Nuclear power plants of low and medium power with SVBR-100 reactor facilities

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Abstract. Installed power capacity’s share of the global nuclear power engineering is about 10% (both current and forecasted) or even less, while forecasted renewables’ one is above 50%. Large-scale development of nuclear energy technologies is curbed by the existing public opinion in relation to safety (including spent fuel and radioactive wastes handling), limited uranium resources, high capital costs and non-proliferation issues. Overcoming of the impediments is assumed to be based on the next generation nuclear energy technologies among them SVBR technology could be considered as a one possible option. The safety of SVBR NPP is ensured due to using chemically inert lead-bismuth coolant. Removal of uranium resource limitations is based on possibility to operate in a closed nuclear fuel cycle. The economic competitiveness is achieved due to using relatively small amount and relatively simple equipment for the reactor production. The non-proliferation is supported by the use of reduced-enrichment fuel and reactor core physics sensitive to unreported fertile material placement. Additionally SVBR nuclear energy technology can enhance their attractiveness by abilities to place SVBR NPP near to consumers, possibilities for multi-purpose applications, capabilities to operate in weak grids and in the load following modes.

1. Introduction

The world power engineering and electric power engineering (EPE), in particular, undergoes a number of structural changes, which shall be considered when establishing the requirements and concept of nuclear power engineering in the mid-term (after 2030) and long-term (after 2050) perspective. These changes are associated both with available environmental restrictions for development of power engineering based on conventional types of fossil energy sources (coal, oil products and natural gas) set forth by the Paris agreements on establishing target level of greenhouse gas emissions, as well as with unreadiness of commercially available nuclear energy technologies (NET) to large-scale replacement of thermal power plants (TPP) non-compliant with modern environmental requirements, and with significant competition on the side of renewable energy resources (RER).

Thus, during the last several years the growth of the global power engineering installed power capacities is determined by the rates of RER and combined-cycle power plants. According to the data of International Energy Agency, during 2010-2016 the share of RER is more than a half of total increment of installed power capacity (annually ~ 130 GW), while putting into operation of NPP power capacities does not exceed 1% [1]. The similar situation is also expected in the mid-term perspective – on the horizon of 2040, according to predictions of the leading analytic agencies, the share of the global nuclear power engineering in the installed power capacity is about 10% or even less, and the share of RER is above 50% [2, 3]. It is also necessary to take into account the plans of some developed countries...
(Germany, Belgium, Republic of Korea) on rolling back the nuclear power engineering (NPE) and refusal of some countries-new users (SAR, Jordan) of NPP construction, of the large scale power plants, first of all.

Unreadiness of NET to large-scale development is mainly determined by the existing public opinion in relation to safety (in wide interpretation, including not only nuclear and radiation safety during NPP operation, but the resource support also, and safe handling of SNF and RAW with account of requirements to sustainable development of such NET), the established market conditions (relatively high values for NET as regards specific capital costs, generated electric power cost per unit and non-recurrent initial capital costs) and concern on compliance with requirements on non-proliferation of nuclear technologies and nuclear materials of military application.

Overcoming of the specified existing NPE features is assumed based on the next generation NET (the main technological objectives are established by the Forum GEN-IV [4]), where NET on the base of fast neutron reactors will play the key role. The new NPE technological platform developed in RF is aimed at removing all mentioned limitations of NET to provide opportunity for really large-scale development of NPE and its implementation of basic tasks in the future power generation industry.

Alongside with that, the structure of the future electrical power engineering, with substantial share of RER, will demand power generation from the rest types of power generation for recovery of RER features related to variable character of power generation and distributed geographical location. The existing conventional power generation technologies with zero emissions \( \text{CO}_2 \) cannot economically and efficiently ensure recovery of the specified RER to full extent at present and in the foreseen future (energy accumulation by various methods requires significant increase of capital investments compared to construction of new TPP; potential of HPP (hydro-electrical power plant) is exhausted practically and their share in the future electrical power engineering will remain at the level existing at present time). The only power generation technology with zero emissions \( \text{CO}_2 \), capable to balance the future electrical power system with significant share of RER reliably, is NET. In this relation, it is necessary to supplement the mentioned next generation NET target performances, which can perform an important system function in the future electrical power engineering with significant share of RER with target capabilities for recovery of the above specified RER features, namely, capabilities for operation in the load following modes and operation in regional and decentralized networks.

We consider SVBR NET as one of the promising NET for integrated solution of tasks facing the future NPE (consisting of next generation NET, GEN-IV) and the electrical power engineering on the whole (with substantial share of RER).

2. Prerequisites for meeting next generation NET requirements

2.1. Safety

The main effect for ensuring high safety level (inherent safety, guaranteed exclusion of severe accidents) at SVBR-100 reactor is reached by use of the fast neutron reactor, the heavy liquid metal coolant and the integral reactor design [5].

The reactor has negative void reactivity effect and negative feedback, and the efficiency of the strongest absorber rod does not exceed the effective share of delayed neutrons, which in combination with the control and protection system technical design excludes prompt neutron run-away accidents.

The coolant high boiling point increases reliability of heat removal from the reactor core and safety due to absence of crisis of heat exchange, and, in combination with the protection shroud of reactor vessel, it excludes LOCA type accidents and high pressure radioactive emissions.

The coolant circulation circuit ensures elimination of water/steam ingress into reactor core with steam generation (SG) leakage due to effective separation of steam on the coolant free level in the reactor.

Inherent safety properties of the reactor allowed for combining performance of majority of safety functions and functions of the normal operating systems. With that, the safety systems do not include the elements, rejection of which or which impact on human factor can lock their actuation:
removal of residual heat is ensured passively during natural circulation of the coolant in the primary circuit by means of heat transfer to the passive heat removal tank, and further, due to water boiling in the tank with removal of steam into atmosphere (non-intervention period for about two days with no excess of allowable temperatures);

- isolation of SG leakage during rupture of several tubes or in case of cancelling gas system capacitor operation is provided passively during increase of steam pressure in gas system above 1 MPa based on rupture of burst diaphragm and steam release into bubbler.

It appears that severe consequences of major accidents, which occurred during operation of NPE (Three-Mile Island, 1979; Chernobyl NPP, 1986; Mondzyu NPP, 1995; Fukushima-1 NPP, 2011) have common reason related to release of various type potential energy concentrated in the structure materials and technology media of the reactors and NPP (coolant compression energy, chemical energy of water steam and zirconium interaction, chemical energy of interaction of radiolytic hydrogen and/or hydrogen of steam-zirconium reaction with aerial oxygen, chemical energy of sodium with aerial oxygen interaction).

Due to chemical and physical properties of the coolant (chemical inertness, high boiling point) and used structure materials, the SVBR-100 reactor (as well as other reactors with lead-based coolants) has significantly less specific reserved energy of the coolant among NPP with other coolants [6], which, in other equivalent conditions, reduces (or, as in case of accidents listed above, excludes) severity of beyond design basis accident consequences.

### 2.2. Efficient use of nuclear fuel

The uranium dioxide with enrichment less than 20% on U-235 with its use in the open nuclear fuel cycle (NFC) is planned as nuclear fuel for the First of a Kind NPP (FOAK) with SVBR-100. Selection of the fuel type and NFC is determined by the adopted design basis of SVBR-100 (use of conservative approaches during design and, if possible, the reference ones having practical experience of using technical solutions) and main purpose of SVBR-100 FOAK (demonstration of basic technology operability). For manufacture of the complete set of fuel assemblies (FA) about 280 t of natural uranium is required. The core life-time is 50000 effective hours (~6.3 years for 90% capacity utilization factor, all reactor core unloading occurs instantaneously during one refuelling operation during 30 days). By the time of unloading, the spent nuclear fuel (SNF) has average core burn-up ~ 6% h.m.a. (maximal burn-up~ 10% h.m.a.).

Specific consumption of natural uranium by SVBR-100 reactor during operation in the open fuel cycle, as well as for fast neutron spectrum reactors (FR), is significantly higher as compared to similar parameters for WWER reactor (~400 tU/(GW-year)). However, for closed NFC, the situation with specific consumption of natural uranium changes significantly (see figure 1). Wherein, the path to closed NFC for SVBR NPP may be different:

- with the use of FR’s SNF (including own SNF) and SNF from thermal neutron spectrum reactors (TR);
- with the use of natural uranium, enrichment-by-product depleted uranium or SNF TR (without separation of uranium, plutonium, minor actinides and fission products) as fuel make-up supply;
- recycling of only plutonium, plutonium and minor actinides by homogeneous and heterogeneous placement in a reactor core.

Some features of transition to closed NFC for an option of SVBR-100 core using only own SNF and own SNF with feeding of SNF TR given in table 1 demonstrate possibility to operate in a fuel self-sufficiency mode (without consumption of natural uranium) with the breeding ratio close to unity (the total mass ratio of 235-U, 239-Pu and 241-Pu at the beginning and at the end of fuel life cycle is ~ 1).
Figure 1. Integrated consumption of natural uranium (accrued) for NPP of 1 GW power capacity with SVBR-100 (closed NFC with own SNF) and WWER-1000 (open NFC).

Table 1. Characteristics of options for transition to closed NFC NPP with SVBR-100.

| Number of SNF recycles | Own SNF + natural U | Own SNF + SNF TR |
|------------------------|---------------------|------------------|
|                        | 0       | 1       | 2       | … | 9       | 1       | 2       | … | 9       |
| Enrichment of U-235 in feed U (%)  | 16.3    | 19.6    | 16.8    | 0.2 | -     | -     | -     | - |
| TR SNF load (t)          | -       | -       | -       | 8.02 | 0.91  | 0.87  |
| Quantity of used natural U for enrichment of feed U (t) | 293.5 | 23.8 | 20.2 | 0.03 | - | - | - |
| Change of reactivity during life-time \( \left( K_{\text{eff}}^{\text{max}} - K_{\text{eff}}^{\text{min}} \right) / \left( K_{\text{eff}}^{\text{max}} \cdot K_{\text{eff}}^{\text{min}} \right) \) (%) | 5.0     | 5.3     | 4.8     | 0.6 | 5.0    | 5.0    | 1.0   |
| Efficient share of delayed neutrons at the beginning of fuel life cycle (%) | 0.72    | 0.62    | 0.54    | 0.35 | 0.37   | 0.36   | 0.35  |
| \( M_{\text{EOC}}^{\text{5+9+1}} / M_{\text{BOC}}^{\text{5+9+1}} \) (rel.units) | 0.84    | 0.86    | 0.88    | 0.998 | 0.911 | 0.954 | 1.002 |

2.3. Economic competitiveness

Competitive position of SVBR NPP was determined based on predictive estimates of technical and economic parameters (TEP) of serial SVBR NPP (NOAK – N’th of a kind). Calculations of economic parameters of SVBR NOAK were carried out based on financial economic model (FEM) developed in accordance with adopted industry-specific guidelines. Due to presence only FOAK NPP design documentation, NOAK NPP initial data for the economy analysis were determined on the basis of FOAK design data with taking into account achievable levels of overnight cost reduction for NOAK NPP, as well as possible raise of reactor module power [8]. NOAK NPP equipment costs were determined based on assessments of costs for required amount of steel and labour intensity to produce reactor equipment.
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IOP Conf. Series: Journal of Physics: Conf. Series 1475 (2020) 012014
doi:10.1088/1742-6596/1475/1/012014

(cost structure specific for engineering industry was adopted). Estimated reactor equipment cost reduction (cumulative value reduction ~50% towards FOAK’s reactor equipment cost) corresponds to cost reduction due to economy of scale (small effect of fixed costs for production preparation) and learning curve (~35%). NOAK construction cost was adopted equal to FOAK one with taking into account of industrial experts' proposals on NPP design optimization (reduction of construction costs by ~30% was validated by the general designer in the updated design documentation). The conservative operation temperature conditions adopted for FOAK NPP design (maximal temperature on fuel element clad ~590 °C) and possibilities for reduction of hydraulic resistance of reactor core with smaller diameter fuel rods allow us to estimate as achievable reactor power raise up to 20-30%.

For estimation of NOAK economic competitiveness, NPP with one, two and four SBVR reactors were considered. Comparison of resulting NOAK SVBR NPP LCOE values (Levelized Cost of Electricity) with alternative electric power generators was carried out under model assumptions adopted in the NEA report [7]. In figure 2 the ranges of calculated LCOE values are presented (discount rate 7%) for large scale NPP, thermal power plants using coal and natural gas, solar and wind power plants (marked as “NPP”, “Gas”, “Coal”, “Sun” and “Wind” respectively) alongside with LCOE ranges for SVBR-120 NPP with one, two and four reactor modules (marked as “NOAK 1”, “NOAK 2” and “NOAK 4” respectively). Given ranges of LCOE for NOAK SVBR-120 correspond to NPP operating in condensing mode (maximal value) and co-generation mode (minimal value, thermal power price 40$/Gcal is adopted), while the ranges for the rest power sources display differences in LCOE values for different countries.

![Figure 2](image-url)

**Figure 2.** Ranges of LCOE values for different electric power plants [7] as compared to different NOAK SVBR NPP.

These data demonstrate some possibilities for achievement of LCOE competitiveness both in relation to large scale NPP, renewable sources and fossil fuel TPP.

The comparable reactor specific quantity of metal and NPP construction volumes may serve as indirect supplementary proof of available possibilities for achievement of NOAK SVBR NPP competitiveness according to LCOE towards large scale NPP (see figure 3).
Correct comparison of LCOE values for different electric power plants is possible provided that single FEM with unified macroeconomic, tax, regulatory and other initial conditions affecting the result is used for all electric power plants. To confirm adequacy and reliability of the results, LCOE structure were analyzed for different foreign NPP (see figure 4).

Share of capital costs in LCOE for NOAK with SVBR is about 40%, while all the rest NPPs have substantially larger corresponding shares (average value is about 70%). Such structural difference can demonstrate the differences in modelling approaches and model assumptions (in macroeconomic, tax, regulatory and other fields), which are not taken into account in LCOE’s calculations. Consideration of such conditions is likely significantly reduce the LCOE values obtained for SVBR.

2.4. NM non-proliferation
SVBR NET provides certain technological support for non-proliferation of nuclear materials:
- at the stage of uranium oxide fuel core production – use of uranium with uranium-235 enrichment less than 20%, which corresponds to IAEA recommendations and allows to use such reactors in non-nuclear countries;
- at the stage of operation – based on comparatively long fuel cycle (approximately 6-7 years), the need for 30-day SNF cooling time prior to refuelling (as well as removal of heavy reactor cover and using special-purpose refuelling equipment);
• at the stage of operation – based on tight reactor core design and, as consequence, absence of space for unauthorised irradiation of nuclear materials (including an absence of breeding blanket as well);
• at the stage of operation – based on fairly significant influence of non-standard placement of nuclear materials on reactivity and thermal and physical properties of reactor core.

3. Possibilities for deployment of SVBR NPP
Demand for SVBR NPP, as well as for other small and medium sized NPP (SMR NPP), will be determined not only by their compliance with internal trends and requirements for development of NPE itself (i.e. membership with the next generation of NET ensuring economic competitive ability of generated electric power with meeting the requirements for sustainable development), and also by flexibility and possibilities for their involvement in existing and future power engineering. In this area, the high level of safety, flexibility of fuel cycle (abilities to operate in open and closed NFC), NPP modular design principle, no requirements for development level of network infrastructure for electric power transition, possibility for operation in the co-generation mode and the load following mode should be considered as the important features of SVBR NET.

3.1. Different installed capacity and multiple purpose NPP
Modular structure of SVBR NPP enables us to build not only different installed capacity NPP (from 100 to 500 MW and above per power unit) based on unified reactor design, but also to provide consecutive putting into operation installed capacity in accordance with regional demands without significant construction works. This can increase attractiveness of such solutions for developing regions and newcomer countries, which are not ready for construction large scale NPP neither technologically nor financially (for example, see Jordan solution on SMR construction [10]).

Possibility to operate in the co-generation mode with heat generation for municipal heat supply seems can be realized for NPP with any reactor type. However, SVBR NPP (as well as other similar SMR with heavy liquid metal coolant) may have certain advantages based on high level of safety (characterized by the absence of disastrous consequences under technically possible initial events of design basis and beyond design basis accidents). Therefore, there is a possibility to place such NPP near to consumers to minimize loss of heat power during its transportation.

Heat for municipal needs is not the only secondary product of SVBR NPP. Steam for industry applications and desalinated water can be considered as secondary products (e.g., assessments of water desalination production with SVBR NPP by using different desalination technologies are given in table 2).

Table 2. Desalinated water production at SVBR-100 NPP by using different desalination technologies.

| Production | Option # | Electric power (MW) | MSF1 (m³/hour) | MED (m³/hour) | RO (m³/hour) | In total (m³/hour) |
|------------|----------|---------------------|----------------|---------------|--------------|------------------|
| 1          | 100      | 0                   | 0              | 0             | 0            | 0                |
| 2          | 77       | 1200                | 0              | 0             | 0            | 1200             |
| 3          | 77       | 0                   | 2300           | 0             | 0            | 2300             |
| 4          | 0        | 0                   | 0              | 20400         | 0            | 20400            |
| 5          | 48       | 2200                | 0              | 7600          | 0            | 9800             |
| 6          | 48       | 0                   | 4400           | 0             | 6900         | 11300            |

1 MSF - multi-stage flash distillation, MED - multiple-effect distillation, RO – reverse osmosis.

Opportunities for multi-purpose use of SVBR NPP should be supplemented with possibilities of various placement options for such NPP (on-shore, floating plants) and different transportation options to the NPP site (by railway, automobile and water transport).
3.2. Integration in multi-component NPE

NPE large-scale development with taking into account limitation of economically available natural uranium resources assumes using FR and closed NFC. Present NPE is based on TR, and, during transition to closed NFC both FR and TR will be operated simultaneously. Since, at present, the unified NFC are not adopted, use different types of nuclear fuel for FR and TR could not be excluded on the national level: mixed uranium and plutonium dioxides and nitrides (Russia), mixed uranium and plutonium dioxides (China), uranium dioxide, mixed uranium and plutonium carbides, mixed dioxides of uranium, plutonium and thorium (India). SVBR NPP can use all listed types of fuel (see table 3, it presents reactor core parameters for 50000 effective hours core lifetime in a uranium-plutonium NFC) without any significant change in reactor design.

| Parameter, dimensions | Fuel type | \((\text{U-Pu})\text{O}_2\) | \((\text{U,Pu})\text{N}\) | \((\text{U,Pu})\text{C}\) | \(\text{UO}_2\) |
|-----------------------|-----------|-----------------|-----------------|-----------------|-----------------|
| Effective share of delayed neutrons, beginning/end of fuel cycle (%) | 0.38/0.35 | 0.40/0.37 | 0.389/0.35 | 0.72/0.58 |
| Total temperature reactivity effect (%) | -0.95 | -0.65 | -0.67 | -0.9 |
| Maximal reactivity margin for fuel burn-up (%) | 1.05 | 0.21 | 0.23 | 5.07 |
| Average fuel burn-up (% h.a.) | 6.55 | 5.35 | 6.15 | 6.4 |
| Maximal fuel burn-up (% h.a.) | 11.5 | 9.5 | 10.9 | 11.3 |
| \(M_{\text{EOC}}^{\text{Fiss}} / M_{\text{BOC}}^{\text{Fiss}}\) (relative units) | 1.013 | 1.029 | 1.029 | 0.841 |

\(M_{\text{EOC}}^{\text{Fiss}}\) and \(M_{\text{BOC}}^{\text{Fiss}}\) – mass of the fissile nuclides at the end and at the beginning fuel cycle accordingly. For mixed types of fuel \(M_{\text{EOC}}^{\text{Fiss}}\) and \(M_{\text{BOC}}^{\text{Fiss}}\) include (239-Pu, 241-Pu) for the end and the beginning fuel cycle accordingly. For dioxide uranium fuel \(M_{\text{EOC}}^{\text{Fiss}}\) and \(M_{\text{BOC}}^{\text{Fiss}}\) include (235-U, 239-Pu, 241-Pu) and (235-U, 239-Pu, 241-Pu) and (235-U) accordingly.

3.3. Integration in EPE system with substantial RER share

The substantial share of RER (above 50% by 2050) predicted by the experts for the future energy mix poses additional system requirements for the rest of electricity generators to take into account and to balance changeable and stochastic nature of RER generation. The main means for balance electric power system with RER integrated in it are the following [11]:

- development of networks infrastructure;
- use of energy storage units;
- demand management;
- load following electrical power plants.

Use of energy storage units and demand management can manage only small part of RER generation variations. Development of networks infrastructure facilitates power transmission only, but it does not exclude the need for available load following electrical power plants.

At present, electric power system is mainly balanced by either HPP or TPP. The large scale NPPs are not considered as a means to balance electric power system. However, the following capabilities of SVBR NPP allows us to create load following electrical power plants with zero net emissions \(CO_2\) for compensation of RER features:

- possibilities for placement of SVBR NPP of different installed power capacity (100-500 MW and above) near to consumers;
- possibility for multi-purpose application (production of heat for municipal heat supply, desalinated water and other energy products alongside with electric power);
- possibility for operation in weak networks and in the load following modes (load following range is 50-100% \(N_{\text{nom}}\) with the rate of 0.5-2% \(N_{\text{nom}}\) per minute).
4. Conclusion
The SVBR NET is one of the promising NETs for integrated solution of problems facing the future NPE. The safety of SVBR NPP is ensured due to using chemically inert lead-bismuth coolant. Removal of fuel resource limitations is based on possibility to operate in a closed NFC and an ability to use different types of fuel. The economic competitiveness is achieved due to using relatively small amount and relatively simple equipment for the reactor production. The non-proliferation is technologically supported by the use of reduced-enrichment fuel and reactor core physics.

The additional features of SVBR NPP, which can enhance attractiveness of this NET for satisfaction of regional demands in future power engineering, are the opportunities for placement of SVBR NPP near to consumers, possibility for multi-purpose application, capability for operation in weak networks and in the load following modes.

Overall, the modular SVBR NPP can supplement the Russian Federation integrated offer in the segment of next generation SMR NPP and enable smooth inclusion into forecasted structure of global power engineering with significant share of RER.

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