NUCLEAR POWER DEVELOPMENT IN MARKET CONDITIONS WITH USE OF MULTI-PURPOSE MODULAR FAST REACTORS SVBR-75/100

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1. Introduction

Despite the prime advantages of the NP conditioned by virtually unlimited fuel resources and considerably low harmful impact on the environment, the number of the problems constrains its worldwide development. In the market condition the first of these problems is to assure the nuclear power plants (NPP) competitiveness with the electric plants which operate using fossil fuel. The proposed key principles developed within the framework of the international INPRO Project, which IAEA supervises, highlight that the cost of NPP-produced power, accounting for all costs, including the servicing of credits, must be competitive with the cost of alternative power sources [1].

The other problems restraining NP development are social and political pressures conditioned by providing safety, handling radioactive waste (RAW) and risk of nuclear fissile materials (NFM) proliferation. In different countries the economic requirements may differ. However, the requirements on safety, non-proliferation and the handling of the long-lived radioactive waste (RAW) must be the same everywhere as violation of these requirements may cause catastrophic consequences all over the world. For that reason, these requirements must be established by the world society under IAEA supervision.

After the severe accidents happened at the NPPs in TMI and Chernobyl, the safety requirements have increased very much. To meet these requirements, the NPPs have been equipped with a lot of safety systems providing both a low probability of catastrophic accidents and their consequences. As a result the capital cost of the NPP construction and operating cost have increased considerably that have reduced competitiveness of the NP. In order to reduce the specific capital cost and to reduce the electricity cost, considerable increase of reactor power up to 1500 MWe and over was needed. However, increase of the unit power of the reactor will cause increases of the total capital cost of the NPP and in the schedule of NPP construction, which will reduce the investment attractiveness in such projects. This conflict between the economic and safety requirements is typical to all traditional NPT. Moreover, the market of the large power units is limited by a small number of countries having large power grids. It is also difficult to find the suitable sites to install the large power units.

The use of the innovative NPT, in which the conflict between safety requirements and economic requirements is eliminated, is a possible way to find the solution to the highlighted cumulative problems. That NPT, which is the most ready to be implemented in practice, is the one based on the use of small power (100 MWe) modular fast reactors for multi-purpose usage with lead-bismuth coolant (LBC), which have the developed inherent selfprotection and passive safety properties – SVBR-75/100 [2]. That NPT was mastered in Russia for the reactors of nuclear submarines (NS) [3].

2. Expedience and opportunity to use lead-bismuth eutectic alloy as fast-neutron reactor coolant

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 safeguard casing, the loss of coolant accident (LOCA) is eliminated. The low pressure in the primary circuit reduces the risk of tightness loss.

Lead-bismuth coolant is chemically inert. It reacts very slightly with water and air. Development of the processes caused by tightness loss in the primary circuit and by 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 reactor installations 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 operation of the NS reactor installations (RI) 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 equipment [4].

2) The available reference information on explored bismuth resources has not allowed the use of LBC in large scale NP. However, just recently, specialized Rosatom enterprises – OAO “Atomredmetzoloto” and VNIP 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 [5].

3. Basic statements of the SVBR-75/100 reactor installation concept

SVBR-75/100 is a Lead-Bismuth Fast-Neutron Reactor that delivers 75 – 100 MWe electric power, depending on the parameters of the associated steam generation system.

The principal hydraulic scheme of RI SVBR-75/100 is shown in Fig. 1, the arrangement of the equipment in the reactor monoblock vessel is shown in Fig. 2.

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

- a monoblock (integral) design of a pool type is used for the primary circuit equipment. Valves and LBC pipelines are 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 vessel 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 shielding function;
- the equipment (SG) can be repaired, the one that cannot be repaired (MCP and so on) can be replaced;
− on ending the lifetime, refueling will be performed at once, cassette-by-cassette, fresh fuel will be loaded as a single cartridge;
− it is an opportunity 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. In this, the safety requirements are met as well.

4. **Concept of providing safety of the SVBR-75/100 RI**

Performed computations and research [6] 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 rods;
− 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 flow rate are terminated;
− guillotine rupture of several SG tubes;
− leak in the reactor monoblock vessel;
− “blackout” of the NPP.

RI safety does not depend on the state of the systems and equipment of the turbo-generator installation. The RI inherent selfprotection and passive safety properties, conditioned by the negative reactor feedback, the natural properties of the LBC and the RI design, make it possible to couple the safety functions (except for the emergency protection function) and the reactor's normal operating functions. Thus, the safety systems operate passively and do not contain elements in which actuation can be blocked, in the event of failures or under the influence of human factors:
− at increasing LBC temperature over a dangerous value emergency protection of the reactor operates passively even in the case of mechanical damage of the servo-drivers. This is due to existing fusible locks which hold the special group of neutron absorbing rods in the upper position, even in the case of mechanical damage of the servo-drivers;
− removal of heat decay when there is no heat removal via the SG is provided passively. This is done by transferring heat via the monoblock vessel and safeguard casing 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 not less than two days long;
− in an 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 bubbling device that is inside the PHRS tank. The RI does not need to be shut down immediately in an event of small SG leak.

In an event of unauthorized insertion of positive reactivity at postulated failure of all emergency protection (EP) drivers, elimination of prompt neutron reactor runaway is ensured by a special algorithm of controlling the compensating rods, which is the part of the automatic control system. In this case, when the reactor operates at nominal power, during a certain time (~ 6 months) a reactivity margin controlled by an operator is much less than 1$. In this, the rest compensating rods have been switched off the control system (this problem does not arise for the uranium nitride fuel loading as burn-up reactivity margin is less than 1$).

For the considered fuel loadings, the total void reactivity effect of the reactor is negative and the local positive void reactivity effect is less than 1$ and cannot be realized due to the coolant's very high boiling point and lacking opportunity for gas or steam bubbles to arise in great quantities in the core.

All these make it possible to speak not only about RI resistance against the equipment failures and personnel errors and their multiple superposition but also about resistance against sabotage i.e. to speak about reactor robustness.

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 the following postulated initial events: damage of the protective shell, rapture 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 “blackout” of the NPP. Radioactivity exhaust into the environment does not reach values requiring population evacuation beyond the NPP fence. Opportunity of severe damage of the core is considerably lower than the value specified in the regulatory documentation.

It is important that the inherent selfprotection and passive safety properties have been verified not only by computations but they can be verified by testing as well. Moreover, being tested in the controlled conditions at the experimental-industrial SVBR-75/100 RI, they can be demonstrated without any economic and radiation damage.

5. Assuring NP competitiveness in market conditions

The competitiveness of the NP based on the proposed NPT will be ensured due to the following features:

1) A high level of the inherent selfprotection and passive safety properties of the RI that makes it possible to implement the stringent safety requirements when the special safety systems are eliminated (except the emergency protection system of the reactor). All these will diminish considerably the specific capital cost and almost eliminate a scale loss when changing over from a single large power reactor to small power reactors of equal capacity.

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, reduce the assembly schedule due to the high factory readiness of the reactor module, broaden the areas of the NPP possible location.

3) A modular structure of the nuclear steam-supplying system (NSSS) of the power unit will make it possible to use the methods of standard design of different power units and in-line methods of organization of construction and assembly works. Along with production of RIs in large quantities, these will make it possible to form a competitive market of RI producers.

4) The modular structure of the power unit's NSSS will make it possible to put the power unit in operation step-by-step with gradual raising of power capacities as the assembly and starting-adjustment works have been completed for the group of modules.

5) On expiring the reactor module's lifetime (50…60 years) and after unloading the 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.

6) 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 [7].

7) A conservative approach adopted for designing the SVBR-75/100 RI consists in
   − closeness of the scale factors of RI SVBR-75/100 and operated 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 diminish a probability of mistakes and failures which are typical during implementation of the innovative nuclear technologies, to reduce considerably the scope, execution schedule and cost of the R&D and to lower noticeably the technical and financial risks.

8) 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.

9) 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.

6. Parameters of the modular NPP based on RI SVBR-75/100 in comparison with those of other type electric power plants

SSC RF IPPE, EDO “Gidropress” and “Atomenergoproekt” have developed the conceptual design of a two-unit NPP, which includes a nuclear steam supply system (NSSS) consisting of 16 SVBR-75/100 RIs (reactor modules) and one turbine installation of 1600 MWe [5].

Table 1 summarizes the basic technical and economic parameters of the two-unit NPP based on SVBR-75/100 RI. These are given in comparison with those of two-unit NPPs of the type BN-1800 [8] and a TEPP with ten steam-gas PGU-325 units.

<table>
<thead>
<tr>
<th>Parameter Name and Unit</th>
<th>NPP based on SVBR-75/100</th>
<th>NPP based on BN-1800</th>
<th>TEPP based on PGU-325</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Installed power, MWe</td>
<td>1625</td>
<td>1780</td>
<td>325</td>
</tr>
<tr>
<td>2. Number of units at the plant</td>
<td>2</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>3. Net power plant unit efficiency, %</td>
<td>34.6</td>
<td>43.6</td>
<td>44.4</td>
</tr>
<tr>
<td>4. Specific capital investment for the industrial construction of the plant, $/kW (in 1991 dollars)</td>
<td>661*)</td>
<td>560**)</td>
<td>860</td>
</tr>
<tr>
<td>5. Design-based cost of produced electricity, cent/kW·h (in 1991 dollars)</td>
<td>1.46</td>
<td>1.6</td>
<td>1.75</td>
</tr>
</tbody>
</table>

*) 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.

The results of technical and economic computations revealed that in compliance with the data obtained at the stage of conceptual design, the corresponding parameters of the NPP with two 1600 MWe units, each based on the use of SVBR-75/100 RI modules, are better, as compared to the parameters of the large-power fast-neutron NPPs and the TEPP containing ten PGU-325 units, which use natural gas as fuel. 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 4) in section 5), the commercial production of electricity will begin no later than three years after the first portion of concrete has been laid.

7. Multi-purpose usage of RI SVBR-75/100

High technical and economical parameters of RI SVBR-75/100, ability of the reactor monoblocks to be transported by railway, inherent safety properties of the RI, opportunity to produce saturated steam, whose pressure can vary within (4,0 … 9,0) MPa without changing the RI design make conditions for their multi-purpose usage:

- Construction of modular NPPs or nuclear heat electric power plants (NTEPP) of different power in the regions with large, medium and small electric grids.
- Construction of autonomous nuclear power sources for different purposes in the far regions with undeveloped infrastructure.
- 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 SVBR-75/100 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 new replacement power capacities.
- Export potentials can be realized by granting on lease the SVBR-75/100 RI for producing electricity, heat and desalinated water. In this case, the requirements to fissile materials non-proliferation are ensured by using uranium enriched in low than 20 %, long time operation without on-site refueling and other measures.
8. Conclusions

- There are potentials to increase considerably the investment attractiveness in nuclear power technology, based on the use of fast-neutron reactors, which will make possible their implementation in NP for the near future, where cost of natural uranium is low.

- These potentials appear with use of the innovative NPT, based on employing “standard” modular multi-purpose FRs with chemically inert lead-bismuth coolant. The SVBR-75/100 modules possess developed inherent selfprotection and passive safety properties (where the possibility 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.

- The modular structure of the power unit's NSSS provides an opportunity to changeover to advanced technologies and standard designs for the different NPP's unit capacity. 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 the changeover to periodical service maintenance the reactor modules, which will also reduce the number of the operating personnel and the corresponding expenses.

- 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 reactors, can operate with different types of fuel and in different fuel cycles, without changing designs. That provides a gradual and economically-justifiable changeover to the closed NFC when the cost of natural uranium is increased. At this, the SNF of thermal-neutron reactors can be utilized as the makeup fuel, instead of waste pile uranium.

9. References


