SVBR Project: status and possible development

V.V. Petrochenko[1], S.A. Grigoriev[1], O.G. Komlev[1], A.V. Kondaurov[1], G.I. Toshinsky[1,2]

[1]JSC AKME-engineering, Moscow, Russian Federation

[2]JSC "State Scienntific Center – Institute for Physics and Power Engineering named after A.I. Leypunsky, Obninsk, Russian Federation

E-mail contact of main author: info@svbr.org

Abstract. The analysis of the developed design documentation for first of kind nuclear power plant shows need of some design optimization to create competitive serial nuclear power plant. This analysis defines the main directions and scales for this optimization. These are reduction in equipment and construction costs, reduction of specific indicators (nuclear power plant site area, volume of the nuclear island buildings and mass of a heat-mechanic equipment to installed capacity), decrease in number of personnel and increase in installed capacity of the reactor.
LCOE assessments for the serial nuclear power plants are evaluated subject to realization of considered design improvements.

Key Words: Keywords: small modular reactor, lead-bismuth coolant, competitiveness, design optimization

1. Introduction

Sustainable development goals, limited resources of fossil fuels (expected time of resource depletion is about 50-100 years [1]) and an understanding necessity to reduce current impact of technosphere to the rest of biosphere result in consideration of nuclear energy option as a significant mean to decarbonize world energy production and to meet sustainable development goals along with gas-fired, hydro, solar, wind and other renewable energy options. However, World Energy Agency pointed out some uncertainty in a rate of development for the nuclear energy that could be overcome by financial distinctness, safety demonstration, reliability and predictability of nuclear energy option. At the same time, it is necessary to consider also significant progress of the competing alternative technologies (decrease, for example, in specific capital costs by 2040 for solar generation and battery to two times, for wind power stations – to 30%) [2]. Along with need to take into account these external challenges, nuclear energy option should clearly demonstrate possibilities to overcome some own system issues in the field of economic competitiveness, safety, spent nuclear fuel and radioactive waste management, non-proliferation and broadening of raw material resources. To address the specified issues the nuclear and power community has formulated requirements to nuclear energy systems of the next generation [3], which are able to solve these issues and to provide a significant share of nuclear energy in world power balance along with the renewable energy resources.

One of the nuclear energy technologies (NET) capable to meet requirements to the next generation nuclear energy systems is NET based on modular fast reactors with lead-bismuth coolant (i.e. SVBR-100) [4].

SVBR-100 is the two-circuit small modular reactor (installed capacity is about 100 MW) which is completely manufactured at plant and delivered to the nuclear power plant (NPP) site in ready-to-fit state by different types of transport (i.e. by rail). Multipurpose modular NPP based on SVBR reactor can possess different installed capacities that is multiple to the reactor module installed capacity. SVBR reactor can operate in base and load following operation mode.

The reactor permits to use different types of nuclear fuel and to operate in different fuel cycles without change of the reactor design [5]. At the first stage, the reactor can operate in an open nuclear fuel cycle (NFC) with the postponed processing of spent nuclear fuel (SNF), similar to WWER reactors. Later, if necessary, the reactor could operate in a closed NFC with full reproduction of own plutonium (in the uranium-plutonium NFC). The SVBR-100 reactor used mixed-oxide fuel (MOX) with breeding ratio close to unity can operate in fuel self-sufficiency mode without consumption of natural uranium.

To meet the IAEA's non-proliferation requirements SVBR reactor provides technology support based on the following characteristics:

- using nuclear fuel with uranium enrichment lower than 20%;
- relatively long reactor core life-time (7-10 years) without accessing nuclear fuel (core reload can be carried out by the supplying country under the IAEA international control);
- SNF reprocessing is not carried out on NPP site (SNF after unloading from the reactor and cooling on site, it is taken out to the supplier country).

Inherent safety level of the reactor deterministically eliminates the need for offsite emergency response under any accidents and allows to place NPP near the cities and to use them for the purpose of heat supply as well [6].

There is a possibility for multi-purpose application of the reactors:

- delivering the NPP of different installed capacity,
- uses as a part of nuclear desalination power complexes,
- renovations of the WWER NPP which reactors should be decommissioned after exhausting of their life-time for the purpose of economy of capital expenditure,
- substitution of the regional coal thermal power plants causing extensive ecological impact on the environment.

The SVBR project is carried out by JSC "AKME-engineering" (shareholders are State corporation "Rosatom" and JSC "Irkutskenergo"). It is recognized as the operating organization at stages of placement and a construction of a first of a kind (FOAK) NPP with SVBR-100. JSC "AKME-engineering" has the right to own on the property rights nuclear materials and nuclear installations. It has licenses of Rostekhnadzor for performance of work and rendering services of the operating organization at construction of nuclear power plants as well as license for FOAK NPP placement in Dimitrovgrad of the Ulyanovsk region.

On making decision for FOAK NPP construction in Dimitrovgrad in July-August 2017, JSC "AKME-engineering" is going to receive license for a FOAK NPP construction at 2021, than to receive the license for operation and to put into operation FOAK NPP at 2025.

The main objectives of the current stage of the project are considered to involve additional partner [7], as well as to optimize FOAK NPP design and to develop preliminary design for n-th of a kind (NOAK) NPP, according to recommendations of industry experts and scientific and technical council No. 8 of State corporation "Rosatom". After that, optimized NOAK NPP design could provide the basis to make more accurate their competitiveness assessments.

2. Development of FOAK NPP design

Lead-bismuth reactor technology has been approved during its navy application at the industrial level. During this period (the 1950-80th years) eight nuclear submarines and two ground full-scale mock-ups have been constructed and operated [8]. This operating experience could be considered as positive, but it should be noted significantly different requirements to reactors and NPP for civil application regarding requirements for safety, operating modes of the reactor, type and enrichment of nuclear fuel, the treatment of irradiated nuclear fuel and radioactive waste, requirements of a sustainable development, economic efficiency and competitiveness in the target markets. Taking into account existed experience of LBC reactor operation, these different requirements as well as importance of timely entry into the market, a main FOAK NPP objective is considered to confirm key technical and economic characteristics of the SVBR technology for civil applications. These are inherent safety, flexibility of a nuclear fuel cycle, effective treatment of spent nuclear fuel and radioactive wastes, non-proliferation compliance, effective operation (on profitability and reliability), industry readiness and, as a result, investment appeal and competitiveness of the main products of this technology.

Demonstration of economic efficiency and competitiveness for FOAK NPP is rather limited due to significant influence on its economic characteristics absence of economy of scale and learning factors [9]. Therefore, use of conservative approach for implementation of the project in the existing normative environment was the main approach to development of the engineering designs of the reactor and NPP. This is supposed to demonstrate the declared properties of safety and reliability of FOAK NPP. Use of the existing regulatory base on safety has been coordinated with Rostekhnadzor. At the same time, separate additions to normative documentation seem to be developed prior to construction license application. Results of FOAK NPP development should create consistently some insight about NOAK NPP design and specify its technical and economic characteristics.

Design documentation has been developed in compliance with the requirements of national legislation. It includes 12 sections and 210 volumes in the fields of architectural, construction, technology and other design details for FOAK NPP. Preliminary materials on safety justification (descriptive part of the preliminary safety report) are developed as well.

The analysis of the developed design documentation shows, on the one hand, need of some FOAK NPP optimization to create competitive NOAK NPP [7]. On the other hand, this analysis defines the main directions and scales for FOAK NPP optimization. These are reduction in equipment and construction costs, reduction of specific indicators (NPP site area, volume of the nuclear island buildings and mass of a heat-mechanic equipment to installed capacity), decrease in number of personnel and increase in installed capacity of the reactor module.

Spent and fresh nuclear fuel management and corresponding equipment placement have significant impact on the NPP design. For example, overall height dimensions of the reactor building are defined by the sizes of the reloading equipment. Whereas plan dimensions of the reactor building are determined by the need of providing storage for the fresh and spent fuel assemblies as well as for reloading equipment.

3. Possibilities of FOAK NPP design optimization for use in NOAK NPP

The FOAK NPP design approaches noted above and resulted from the main goal of FOAK NPP construction (confirmation of key characteristics of the basic SVBR technology) define possibilities of FOAK NPP optimization. These optimized design solutions corroborated by FOAK NPP successful operation plan to be used in the NOAK NPP design as well.

The main fundamental possibilities of NOAK NPP improvements include:

- a high share of plant production of the reactor that excludes laborious installation procedures on the primary circle and significantly reduce NOAK NPP construction duration;

- effect of a modularity (flexible installed capacity, use of common NPP equipment by all reactors);

- economy of serial effect (fixed cost decrease, learning curve);

- multi-purpose application of the reactor (generating electricity, heat, potable water, renovation of WWER-440 NPP).

According to the main components of the levelized cost of electricity parameter (LCOE) that commonly used to measure economic competitiveness of energy sources below we briefly discuss opportunities to optimize installed capacity (for the reactor unit), NOAK NPP capital expenditure (costs of the equipment and construction) and operational expenses (costs of own needs, personnel, costs of service and repair). The received estimates is supposed to be refined by NOAK NPP preliminary design development.

3.1 Reactor installed capacity

There are several possibilities to increase the installed capacity of the NOAK NPP reactor in comparison with FOAK NPP. These are use of less tight fuel rod lattice , use of a superheated steam, increasing of outlet coolant temperature and use of a special algorithm for control rod movement.

Experimental justification of the mentioned design improvements can be carried out during construction period and an initial stage of operation for NOAK NPP. While full or even partial implementation of the design improvements allows us to increase the installed capacity of one reactor module by more than 30% (what should subsequently decrease core life-time by at least 30%).

Once through nuclear fuel cycle mode seems to be the most probable one at the initial stage of operation of NOAK NPP. To improve fuel utilization of NOAK NPP with increased reactor capacity, core lifetime should be either unchanged or, if possible, increased in respect to FOAK NPP’s one. Design value of core lifetime (50000 full power hours) for increased capacity NOAK NPP may be achieved due to existence some fissile material margins that need for providing safety requirements under technology uncertainties in fuel elements and the absorbing rods in a case of FOAK NPP. These margins will mainly be unnecessary for the NOAK NPP by accumulation of production and operation experience of FOAK NPP nuclear cores. In addition, there is a possibility to increase reactor core lifetime by use nitride fuel [10], which is successfully mastered for other reactor projects. Use of such fuel does not require essential modernization of a reactor design [5].

The available possibilities of optimization on the FOAK NPP reactor allows us to consider increasing NOAK NPP reactor capacity by 30% as feasible design option while core lifetime remains unchanged.

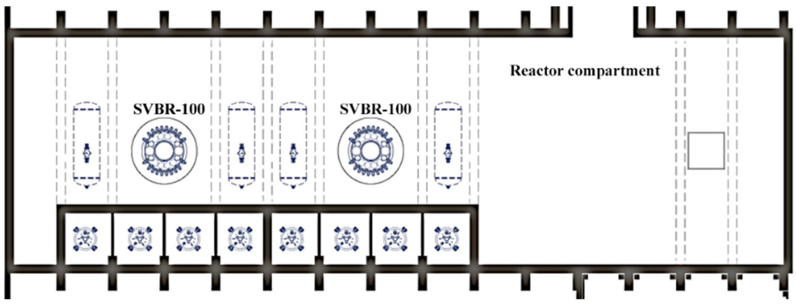
3.2 Equipment Cost

The equipment cost (reactor, reload equipment, turbine, I&C system) makes an essential part of the FOAK NPP cost (more than 60%) and it strongly impact on competitiveness and investment attractiveness of the project. The high cost of the FOAK NPP equipment leads to high FOAK NPP cost itself. At the same time, the cost of the FOAK NPP equipment is obviously influenced by inevitable for FOAK NPP factors. These are need of production equipment preparation, lack of experience, single unit order, absence of market for such equipment production, risks of ensuring required quality of the equipment in established periods. Exception of initial fixed cost, serial effect and learning curve factors can lead to essential reduction in equipment cost (according to paper [9] up to three times). Our assessments carried out for the NOAK NPP equipment on the basis of required material cost and typical cost structure for machinery construction give 50% cost reduction of the NOAK NPP reactor equipment.

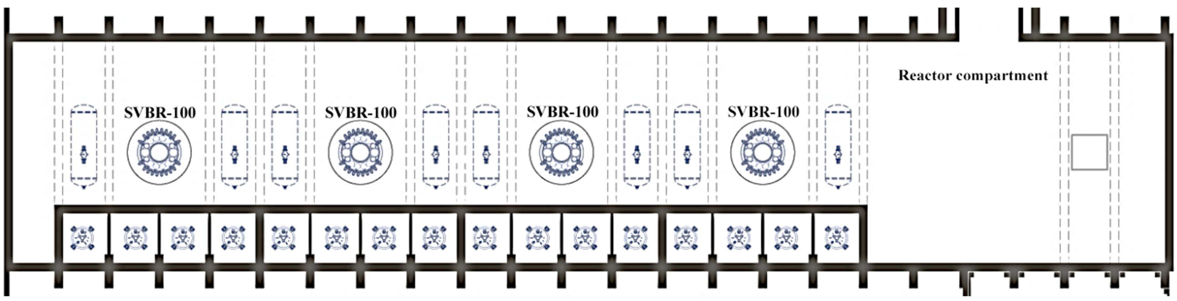
Turbine and I&C costs amount no more than 15% of NOAK NPP equipment. Thus, for the first stage of cost optimization this equipment can be not considered. At the same time, serial effect and learning curve factors could result in up to 50% cost reduction of this equipment. In addition I&C cost will increase with coefficient of proportionality ~0,5 in number of additional reactors (i.e. for two reactors overall I&C cost is about 1,5 times larger than for single reactor overall I&C cost). Such proportionality results from the assumption of proportionality of I&C cost to automation volume (i.e. number of signals, number of management and control objects, etc.) and structure of signals from the NOAK NPP equipment (including reactor, turbine, power generating unit and NPP). This structure shows that the part of signals from the reactors and turbines is about half of total I&C signals.

3.3 Construction cost

Construction cost reduction for NOAK NPP could be carried out by means of site layout optimization, application of the optimized methods of justification and ensuring durability for a reactor building (removal of excessive margins), optimization of the reload equipment (reduction of overall height dimensions of the reactor building). These improvements can reduce construction expenditure by ~ 25-30%.



a) NOAK NPP with two reactors



b) NOAK NPP with four reactors

FIG. 1. NOAK NPP reactor compartments

In addition, there is some modularity effect that leads to reduction of the specific NPP site area (counting to one reactor unit) by ~40% (for two reactors) and ~60% (for four reactors) with increasing number of reactors. While the specific reactor building volume (counting to one reactor unit) decreases by ~40% (for two reactors) and ~50% (for four reactors). Possible reactor placements in the NOAK NPP main building with two and four reactors are given in FIG. 1. Total decrease in specific volume of NOAK NPP buildings (counting to one reactor unit) at increase in number of reactors will amount ~25-40% (for NOAK NPP with two and four reactors respectively).

3.4 Number of personnel

FOAK NPP personnel list is determined with use of nomenclature and operating experience for the large capacity NPP to ensure safe and reliable operation as well as to accumulate necessary operation experience for the subsequent NOAK NPP optimization of number of personnel. It results in rather high value of number of personnel to installed capacity ratio. At the same time, there are several opportunities to decrease number of NOAK NPP personnel:

– optimization personnel list by excluding positions connected with experience and demonstration goals of FOAK NPP (construction tasks, use only 6 changes of operation personnel etc.);

– modularity effect;

– optimization department structure of NPP operation management.

Excluding positions connected with experience and demonstration goals of FOAK NPP leads to decrease in number of NOAK NPP personnel by ~40% (in relation to FOAK NPP’s one). Due to modularity effect, in addition, number of NOAK NPP personnel will increase with coefficient ~ 0,1 with increase in number of subsequent reactors in relation to NPP with single reactor (it results from a high part of personnel for overall NPP needs).

3.5 Expenditure of own needs

The main contributors to the own needs expenditure are feed water pumps, cooling water pumps, primary circuit pumps, conditioning and ventilation (all of these contribute more than two thirds of all own needs expenditure). Minimization of own needs expenditure is possible due to optimization of hydraulic properties of secondary circuit (reduction capacity of feed water pumps and cooling water circulation pumps), optimization of aerodynamic properties of ventilation system (reduction capacity of air supply pumps) and reduction of NPP main building volume (as it is discussed in chapter 3.3).

In addition, due to modularity effect on NOAK NPP with several reactors, increase in own needs expenditure with increasing of number of reactors results in ~50% increase of own needs expenditure of single reactor NPP per one additional reactor unit (it corresponds with fixed part of own needs expenditure that do not change with the number of used reactors). It leads to the corresponding decrease in a specific own needs expenditure for NOAK NPP with several reactor units and approaching of this value to the large capacity NPP’s one (5-6%).

4. Competitiveness assessment of SVBR NOAK NPP

4.1 Assessment prerequisite

NOAK NPP competitiveness could be evaluated through the LCOE comparison among competing power plants. Simple economic model capable to calculate net present value of the project is used to calculate NOAK NPP LCOE values. All numerical results have been obtained under certain conditions adopted in the joint report prepared by the International Energy Agency and the OECD Nuclear Energy Agency [11]. LCOE value is evaluated by the following relation:

$$\mathrm{LCOE} = \frac{\sum_t (\mathrm{Investment}_t + \mathrm{O\&M}_t + \mathrm{Fuel}_t + \mathrm{Decommissioning}_t) \cdot (1+r)^{-t}}{\sum_t \mathrm{Electricity}_t \cdot (1+r)^{-t}},$$

here $\mathrm{Investment}_t$ – investment expenditures at year t, $\mathrm{O\&M}_t$ – operational expenditures at year t, Fuel_t – nuclear fuel expenditures at year t, $\mathrm{Decommissioning}_t$ – decommissioning expenditures at year t and r – discount rate at year t.

NOAK NPP investment expenditures include results of cost optimization and modularity effect discussed in chapters 3.2 and 3.3. Operational expenditures include results of spent nuclear fuel management expenditures, safety and security provision expenditures as well as results of personnel and own need optimization results discussed in chapters 3.4 and 3.5. Nuclear fuel expenditure include costs for all stage of its production (natural uranium costs, conversion, enrichment, fuel pellets and fuel assembly fabrication, fuel assembly transportation). Decommissioning expenditures account by annual allocation to special reserve. All numerical results were obtained for Russia tax regulations.

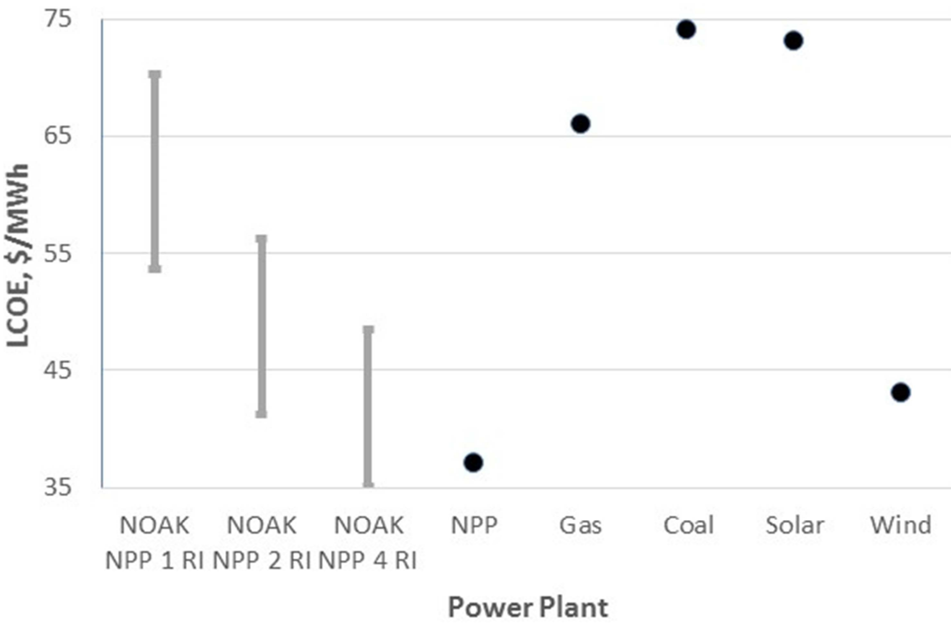
Amount of produced electricity was evaluated for the design values of installed capacity utilization factor (90%) and increased value of reactor installed capacity (130 MW as it discussed in chapter 3.1).

4.2 SVBR NOAK NPP competitiveness

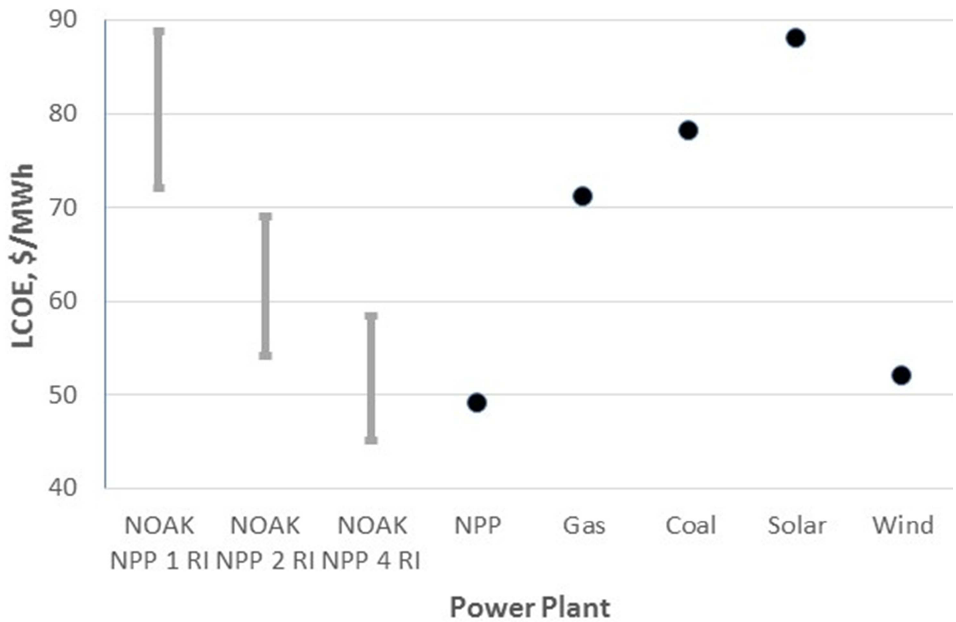
LCOE values were calculated with taking into account optimization results discussed in the previous chapters for NPP with one, two and four reactors (see FIG. 2.); where NPP with one reactor denoted as “NOAK NPP 1 RI”, NPP with two reactors denoted as “NOAK NPP 2 RI” and NPP with four reactors denoted as “NOAK NPP 4 RI”). Minimal LCOE values of NOAK NPP on this figure present LCOE values with full optimization of NOAK NPP discussed in chapter 3. Whereas maximal LCOE values present results for 50% realization of the investment optimization capability (i.e. equipment cost reduction is only 25% instead of 50% reduction corresponded to full optimization capabilities, for example). In addition, the figures include minimal LCOE values for the large capacity NPP (denoted as “NPP”), natural gas-fired power plants (denoted as “Gas”), coal-fired power plants (denoted as “Coal”), solar power plants (denoted as “Solar”) and on-shore wind power plants (denoted as “Wind”) [11].

LCOE values for NOAK NPP with four reactors show competitiveness level comparable with large capacity NPP and on-shore wind power plants. LCOE values for NOAK NPP with two reactors show competitiveness level that is slightly better than natural gas-fired and coal-fired power plant levels (as well as for solar power plant level). LCOE values for NOAK NPP with one reactor show competitiveness level comparable with natural gas-fired and coal-fired power plant levels (as well as for solar power plant level).

LCOE sensitivity to initial data is rather important (~ 0,5% change of LCOE to 1% change of investment expenditures) but it tends to decrease with increasing number of reactors.



a) discount rate 7%



b) discount rate 10%

FIG 2. LCOE values for different types of power plants

5. Conclusions

The global challenges facing world energy production and inherent issues of current nuclear energy (regarding safety, profitability, non-proliferation and security, spent nuclear fuel and radioactive waste management and broadening of raw material resources) seem to make necessary development of the next generation NET to address these problems.

One of possible NET capable to meet requirements to the next generation NET is modular fast reactor technology based on using of lead-bismuth coolant.

The SVBR-100 FOAK NPP should demonstrate key characteristics in the fields of safety and reliability, non-proliferation technology support, opportunities to operate in the different nuclear fuel cycles (in open NFC and, if necessary, in closed NFC as well), safe SNF and radioactive wastes management. However, to use this NET commercially it is necessary to demonstrate also its economic efficiency in the current and future conditions. To assess economic efficiency of this NET based products possible design improvements ready to implement in NOAK NPP have been evaluated (with one, two and four reactors per NPP).

The main directions of FOAK NPP design optimization include increase reactor installed capacity (~30%) with the design based value of core lifetime; equipment cost reduction based on economy of scale, learning curve and modularity (by ~50% reduction for reactor and I&C equipment and by ~30% for other equipment); construction cost reduction due to optimization of site layout (by ~ 30%) and modularity; operational cost reduction due to personnel optimization and reduction of own needs expenditure (by ~40%).

LCOE values of the four reactor NOAK NPP demonstrate comparable competitiveness with all types of the existing electricity generating power plants (including large capacity NPP, fossil fuel fired power plants and renewable energy power plants). NOAK NPP with less number of reactors demonstrate reduced competitiveness but even for NOAK NPP with single reactor (the least competitive product) competitiveness is found to be at the level of fossil fuel (gas, coal) power plants.

Appendix 1: References

[1]. BP Statistical Review of World Energy, 64 th edition, 2015.

[2]. World Energy Outlook 2015, International Energy Agency, 2015.

[3]. A Technology Roadmap for Generation IV Nuclear Energy System, GIF-002-00, U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, December 2002.

[4]. Toshinskii, G.I., Komlev, O.G., Martynov, P.N. et al. At Energy (2012) 111: 361. doi:10.1007/s10512-012-9504-y

[5]. A.V. Zrodnikov, G.I. Toshinsky, O.G. Komlev et al. Fuel Cycle of Reactor SVBR-100, Proceedings of Global 2009, Paris, France, September 6-11, 2009.

[6]. Petrochenko, V., Toshinsky, G. and Komlev, O. (2016) Safety of Future NPPs Must Not Be in Conflict with Economics. World Journal of Nuclear Science and Technology, 6, 284-300.

[7]. Rosatom allow for the arrival of foreign investors in the project of the SVBR-100 reactor, RIA Novosti, 07.11.2016 (https://ria.ru/atomtec/20161107/1480836417.html).

[8]. The Analysis of Operating Experience of Reactor Installations Using Lead-Bismuth Coolant and Accidents Happened". G.I. Toshinsky, V.S. Stepanov, L.B. Nikitin et al. Proceedings of 1st International Conference on Heavy-Liquid Metal Coolants in Nuclear Technologies (HLMC-98) Obninsk, Russia, 1999, Vol. 1, pp. 63 69.

[9]. A Large Modular LMR Power Station which Meets Current Requirements, Sadao Hattori, Akio Minato, Proceeding of ICONE-3, S207-4, Kyoto, Japan, 1995, 2, pp. 787-790.

[10]. Perspective fuel, Atomny ekspert (in Russian), 02.09.2014, http://atomicexpert-old.com/content/perspektivnoe-toplivo.

[11]. Projected Costs of Generating Electricity, IEA, NEA, OECD, ISBN 978-92-64-24443-6, 2015, 215 p.