Innovative nuclear technology based on modular multi-purpose lead—bismuth cooled fast reactors

A.V. Zrodnikova a, G.I. Toshinsky a,*, O.G. Komlev a, Yu.G. Dragunov b, V.S. Stepanov b, N.N. Klimov b, V.N. Generalov c, I.I. Kopytov c, V.N. Krushelnitsky c

a FSUE State Scientific Center of Russian Federation Institute of Physics and Power Engineering, 1 Bondarenko Square, 249033 Obninsk, Kaluga Region, Russia
b FSUE Experimental Design Bureau “Gidropress”, 21 Ordzhonikidze Street, 142103 Podolsk, Moscow Region, Russia
c FSUE “Atomenergoproekt” Building 1, 7 Bakuninskaya Street, Moscow B-5 107005, Russia

Abstract

Today’s nuclear power is in the state of an intrinsic conflict between economic and safety requirements. This fact makes difficult its sustainable development.

One of the ways of finding the solution to the problem can be the use of modular fast reactors SVBR-75/100 cooled by lead—bismuth coolant that has been mastered in conditions of operating reactors of Russian nuclear submarines.

The inherent self-protection and passive safety properties are peculiar to that reactor due to physical features of small power fast reactors (~100 MWe), chemical inertness and high boiling point of lead—bismuth coolant, integral design of the pool type primary circuit equipment.

Due to small power of the reactor, it is possible to fabricate the whole reactor at the factory and to deliver it to the NPP site in practical readiness by using any kind of transport including the railway.

Substantiation of the high level of reactor safety, adaptability of the SVBR-75/100 reactor relative to the fuel type and fuel cycle, issues of non-proliferation of nuclear fissile materials, opportunities of multi-purpose usage of the standard SVBR-75/100 reactors have been viewed in the paper.

© 2007 Elsevier Ltd. All rights reserved.

Keywords: Lead—bismuth coolant; Modular fast reactor; Innovative nuclear technology

1. Introduction

The nuclear power plants (NPPs) with light water reactors (LWRs) operating in an opened nuclear fuel cycle (NFC) will be competitive with thermal electric power plants (TPPs) at the electricity market for a long time even in case the cost of natural uranium increases greatly. This is mainly caused by low sensitiveness of the cost of electricity produced by NPPs to that of natural uranium. Along with this, gradual exhaustion of cheap natural uranium resources and increase of its cost create a problem of fuel-providing the nuclear power (NP) for a long period that cannot be solved on the basis of LWRs. That is why the fast reactors (FRs) operating in a closed NFC will be of great importance in the large-scale NP solving this problem for hundreds and thousands of years. It is presumed that the resources of thorium are also used. Large capacity sodium-cooled FRs, which are more expensive as compared with LWRs, are able to provide a high rate of plutonium breeding. At this, the excess plutonium extracted in the closed NFC must provide competitiveness of LWRs in conditions of exhaustion of cheap natural uranium resources.

As there are alternative power sources for NPPs, at each stage of NP development in conditions of a liberalized electricity market, the NPPs must be competitive with TPPs operating by using fossil fuel. Bearing in mind the limited opportunities of self-financing the NP development, the NPPs must be also competitive with TPPs at the investment market. The higher
The NP competitiveness will be, the more opportunities will be for its development, both via the own financing resources and via the borrowed ones (at diminished repayment schedules). These all are conditioning the necessity of research and development of the innovative NPT that can assure the specific capabilities not only with LWR based NPPs but with modern TPPs self-protected against the severest accidents and are competitive not only with LWR based NPPs but with modern TPPs operating by using fossil fuel (Zrodnikov et al., 2006). That is a necessary requirement for the RI possesses the developed inherent self-protection and passive safety properties.

In this case the scale economical loss is plentifully compensated for: (1) lack of lots of special safety systems operating in a waiting mode, which are necessary for traditional type reactors with a purpose to diminish a probability of severe accidents and to reduce a burden of their consequences, but which do not eliminate the causes of such accidents; (2) high quantity production of the “standard” reactor modules; (3) complete factory fabrication of the basic element of the RI, i.e. the reactor monoblock in which the whole equipment of the primary circuit is installed; (4) reduction of the duration of the investment cycle.

Thereby, a new drive for FRs development is arising, i.e. construction of modular NPPs based on HLMC cooled FRs, which are able to operate in the closed NFC in a mode of fuel self-providing (or with a small breeding), which are self-protected against the severest accidents and are competitive not only with LWR based NPPs but with modern TPPs operating by using fossil fuel (Zrodnikov et al., 2003a). That is a necessary requirement for NP development in market conditions. Moreover, when implementing FRs widely, an opportunity of economically effective utilization of spent nuclear fuel (SNF) of all types thermal reactors with transmutation of built-in minor actinides (MA) arises.

### Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR</td>
<td>breeding ratio</td>
</tr>
<tr>
<td>CBR</td>
<td>core breeding ratio</td>
</tr>
<tr>
<td>CPS</td>
<td>control and protection system</td>
</tr>
<tr>
<td>EP</td>
<td>emergency protection</td>
</tr>
<tr>
<td>FR</td>
<td>fast reactor</td>
</tr>
<tr>
<td>FSA</td>
<td>fuel sub-assembly</td>
</tr>
<tr>
<td>HLMC</td>
<td>heavy liquid-metal coolant</td>
</tr>
<tr>
<td>IPPE</td>
<td>Institute for Physics and Power Engineering</td>
</tr>
<tr>
<td>LBC</td>
<td>lead–bismuth coolant</td>
</tr>
<tr>
<td>LF</td>
<td>loading factor</td>
</tr>
<tr>
<td>LMC</td>
<td>liquid-metal coolant</td>
</tr>
<tr>
<td>LOCA</td>
<td>loss of coolant accident</td>
</tr>
<tr>
<td>LWR</td>
<td>light water reactor</td>
</tr>
<tr>
<td>MA</td>
<td>minor actinides</td>
</tr>
<tr>
<td>MCP</td>
<td>main circulation pump</td>
</tr>
<tr>
<td>MOX-fuel</td>
<td>mixed oxide (mixed PuO2 + UO2) fuel</td>
</tr>
<tr>
<td>NC</td>
<td>natural circulation</td>
</tr>
<tr>
<td>NFC</td>
<td>nuclear fuel cycle</td>
</tr>
<tr>
<td>NHPP</td>
<td>nuclear heat electric power plant</td>
</tr>
<tr>
<td>NP</td>
<td>nuclear power</td>
</tr>
<tr>
<td>NPP</td>
<td>nuclear power plant</td>
</tr>
<tr>
<td>NPT</td>
<td>nuclear power technology</td>
</tr>
<tr>
<td>NS</td>
<td>nuclear submarine</td>
</tr>
<tr>
<td>NSSS</td>
<td>nuclear steam-supplying system</td>
</tr>
<tr>
<td>NVNPP</td>
<td>Novovoronezh nuclear power plant</td>
</tr>
<tr>
<td>PGU</td>
<td>steam-gas installation</td>
</tr>
<tr>
<td>PHRS</td>
<td>passive heat removal system</td>
</tr>
<tr>
<td>PWR</td>
<td>pressurized water reactor</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>research and development works</td>
</tr>
<tr>
<td>RAW</td>
<td>radioactive waste</td>
</tr>
<tr>
<td>RI</td>
<td>reactor installation</td>
</tr>
<tr>
<td>SG</td>
<td>steam generator</td>
</tr>
<tr>
<td>SNF</td>
<td>spent nuclear fuel</td>
</tr>
<tr>
<td>SVBR</td>
<td>lead–bismuth cooled fast reactor</td>
</tr>
<tr>
<td>TPP</td>
<td>thermal power plant</td>
</tr>
<tr>
<td>TR</td>
<td>thermal reactor</td>
</tr>
<tr>
<td>VVER</td>
<td>water cooled water moderated power reactor</td>
</tr>
</tbody>
</table>

### 2. Basic statements of the NPT based on RI SVBR-75/100

#### 2.1. Reactor installation SVBR-75/100

RI SVBR-75/100 (Lead–Bismuth Fast Reactor) has been designed as a standardized reactor installation of 75–100 MWe, depending on the parameters of the generated steam, for multi-purpose usage as a component of modular nuclear plants or as the autonomous power sources (Zrodnikov et al., 2003a).

The distinctive features of the SVBR-75/100 RI are as follows:

1. A fast-neutron reactor with chemically inert lead–bismuth coolant (LBC), i.e. eutectic lead–bismuth alloy in the primary circuit. Boiling point of LBC is 1670 °C, melting point of LBC is 123.5 °C.
(2) An integral design of the reactor at which the whole primary circuit equipment is mounted in a single strong vessel of the reactor monoblock. Valves and LBC pipelines are completely eliminated.

(3) A reactor monoblock with a safeguard casing is installed in a tank with water. The tank, which has a seismic resistant supporting structure, performs a function of radiation shielding and also a function of a passive heat removal system (PHRS) when heat decay of the RI is removed.

(4) A two-circuit scheme of heat removal and a steam generator (SG) with multiple natural circulation (NC) over the secondary circuit are used.

(5) The coolants’ NC in the heat removal circuits is sufficient to ensure heat decay removal from the reactor without dangerous over-heating of the core.

(6) The number of the special safety systems is noticeably reduced. The safety functions are realized by normal operating systems.

(7) The basic components of the reactor monoblock and reactor installation have been designed as separate modules. At this, an opportunity of their replacement and repair has been ensured.

(8) On ending the lifetime, fuel unloading will be performed at once, cassette-by-cassette, and fresh fuel will be loaded as a single cartridge (new core).

(9) The primary circuit equipment can be repaired and refuelling can be realized without LBC draining at maintaining the liquid state of LBC due to heat decay or heating system’s operation.

The reactor monoblock, arrangement of the RI equipment and the hydraulic diagram of the RI are presented in Figs. 1—3, the basic characteristics of the RI are summarized in Table 1.

2.2. Reasoning of the option for the power level of the reactor

The option for the reactor power level to be 100 MWe or 280 MWt and, consequently, the option for the reactor dimensions has been reasoned by the following:

(1) As computations have revealed that this is a minimal power level that provides core breeding ratio (CBR) slightly exceeding 1 for the MOX-fuel. This enables operation of the reactor in the closed NFC in the mode of fuel self-providing without consuming the natural uranium and use of such reactors in the large-scale NP.

(2) On the other hand, this is the maximal power at which the dimensions of the reactor monoblock assure an opportunity to transport it in complete factory readiness by railway, as well as by sea or by road. Therefore, the opportunities of choosing the sites for NPP construction will be
2.3. Use of real operating experience and conservative approach

The proposed reactor technology for modular fast reactors trusts first of all to the 40-year experience of development and operation of LBC cooled RIs at the NSs and ground facilities-prototypes (Toshinsky et al., 1998). The total sum of operating time is \( \sim 80 \) reactor-years. In the process of mastering this new technology a number of scientific and technical problems have been solved.

First, this is a problem of providing corrosion resistance of structural materials, control and maintenance of coolant’s quality (coolant technology) in the process of operating. The result of performed works has revealed that assurance of the reliable RI operation requires measuring and maintenance of a certain parameter, namely, concentration of oxygen dissolved in LBC, within the specified interval, and this is possible to be realized in an automatic mode.

The viable problem of providing radiation safety that was caused by formation of polonium-210 in the process of irradiating bismuth with neutrons was solved too. The personnel, who took part in such works, were under the periodical medical observations. On the basis of the numerous radiometric investigations of biological samples of the personnel (both military one and civilians), it was fair established that there were no cases of polonium intake over the permissible values. This fact validates a high efficiency of the used individual and collective protection measures, the right choice of the technology and the correct organization of repair-maintenance works (Pankratov et al., 2005).

It should be highlighted that due to the monoblock (integral) design of the primary circuit equipment and the safeguard casing on the monoblock vessel, coolant’s leaks are virtually eliminated for the SVBR-75/100 RI. A probability of radioactive gas release is also reduced considerably as argon pressure in the gas system approximately equals to the atmospheric one.

The paper published in the USA (Wiggs et al., 1991) summarizes the data of the retrospective analysis on mortality among the personnel (about 4500 men) who were dealt with Po-210 in 1944–1972 and whose internal intakes of Po-210 were examined. The authors made a conclusion that there was no connection between the doses of internal intake caused by \( \sim 1 \text{ Sv} \) (100 rem) of incorporated polonium and the death-rate caused by cancer. For the examined personnel almost all trends characterizing the death-rate caused by various cancer diseases were negative, i.e. the death-rate was even less than that for the control representative groups of people who were not dealt with polonium.

As operating experience has revealed, the quantity of liquid radioactive waste is very low due to lack of the necessity to perform the primary circuit’s decontamination.

A problem of multiple “freezing-defreezing” of LBC while keeping operability of the RI equipment was solved too.

A conservative approach was used to design RI SVBR-75/100. This approach presumed that the technical solutions borrowed or scaled with small coefficients from the NS RIs were

---


Table 1
Basic parameters* of the SVBR-75/100 RI (basic variant)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set up power (thermal/electric), MW</td>
<td>280/101.5</td>
</tr>
<tr>
<td>Steam-producing rate, t/h</td>
<td>580</td>
</tr>
<tr>
<td>Steam parameters: pressure, MPa/temperature, °C</td>
<td>9.5/307</td>
</tr>
<tr>
<td>Flow rate of the primary circuit’s coolant, kg/s</td>
<td>11,760</td>
</tr>
<tr>
<td>Temperature of the primary circuit’s coolant: inlet/outlet, °C</td>
<td>482/320</td>
</tr>
<tr>
<td>Fuel (UO2): U-235 loading, kg/U-235</td>
<td>( \sim 1470/16.1 )</td>
</tr>
<tr>
<td>Change of reactivity within the range from 200 to operating temperatures at ( N_{\text{ref}} ) (beginning of lifetime/ending of lifetime), $</td>
<td>(-3.74) (-5.72)</td>
</tr>
<tr>
<td>Change of reactivity during the lifetime, % ($)</td>
<td>(-1.2) (-1.45)</td>
</tr>
<tr>
<td>Core dimensions: ( D \times H ) (diameter ( \times ) height), m</td>
<td>1.645 \times 0.9</td>
</tr>
<tr>
<td>Average power density of the core, kW/dm³</td>
<td>140</td>
</tr>
<tr>
<td>Average linear load of the fuel element, kW/m</td>
<td>( \sim 25.7 )</td>
</tr>
<tr>
<td>The number of fuel elements</td>
<td>12,114</td>
</tr>
<tr>
<td>The number of CPS rods</td>
<td>37</td>
</tr>
<tr>
<td>Core lifetime, thousands of effective hours</td>
<td>( \sim 53 )</td>
</tr>
<tr>
<td>Time interval between refuelling, years</td>
<td>( \sim 8 )</td>
</tr>
<tr>
<td>The number of steam generator modules</td>
<td>12</td>
</tr>
<tr>
<td>The number of MCPs</td>
<td>2</td>
</tr>
<tr>
<td>MCP head/electric driver’s power, MPa/kW</td>
<td>0.55/450</td>
</tr>
<tr>
<td>LBC volume in the primary circuit, m³</td>
<td>18</td>
</tr>
<tr>
<td>Dimensions of the reactor monoblock vessel: ( D \times H ) (diameter ( \times ) height), m</td>
<td>4.53 \times 6.92</td>
</tr>
</tbody>
</table>

---

* The presented characteristics may change depending on the use of RI SVBR-75/100.
used in the reactor design. Also, these technical solutions have been verified by operating experience of NS RIs and other RIs.

These refer to almost all basic elements, units and such components of the RI as: fuel pellets, fuel elements’ claddings, fuel sub-assemblies, absorbing rods, vessel-internal devices, actuating mechanisms of the absorbing rods, LBC technology system’s devices, steam generators with bayonet tubes generating saturated steam, separators, autonomous cooling condensers, gas system condensers, refuelling system’s equipment and so on.

The conservative approach is also peculiar in the use of the mastered mode parameters of the primary and secondary circuit and orientation to the existing fuel infrastructure and technological opportunities of the machine building enterprises.

Such approach makes it possible to reduce considerably the technical and financial risks, narrowing down the possibility of having errors and failures, which are typically found in the implementation of innovative nuclear technologies, while significantly reducing the bulk, the execution schedule and the cost of the R&D.

2.4. Inherent self-protection and passive safety of the RI

The main effect in assuring the safety level of the SVBR-75/100 RI specified in the INPRO requirements (inherent safety and assured elimination of severe accidents) is achieved due to use of a fast-neutron reactor, heavy liquid-metal coolant and an integral design of the reactor and this has been verified by realized computations and developmental works.

The reactor possesses a negative void reactivity effect and negative feedbacks, the efficiency of the strongest absorbing rod does not exceed 1S, that coupled with technical realization of the control and protection system (CPS) eliminate prompt neutron runaway of the reactor.

The high boiling point of the coolant heightens the reliability of heat removal from the core, and provides safety due to lack of the heat transfer crisis. Also, being coupled with a provided safeguard casing of the monoblock, it eliminates the loss of coolant accidents (LOCAs) and high pressure radioactive release.

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

The RI components do not contain materials that release hydrogen as a result of thermal and radiation effects and chemical reactions with coolant, water and air. Therefore, the likelihood of chemical explosions and fires is virtually eliminated.

The circulation scheme of LBC provides elimination of water/steam ingress into the core in an event of SG leak due to effective separation of steam on the free level of LBC in the monoblock.

The performed computations and researches (Toshinsky et al., 2002) have revealed that safety operating limits for the maximal temperature of the fuel elements’ claddings 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 main circulation pumps (MCPs) are shut down;
- steam intake to the turbine installation and feed-water supply are terminated;
- guillotine rupture of several SG tubes;
- leak in the reactor monoblock vessel;
- postulated “freezing” of LBC in a single SG (out of two ones);
- “blackout” of the NPP.

We have not found any other accidental scenarios which are potentially realized and in which consequences are dangerous.

RI safety does not depend on the state of the systems and equipment of the turbine generator installation that has been designed and manufactured in compliance with the accepted non-nuclear rules and standards. The RI inherent self-protection and passive safety properties make it possible to couple the realization of much of the safety functions and the normal operating functions of the RI.

At this, the safety systems do not contain the elements in which actuation can be blocked in an event of failures or under the impact of human factors:

- removal of heat decay when there is no heat removal via the SG is provided passively by natural circulation of LBC in the primary circuit. This is realized by transferring heat via the reactor monoblock vessel to the water in the PHRS tank and further due to water boiling in the tank, with steam removal to the atmosphere. (This represents a grace period of about two days long without exceeding the allowed temperature limits);
- in the event of rupturing the several tubes or terminating the operation of the gas system’s condenser, localization of the SG leak is provided also passively at increasing steam pressure in the gas system over 1 MPa. This is provided due to breaking of the preserve membrane and discharge of the steam into the bubbling device that is inside the PHRS tank. While normal operation, the PHRS tank performs the neutron shielding function. (It should be mentioned that the RI does not need to be shut down immediately in an event of small leak in the SG);
- at increasing the LBC temperature over a dangerous value, the rods of the additional emergency protection system, which have been mounted in the “dry” channels and do not have drivers on the reactor lid, operate passively due to existing fusible locks made of the alloy with a corresponding melting temperature and hold the rods in the upper position under the normal temperature modes;

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 coincidence of the following postulated initial events: damage of the protective shell, damage of the reinforced concrete overlapping over the reactor, tightness failure of the primary circuit’s gas system with direct contact between a LBC surface in the reactor monoblock and atmospheric air, and total “blackout” of the NPP. Radioactivity exhaust into the environment does not reach values requiring population evacuation beyond the NPP fence. According to the assessments, the probability of severe damage of the core is considerably lower than the value specified in the regulatory documentation.

These enable speaking not only about RI tolerance to the equipment’s failures and personnel’s errors and their multiple super-positions but also about tolerance to malevolent actions when all special systems have been intentionally blocked.

It is viable that the inherent self-protection and passive safety properties have been proved not only by computations but can be demonstrated without economical loss and radiation damage.

2.5. Modular structure of the NSSS power-unit

The modular structure of the NSSS power-unit enables:

(1) to provide the higher reliability (tolerance to failures of the power-unit being a system composed of the separate RIs) and safety (reducing the potential radiation risk) as compared with a power-unit based on a large capacity single reactor;

(2) not to organize reserve power for the regional NPPs in the areas of distributed power supply;

(3) for long reactor operating without refuelling to provide the load factor (LF) determined by the turbine installation’s reliability parameters to be no less than 90%. When each RI is shut down for refuelling or maintenance, the power-unit’s capacity reduces only slightly as compared with a power-unit based on a large capacity single reactor;

(4) to provide organization of production of reactor monoblocks in large quantities (10 monoblocks per year) and continuous work load of engineering factories. Thus, the manufacturing costs will be considerably reduced. As fabrication of the reactor monoblock of the RI does not require a unique engineering equipment, an opportunity to form a competitive market of producers arises;

(5) to use the standard designs for different capacity power-units and to use the factory production-line methods for their assembly and construction. Along with high quantity production of the RIs, these provide reduction in the schedule and the costs of constructing the power-units to the values compared with the similar parameters of the modern steam-gas TPPs at considerably lower cost of produced electricity;

(6) to locate the modular NPPs of required capacity in the power consuming centres. Therefore, the expenditures for constructing the high-voltage lines have been eliminated;

(7) to provide stage-by-stage putting the power-unit in operation by turns with gradual raising of power capacity as the assembly and starting-up and adjustment works for the group of modules have been completed. This makes it possible to reduce the pay-back term of the capital investments due to earlier output of the production and earlier beginning of repaying a credit as compared with a power-unit based on a large capacity reactor.

These all multiplies the customer benefits of RI SVBR-75/100.

Reduction of the investment cycle of NPP construction, which is assured by the modular structure of the NPP, and the delivery of factory-ready modules, is extremely viable for technical and economic parameters of the NPP. At this, technical and economic parameters nearly attain those of the steam-gas plants that have short investment cycles. This also makes it possible to reduce considerably the financial risks (Zrodnikov et al., 2004).

As the RI has only two states, operating and shut down, control of the modular NSSS is carried out by an operator using the common power master unit. If there is any fault in a given RI, it is automatically shut down and can be cooled down autonomously, away from the turbine installation systems.

The RI has only three automatic control devices, namely, two control devices of flow rate of feeding water supplied to the SG separators which maintain the constant level of water in the separators independently of the power level and a control device of the reactor power level, which maintain the required capacity level of the RI independently of the feeding water flow rate. This independence and adjustment of the individual regulating devices with required static characteristics eliminate the causes of arising the mode’s instability while operating the group of modules connected in parallel at a single turbine.

On expiring the RI lifetime (50—60 years) and after unloading the spent nuclear fuel and LBC, the basic element of the RI — the reactor monoblock — will be dismantled and placed in a storage of solid radioactive waste. The new reactor monoblock will be installed instead. The other elements of the RI and power-unit may be dismantled and replaced as well, i.e. the renovation is performed. At this, the lifetime of the modular NPP will be limited by the lifetime of the concrete construction structures and will increase up to 100—120 years at the costs being much less as compared to those required for construction of a new power-unit. When the power-unit has been completely decommissioned, practically no radioactive materials will remain in the NSSS building after dismantling the reactor monoblocks. This considerably reduces the cost of decommissioning.

2.6. Flexible fuel cycle

The design of the SVBR-75/100 RI allows it to operate using different types of fuel and in various NFC, without changing the RI design or deteriorating the safety characteristics.
During the next decades, at the existing low cost of uranium and its enrichment, the most economically effective fuel type will be the mastered oxide uranium fuel and operation in the opened NFC with postponed reprocessing. Changeover to the mixed uranium—plutonium fuel and to the closed NFC, with \( CBR \geq 1 \) will be economically effective when the cost of natural uranium increases. At this, the expenditures for constructing the factories for SNF reprocessing and re-fabrication of fresh fuel with plutonium, and their operating costs must be less than the corresponding costs of natural uranium, its enrichment, the cost of manufacturing the fresh uranium fuel and the cost of long-term SNF storage.

The most expedient is use of the “dry” pyro-electro-chemical methods of SNF reprocessing in the chloride melts and vibro-technology for re-fabrication of fresh fuel (Zrodnikov et al., 2003b).

The expenditure caused by changeover to the closed NFC will be lower, if plutonium extracted from the own SNF of uranium loads is used in fabrication of the first MOX-fuel loads. The content of plutonium in that SNF is higher by an order of magnitude than the plutonium content in the thermal reactors’ (TR) SNF, which is usually considered as a source of plutonium to launch the FRs. Due to the fact that the scope of SNF reprocessing per ton of plutonium is inversely proportional to the content of plutonium in the SNF, the cost of plutonium extraction correspondingly will be lower.

As FRs operating in the opened NFC by using uranium fuel consume much more natural uranium in comparison with thermal reactors, and at the expected high paces of nuclear power development the cheap resources of natural uranium will be exhausted quickly, the period of FRs operating in the opened NFC must be maximally reduced.

As the computations have revealed, changeover to the closed NFC is possible to be begun after the second lifetime, i.e. in 16 years. At this, during the first 16 years the consumption of natural uranium calculated for 1 GWe will be \( \sim 5670 \) tons (when operating by using oxide uranium fuel, \( CBR = 0.84 \)). During the 60 years of the RI service lifetime, the consumption of natural uranium calculated for 1 GWe will be by 30/40% lower than its consumption by a pressurized water reactor (PWR) during that time. Further FR operating in the closed NFC prior to reaching the equilibrium mode will be realized without consumption of natural uranium.

As make-up fuel, the LWR SNF may be utilized in the closed NFC (similar to the DUPIC-technology) instead of waste pile uranium (Lee et al., 1993).

SNF storing prior to reprocessing is presumed to realize as follows. After the spent fuel sub-assembly (FSA) has been extracted from the reactor, it is installed in a penal, in which lead has been previously heated in an electric furnace over its melting point. Then the penal is sealed and transported to the “dry” SNF storage with natural convection air-cooling. At this, lead in the penal is solidifying gradually and forms an additional protection barrier.

Adaptability of the SVBR-75/100 reactor relative to the fuel type and fuel cycle makes it possible to realize a timely and gradual changeover to the closed NFC, which will be economically justified. Simultaneously, this solves a problem of radiation-equivalent burial of long-lived RAW, taking into account that minor actinides are effectively burned in the FR.

2.7. Proliferation risk decreasing

The solution to the problem of non-proliferation can be only achieved by coupling both technological and political measures. The relationship of those measures will be different for nuclear and non-nuclear countries. During the recent decades all nuclear countries, which are the members of the “Nuclear Club” and legally possess the nuclear weapons, have solved this problem successfully, using the measures of physical protection, accounting, control and safeguarding. For that reason, the additional measures of technological maintenance of non-proliferation will be justified if they do not reduce the NP competitiveness.

When using NPPs in developing countries, the additional measures of technological maintenance for non-proliferation should be implemented, together with political measures and international control.

Compactness of the module and LBC properties provide a unique opportunity to realize return of the SNF without its unloading from the reactor in the User-Country. Transportation of the fuel in the reactor monoblock with solidified LBC creates an additional technical barrier for the theft of fuel. The solidified LBC in the monoblock eliminates a risk of nuclear and radiation accident while transportation is performed.

In all these applications, the technological support for non-proliferation is also assured by the following features. When uranium fuel is fabricated, uranium enriched in less than 20% will be used. At the stage of SNF reprocessing, 2% of fission products built-up in the SNF and all minor actinides (MA) will remain in the re-fabricated fuel, except for curium that is released and kept to decay in plutonium with return to the fuel cycle. Handling that fuel needs the special technological equipment, which makes it easy to account and control the fuel movements. Breeding zones in which plutonium for weapons can be built-up are also absent in the reactor.

2.8. Opportunities of multi-purpose usage

The properties of RI SVBR-75/100 assure the opportunities of its multi-purpose usage as the “standard” reactor modules with electric power of each being \( \sim 100 \) MW for the following:

1. renovation of the NPP units in which reactors have expired their lifetime. Renovation means installation in the original NPP’s SG and MCP emptied compartments the necessary number of SVBR-75/100 RIs which generate the same quantity of steam of the identical parameters as the RIs which lifetime have been expired. The results of technical and economic research into the technical opportunity and economic expediency to renovate the 2nd, 3rd and 4th units of the Novovoronezh NPP (NVNPP) on the basis of
RI SVBR-75 (Ignatenko et al., 1997) have revealed that such a renovation would reduce the specific capital costs by a factor of two, as compared to the construction of new replacement power capacities. Moreover, when renovation of the NPP is realized on the basis of such installations, the expenditures for decommissioning the power-units will be reduced. Performing the renovation in turn will make it possible to save viability of the satellite cities of the NPPs and electric supply network, transport and water infrastructures.

(2) construction of the regional NPPs and NHPPs of small and medium capacity, which are located not far from the cities, including developing countries which do not have developed networks for power transfer and distribution. Moreover, the large power-units require the large lump-sum capital investments, which are unrealizable for economics of developing countries.

(3) construction of large capacity modular type NPP power-units (Zrodnikov et al., 2006) with due account of a general tendency to heighten the NPP competitiveness as compared with TPPs with increasing the power-unit’s capacity.

(4) their use as parts of the nuclear desalinating power-complexes or floating NPPs. In this case the principle “build-possess-lease (or operate)” is realized (Gromov et al., 2001).

These opportunities are assured by the following:

- acceptable level of specific capital investments at low capacity of the installation that provides competitiveness in the regions with a higher cost of fossil fuel;
- opportunity to transport the factory-ready reactor monoblocks to the NPP site;
- unification of the RI, i.e. an opportunity to obtain the required steam parameters without changing the design and operate by using different types of fuel;
- high level of inherent self-protection and passive safety which deterministically eliminates the severe accidents requiring population’s evacuation beyond the NPP site in an event of multiple equipment’s failures, superposition of personnel’s errors or malevolent actions;
- simplicity of the RI scheme that is conditioned by reduction of quantity and diminishing of complication of the special safety systems that simplifies and cheapens the RI maintenance, sharply reduces the probability of personnel’s errors, which consequences do not affect safety;
- large duration of the reactor core lifetime (8–10 years).

Especially:

- Increasing the LBC temperature at the reactor outlet while increasing the maximal temperature of the fuel element’s cladding from 600 to 650 °C (there are all necessary backgrounds) will provide (as the computations have revealed) the increase of the reactor’s thermal power by 20% without changing the reactor design and cost.
- Use of SG, producing super-heated steam, makes it possible to increase the thermodynamic cycle’s efficiency and the electric power of the NPP by 10–15% without virtual increase of capital costs.
- Use of nitride fuel can provide increase of the reactor lifetime up to two times (the operability of fuel elements has been verified) and correspondingly reduce the fuel consumption.

2.10. Commercialization concept

Despite maximal possible use of experience of operating the LBC cooled reactors at the NSs, the conditions of operating the equipment of NS RIs and NPP RIs are much different. The operating mode of NS RIs is characterized by operation mainly at low power levels under lowered LBC temperatures, whereas the NPP RIs operate mainly at nominal power. Moreover, the requirements to the lifetime of the NPP RIs equipment are much higher than those to the lifetime of the NS RIs equipment. The technical and economical parameters also need direct verification.

These all require construction of the experimental-industrial power-unit with RI SVBR-75/100. According to the realized assessments, the cost of its construction including the R&D cost will be ~US $ 200 M. It should be highlighted that there will be only one-time expenditures for the R&D and for constructing the experimental-industrial prototype.

The experimental-industrial prototype equipped with additional sensors and devices may be used for demonstration of the inherent self-protection and passive safety properties of the RI in the controlled conditions while simulating all the possible super-positions of equipment failures, personnel’s errors and malevolent actions.

After the certified tests of the experimental-industrial prototype have been performed and the design characteristics have been proved, the SVBR-75/100 RI will be ready for commercialization and wide use as a part of the NPP power-units of different capacity and usage.

3. Conclusion

- There is an opportunity to increase much of the investment attractiveness of the NPT based on use of FRs that allows their effective implementation in the NP in the near future at low costs of natural uranium.
- This opportunity appears with use of an innovative NPT based on the “standard” modular multi-purpose FRs with chemically inert LBC (SVBR-75/100) which possess...
the developed inherent safety properties (deterministic elimination of severe accidents) that enable to assure a high level of social acceptability of the NP.

- The modular structure of the power-unit’s NSSS provides an opportunity to changeover to the advanced technologies of standard designs for the different capacity power-units on the basis of series factory-manufacture of the “standard” reactor modules and changeover to the production-line methods for their assembly and construction. This will make it possible to reduce considerably the schedule period of the NPP construction as well as to changeover to technical maintenance of the reactor modules on a servicing base, which will also reduce the number of the operating personnel and corresponding expenditures.

- At different stages of NP development, RI SVBR-75/100, developed on the basis of the conservative approach and accounting for operating experience of LBC cooled NSs’ reactors, can operate using different types of fuel and in different fuel cycles without changing the design and providing a gradual and economically justified changeover to the closed NFC when the cost of natural uranium is increasing. At this, the thermal reactors’ SNF can be utilized as make-up fuel, instead of waste pile uranium.

- The conservative approach adopted in the RI design has predetermined a high potential to improve further the RI (such as changeover to the use of over-heated steam and other advanced features). Realization of the designated measures that requires performing the corresponding R&D will make it possible to bring closer the specific capital cost of constructing the modular NPP and the construction schedule to the values that are typical for steam-gas TPPs. This will heighten the NPP’s competitiveness at the investment market and while widely implementing such NPT, this will restrain the increase of electricity costs.

- Rosatom’s Scientific and Technical Council No. 1 dated on 15.06.06 considered the prospects of use of reactors SVBR-75/100 in nuclear power and recommended in 2007 to continue development of the technical design of the experimental-industrial power-unit with RI SVBR-75/100 with fixing it on the particular site.

- The Federal Target Program “Development of the nuclear power-industrial complex in Russia for the period of 2007–2010 years and up to the year 2015” has provided construction of the experimental-industrial power-unit with RI of the SVBR-75/100 type. There will be only one-time expenditures for demonstration of the present NPT as on the basis of the tested “standard” reactor module the nuclear power-units of different capacities and purposes can be constructed without performing the additional R&D.

References


