazard of the alpha-active polonium-210 radionuclide, which is formed in the process of irradiating bismuth with neutrons, high cost of bismuth, the small scale of bismuth production in metallurgy and the insufficiently explored bismuth resources worldwide.

In connection with these issues the following is highlighted:

1) Experience in the operating of the NS RIs revealed the following. Developed measures of providing radiation safety eliminated the over-allowable doses of irradiating personnel who were in the NS compartments when accidental spillage of LBC occurred, and took part to repair and recondition the system. Having carried out the research and analyzed the experience gained, American and Japanese experts came to the conclusion that the formation of polonium-210 in LBC cannot hamper its future use in NP (Pankratov, Yefimov, Toshinsky, Ryabaya, 2005).

2) The available reference information on explored bismuth resources has not allowed the use of lead-bismuth coolant in large scale NP. However, just recently, specialized Rosatom enterprises – OAO “Atomredmetzoloto” and VNIPI of industrial technology – made technical and economic investigations into the opportunities to organize large scale bismuth production in Russia and estimated the bismuth resources in the Commonwealth of Independent States. On the basis of explored bismuth mines of only the Chita region in Russia, it is possible to produce bismuth in quantities sufficient to put in operation at a pace of 1 GWe per year, for approximately 70 GWe of NPPs with LBC FRs (Zrodnikov, Dragunov, Toshinsky, Stepanov, 2001). In addition, there are large bismuth resources in the North Caucasus. Also, it is possible to put in operation ~ 300 GWe exploiting the bismuth mines of Kazakhstan. According to assessments made by Japanese experts, the available bismuth resources worldwide are ~ 5 million tons (Masakazu Ichimiya, 2000).

It should be highlighted that according to a geological-economic general law, the quantity of mineral raw ore increases as the square of the cost that consumers are willing to pay for the resources.

At current world price of bismuth, its contribution to the capital cost for the construction of a large FR-based NPP is considered to be ~ 1% (Zrodnikov, Dragunov, Toshinsky, Stepanov, 2001). For this reason, the technical and economic parameters of NPPs will not be affected noticeably, even when bismuth prices are increased several times.

In the future, when the cheap bismuth resources have expired, it will be possible to changeover to a lead-bismuth alloy of a non-eutectic composition that has reduced bismuth content and higher melting point. For example, when bismuth content in the alloy is reduced to 10% (a reduction of 5.5 times), the melting point increases from 125 to 250 °C, which is still considerably lower than the melting point of pure lead (~ 327 °C). This does not introduce excessive difficulties in RI operating yet. Moreover, after performing relevant refinement, it is possible to reuse the recovered LBC in subsequent RIs.

Since the development of lead-bismuth-cooled FRs is based on the experience of its previous use in NS reactors, the gained experience needs to be described briefly.

4. BRIEF DESCRIPTION OF THE LEAD-BISMUTH-COOLED REACTOR OPERATING EXPERIENCE

In the early 1950s, nearly at the same time, the USA and the USSR launched development programs on nuclear submarine RIs. Both countries developed two types of RIs— pressurized water reactors and reactors cooled by liquid-metal coolants (LMC).

In the USA sodium was selected as LMC, because its thermal and physical characteristics were better, as compared to those of LBC. A ground-based test-facility RI prototype was constructed for the experimental Sea Wolf NS. After several reactor accidents, which occurred at this NS, the installation and compartment was decommissioned and replaced with a pressurized-water RI.

R&D on mastering LBC was also carried out in the USA. However, the chosen approach of finding solutions to the problems of corrosion resistance of structural materials, coolant control and quality maintenance (coolant’s technology) did not produce positive results and the effort was terminated.

From the very beginning, in the USSR lead-bismuth eutectic alloy was selected as the LMC. For fifteen years designated organizations made efforts to master the LBC technology under the scientific supervision of the SSC RF-IPPE. As a result, problems of lead-bismuth technology were solved successfully and were further verified in the multiyear experience of operating RIs in serial nuclear submarines (Toshinsky, Stepanov, Nikitin, 1998).

At this time, with due account of the experience gained, conditions to implement the same technology in the civilian-commercial NP industry were established.

5. BASIC STATEMENTS OF RI SVBR-75/100 CONCEPT

The following basic approaches and technical solutions have been realized in the RI SVBR-75/100 design:

- a monoblock (integral) design of a pool type is used for the primary circuit equipment. Valves and LBC pipelines have been completely eliminated;
- a two-circuit scheme of heat removal is used;
- the levels of coolants' natural circulation (NC) in the heat-removal circuits are sufficient enough to ensure reactor's heat decay removal without dangerous over-heating of the core;
- a reactor monoblock (RMB) with a safeguard casing is installed and fixed in the tank of the passive heat removal system (PHRS). The tank is filled with water and also performs the neutron protection function;
- the equipment can be repaired (SGs) or replaced (MCPs, etc.);
- on ending the lifetime, fuel can be unloaded at once, cassette-by-cassette, the fresh fuel is loaded as a single cartridge;
- it is possible to use different kinds of fuel (UO_2, MOX fuel with weapon or reactor Pu, mixed oxide fuel with minor actinides – TRUOX fuel, nitride fuel) without changing the reactor design and at meeting the safety requirements.

With due account of the LBC higher cost being higher as compared to that of other LMCs, the measures that reduce the specific mass of LBC in the RI have been developed. The summarized analysis of experience of designing RIs of different power capacities (Grigoriev, Toshinsky, Leguenko, 1998) has revealed the LBC specific mass decreases at reducing the RI nominal power.

Along with this, reducing the LBC specific mass is limited. It is caused by the fact that at small dimensions of the core, it is impossible to provide core breeding ratio (CBR) ≥ 1. Computations have revealed that an optimal diameter of the core should be not less than 1600 ÷ 1700 mm at height being 900 mm. These core dimensions make it possible to achieve equivalent electric power of the reactor ~ 100 MWe. In this case, CBR $\cong 1$ is provided not only for the mixed nitride fuel but also for the less dense but well mastered MOX fuel. This is realized for the volumetric fuel fraction being not less than 55 ÷ 60 %.

Reduction of the LBC specific mass in small-sized FRs, for which the core power density is several times less than that of sodium cooled FRs, is also achieved by elimination of the in-reactor storage of spent nuclear fuel (SNF) and in-reactor refueling mechanisms (rotating plugs, etc.).

Another way of reducing the LBC specific mass is increasing its average velocity in the RI and diminishing the length of the LBC circulation circuit. However, this way has its own constraints caused by the necessity to provide the safety requirements.

The first requirement is caused by the necessity to provide the power level of the reactor with naturally circulating LBC to be not less than 5…7 % of N_{nom}. This makes it possible to eliminate dangerous increase of temperature in case of shutting down the MCPs.

The second requirement is caused by the necessity to provide an effective separation of steam bubbles from LBC with steam surfacing to the LBC free levels in case of the accident with leaking SG tubes. This is necessary for elimination of steam ingress into the core and impermissible increase of pressure in the monoblock vessel.

The necessity to satisfy the highlighted requirements resulted into development of such LBC circulation scheme in which the core hydraulic resistance equals to 90 % of the total hydraulic resistance of the primary circuit and the hydraulic resistance of SGs, in which LBC flow rate is much less, only equals to 10 %.

With due account of the highlighted design features, the specific mass of bismuth in RI SVBR-75/100 is ~ 1100 t/GWe.

The basic parameters of the SVBR-75/100 RI are listed in Table 1. The principal hydraulic scheme of the SVBR-75/100 RI is presented in Fig. 1, the equipment arrangement in the reactor monoblock vessel is presented in Fig. 2.

Table 1. Basic Parameters of the SVBR-75/100 RI

Parameter	Value
Thermal power (nominal), MW	280*
Electric power, MW	101.5*
Steam production rate, t/h	580*
Steam parameters: pressure, MPa temperature, °C	9.5* 307*
Feed water temperature, °C	241*
LBC temperature, °C: at the core outlet at the core inlet	482* 320*
Core dimensions: D×H (diameter × height), m	1.645 × 0.9
Average volumetric power density of the core, kW/l	140*
Average linear load on the fuel element, kW/m	~ 24.3*
Fuel (UO_2): U-235 loading, kg U-235 enrichment, %	~ 1470* 16.1*
Core lifetime, thousand effective hours	~ 53
Time interval between refueling, years	~ 8
SG number	2
SG modules' number	2 × 6
MCP number	2
Power of the MCP electric driver, kW	450
MCP head, MPa	~ 0.55
LBC volume in the primary circuit, m^3	18
Dimensions of the reactor vessel: D×H (diameter × height), m	4.53 × 6.92

[*] – the presented characteristics are those of the SVBR-75/100 RI, as a component of a modular NPP that consists of dual units, each 1600 MW (Zrodnikov, Dragunov, Toshinsky, Stepanov, 2001). These characteristics may change if the SVBR-75/100 RIs are used as modules of other NPPs.

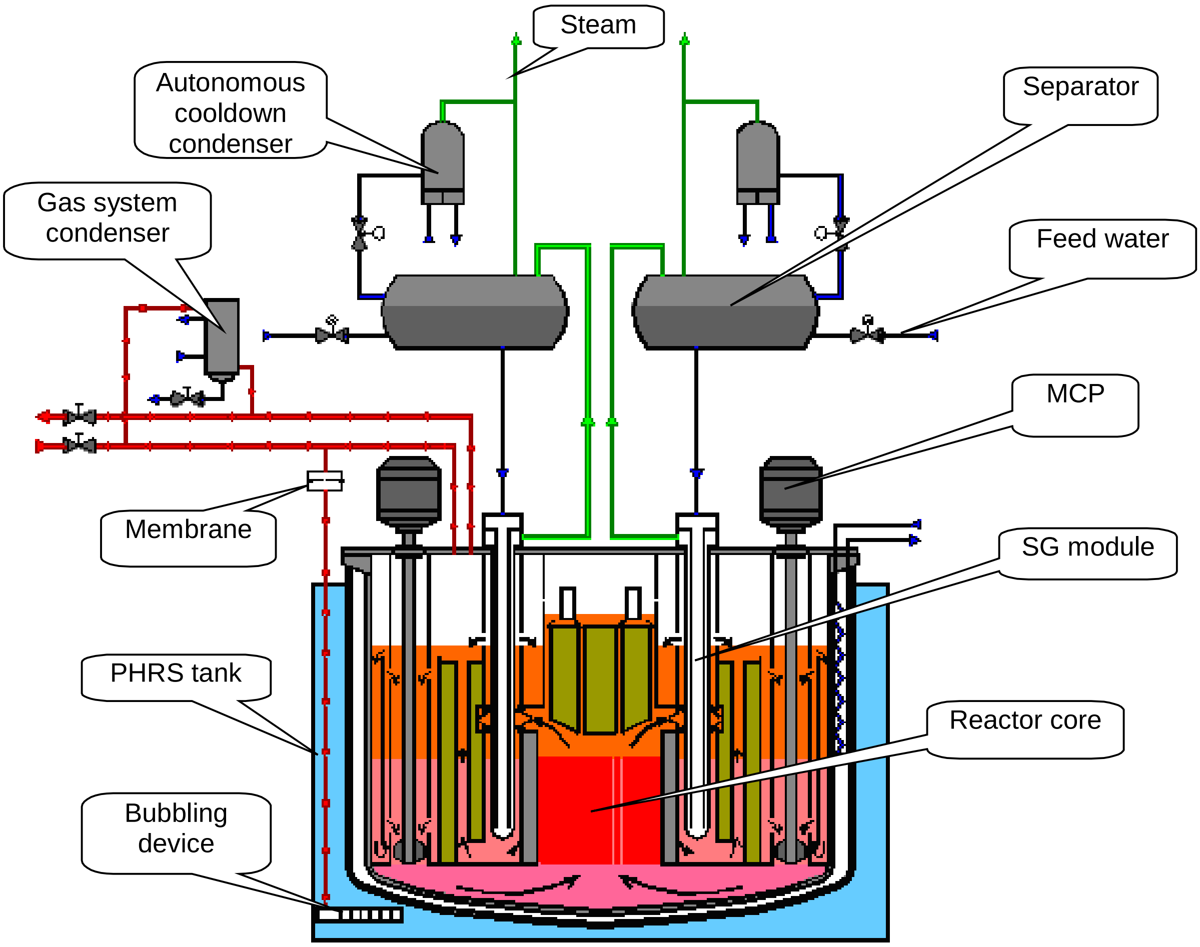


Fig. 1 Principal hydraulic scheme of the SVBR-75/100 RI

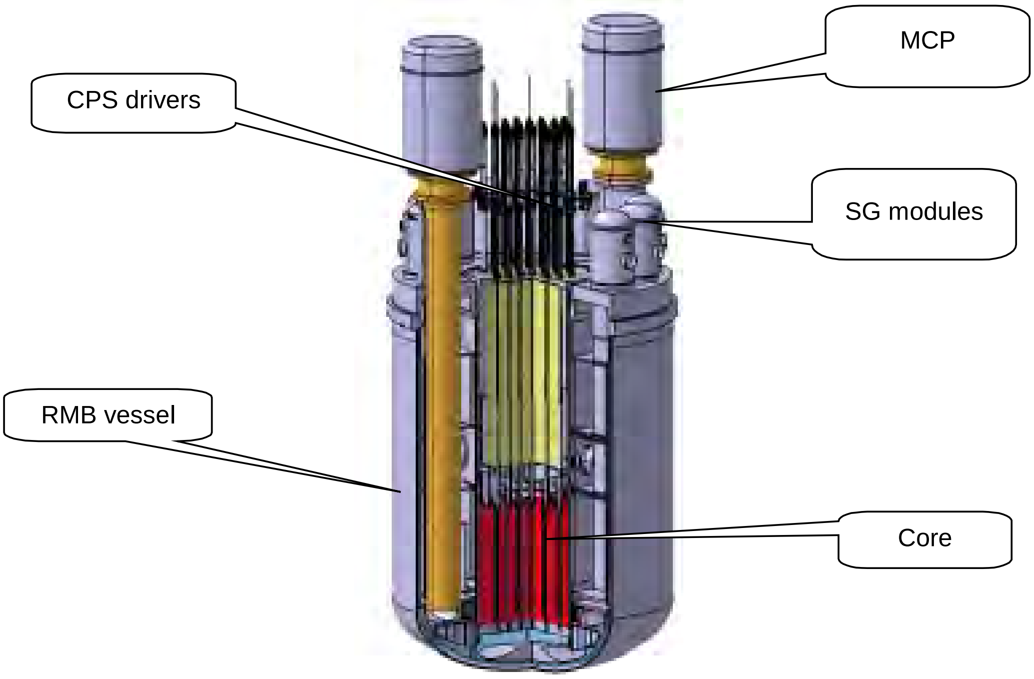


Fig. 2 Equipment arrangement in the reactor monoblock vessel

6. SAFETY PROVIDING CONCEPT OF THE SVBR-75/100 RI

Performed computations and research (Toshinsky, Grigoriev, Yefimov, 2002) revealed that safety operating limits will not be reached in the event of the following postulated accidental conditions:

- unauthorized extraction of the most effective absorbing rod;
- at the core inlet the coolant pass-through section is 50% plugged;
- all MCPs are shut down;
- steam intake to the turbo-installation and feed-water supply are terminated;
- guillotine rupture of several SG tubes;
- leak in the reactor monoblock vessel;
- “freezing” LBC in the SG;
- blacking out the NPP.

RI safety does not depend on the state of the systems and equipment of the turbo-generator installation.

The RI inherent self-protection and passive safety properties, conditioned by the reactor feedback, the natural properties of the LBC and the RI structure, make it possible to couple the safety functions (except for the emergency protection function) and the reactor’s normal operating functions.

Thus, the systems important for safety actuate passively and do not contain elements in which actuation can be locked, in the event of failures or under the influence of human factors:

- in case of increasing LBC temperature over a dangerous value, the emergency protection system of the reactor operates passively due to the gravity force. This is due to existing fusible locks which hold a special group of the absorbing rods in the upper position even in the case of mechanical damage of the servo-drivers;
- removal of residual released power when there is no heat removal via the SG is provided passively. This is done by transferring heat via the monoblock vessel to the water in the PHRS tank and subsequently, due to boiling the water in the tank, with steam removal to the atmosphere. This represents a huge grace period of about five days long;
- in the event of rupturing several tubes or terminating the operation of the gas system's condenser, at increasing steam pressure in the gas system over 1 MPa, localization of the SG leak is provided also passively. This is due to the breaking of the protective membrane and the discharging of the steam into the bubbler that is inside the PHRS tank. In an event of small SG leak, urgent removing of the RI from operating is not required.

In case of unauthorized insertion of positive reactivity at postulated failure of all emergency protection drivers, elimination of prompt neutron reactor runaway is ensured by a special algorithm of compensating rods control, which is has been included into the automatic control system. In this case, when the reactor operates at nominal power, during a certain time (~ 4 months) a reactivity swing controlled by an operator is much less than β_{eff}. In this, the rest compensating rods are switched off the control system (the stated problem does not arise for the uranium nitride fuel load as the burn up reactivity swing is less than β_{eff}).

Besides, the efficiency of each rod is much less than β_{eff}, the rate of moving the absorbing rods extracted gradually is technically limited. For that reason, the inserted positive reactivity has time for being compensated by negative feedbacks without dangerous increase of core temperature.

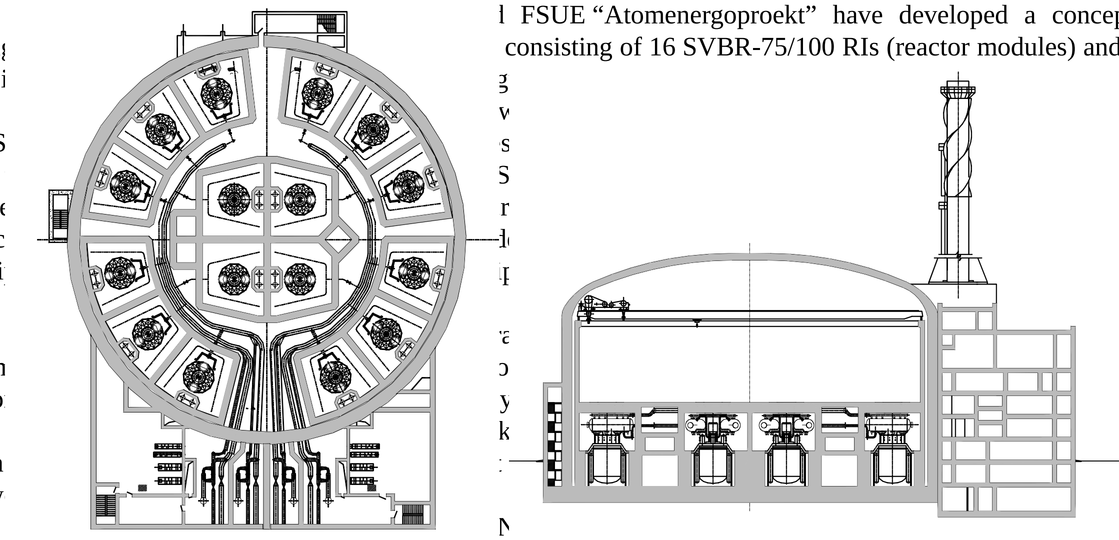
For the considered fuel loads, the total void reactivity effect of the reactor is negative and the local positive void reactivity effect of the core is less than β_{eff}. and cannot be realized due to the very high boiling point of coolant and lack of the opportunity for gas or steam bubbles to arise in great quantities.

All these ensure the RI resistance not only against the equipment failures, personnel errors and their multiple combinations, but also against ill-intentioned actions (sabotage and so on). Thus, robustness of the RI is assured.

As computations have revealed, the safety potential of the SVBR-75/100 RI is characterized by the following features. No reactor runaway, no explosion and no fire occurs, even in the case of overlapping the following postulated initial events: damage of the shielding shell, reinforced concrete overlapping over the reactor, tightness failure of the primary circuit gas system with direct contact between LBC surface in the reactor monoblock and atmospheric air, and total blacking out of the NPP. Radioactivity exhaust into the environment does not reach values requiring population evacuation beyond the NPP fence. An opportunity of severe damage of the core is considerably lower than the value specified in the normative documentation.

It is viable that the inherent self-protection and passive safety properties have been verified not only by computations but they can be demonstrated by tests in the control conditions at the experimental-industrial SVBR-75/100 RI with no economical and radiation damage.

7. PARAMETERS OF THE MODULAR NPP BASED ON RI SVBR-75/100 IN COMPARISON WITH THOSE OF OTHER TYPE ELECTRIC POWER PLANTS



l FSUE “Atomenergoproekt” have developed a conceptual
desi consisting of 16 SVBR-75/100 RIs (reactor modules) and one
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SVBR-75/100 modules are shown in Fig. 3.

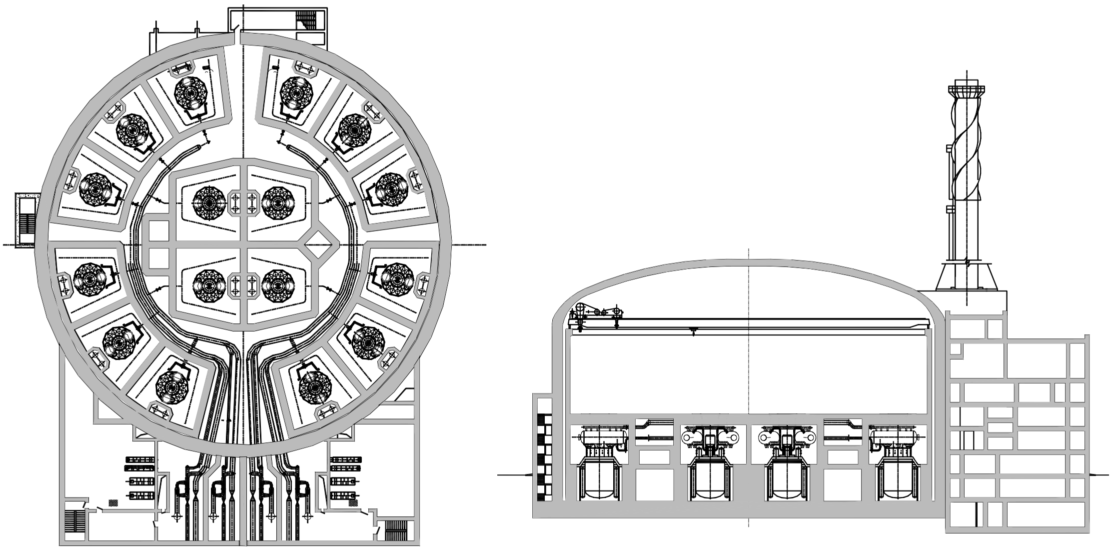

Fig. 3 Plan view and vertical section of the basic vessel of an NSSS based on 16 SVBR-75/100 modules

Table 2 summarizes the basic technical and economic parameters of the dual-unit NPP based on the SVBR-75/100 RI. These are given in comparison with those of dual-unit NPPs with RI VVER-1500, RI VVER-1000 (V-392) and RI BN-1800 (Poplavsky, Vasiliev, Suknev, 2003), and a steam-gas TEPP with ten steam-gas PGU-325 units.

The results of technical and economic computations have revealed that in compliance with the data obtained at the stage of a conceptual design, the corresponding parameters of the NPP with dual 1600 MWe units, each based on the use of SVBR-75/100 RI modules, are better, as compared to the parameters of the high-power thermal-neutron and fast-neutron NPPs, and to the TEPP containing ten PGU-325 units, which are fuelled by natural gas.

The schedule to construct this NPP can be ~ 3.5 years and with due account of an opportunity of gradual increasing capacities of the modular NSSS (see point 1.5), the commercial production will begin no later than 3 years after the first portion of concrete has been laid. Accounting for the required additional financing to service the credit (if the construction is realized at the expense of borrowed capital), the advantage of the modular NPP over the other type NPPs based on the reactors with larger unit capacity will be even higher.

The costs were computated in 1991 rubles for the Russian costs and terms when a ruble was regarded to be equal to a US dollar for the opportunity of comparing the Projects accomplished in different years.

Table 2. Comparable parameters of different power plants

Parameter Name and Unit	NPP based on SVBR-75/100	NPP based on VVER-1500	NPP based on VVER-1000	NPP based on BN-1800	TEPP based on PGU-325
1. Installed power, MWe	1625	1550	1068	1780	325
2. Number of units at the plant	2	2	2	2	10
3. Fractional electric power used to operate the plant, %	4.5	5.7	6.43	4.6	4.5
4. Net power plant unit efficiency, %	34.6	34.4	33.3	43.6	44.4
5. Specific capital investment for the industrial construction of the plant, $/kW	610*) 550**)	625	819.3	860	600
6. Design-based cost of produced electricity, cent/kW·h	1.3	1.35	2.02	1.6	1.75

*) The additional margin cost of ~17 % (over the normative one) has been introduced that is 60 % of the cost of the RI equipment.

**) With due account of realizing the opportunities to changeover to the over-heated steam or to increase the temperature of the fuel elements claddings up to 650 °C.

8. CONCLUSIONS

- There are potentials to increase considerably the investment attractiveness in the NPT, based on the use of fast-neutron reactors, which will make possible their implementation in NP for the immediate future, where cost of natural uranium is low.
- These potentials are revealed with use of the innovative NPT, based on employing “standard” modular multi-purpose FRs with chemically inert LBC (SVBR-75/100). The SVBR-75/100 modules possess developed inherent self-protection and passive safety properties (where the potential of severe accidents is eliminated in a deterministic manner). This makes it possible to eliminate conflicting requirements among safety needs and economic factors, which is particularly found in traditional reactor technologies. These properties also provide a high level of social acceptance of NP.
- Among different areas of applying SVBR-75/100 RIs, we highlight particularly their use to renovate those NPP units that have expired lifetime reactors. As performed computations revealed, if the proposed innovative NPT is used in renovations, the pace of NP development due to own investment potentials may be considerably higher, as compared to the pace of NP increases where only the evolutionary NPTs are employed on the basis of high-power LWR units.
- The modular structure of the power unit's NSSS provides an opportunity to changeover to advanced technologies and standard designs for different power levels. These “standard” reactor modules will be fabricated using factory production-line methods for their assembly and construction. This will make it possible to reduce considerably the schedule of NPP construction and to changeover to technically maintenance and servicing of the reactor modules, which will also reduce the number of operating personnel and the corresponding expense.
- At different stages of NP development, SVBR-75/100 RIs, developed on the basis of conservative approach and accounting for the operating experience of lead-bismuth-cooled nuclear-submarine’s reactors, can operate with different types of fuel and in different fuel cycles, without changing designs. They provide a gradual and economically-justifiable changeover to the closed NFC when the cost of natural uranium is increased. This is

when the SNF of thermal-neutron reactors can be utilized as the makeup fuel, instead of remaining as a waste pile of uranium (DUPIC technology).

- The conservative approach adopted in the design of the SVBR-75/100 makes it possible to reduce considerably the R&D scope, the construction schedule and the cost. This will reduce the technical and investment risks in the construction of the first demonstration-industrial RI. At the same time it will provide competitiveness of the modular NPP in the electricity production market. Moreover, the conservative approach predetermines the high potential to improve further the modular RI (such as changeover to the use of super-heated steam and other advanced features). Realizing designated measures and performing the required R&D will make it possible to assure the NPP’s competitiveness with modern steam-gas TEPPs in the investment market.

NOMENCLATURE

BN – fast sodium reactor
$\beta_{eff.}$ – delayed neutron fraction
BR – breeding ratio
CBR – core breeding ratio
FR – fast-neutron reactor
HLMC – heavy liquid-metal coolant
LBC – lead-bismuth coolant
LF – loading factor
LMC – liquid-metal coolant
LOCA – loss of coolant accident
LWR – light water reactor
MCP – main circulation pump
MOX fuel – mixed oxide (mixed PuO_2+UO_2) fuel
NFC – nuclear fuel cycle
NFM – nuclear fissile materials
NHEPP – nuclear heat electric power plant
NP – nuclear power
NPP – nuclear power plant
NPT – nuclear power technology
NS – nuclear submarine
NSSS – nuclear steam-supplying system
PGU – steam-gas installation
PHRS – passive heat removal system
RAW – radioactive waste
RI – reactor installation
RMB – reactor monoblock
SG – steam generator
SNF – spent nuclear fuel
SVBR – lead-bismuth cooled fast reactor
TEPP – thermal electric power plant
TR – thermal-neutron reactor
VVER – water cooled water moderated power reactor

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