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Some Technical and Institutional Issues to Accelerate the Deployment of Small Modular Reactors

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Abstract
The vision on the development and deployment of SMRs is presented in the paper. SMRs have been built in Russia since 1954. Before the early 2000s only shipboard nuclear power facilities were used while land-based SMRs of various types were designed but not built. New driving forces for the penetration of SMRs into the energy sector of the country, which have arisen recently, are discussed in the paper. The accelerated development of the north-eastern regions with rich natural resources but low population density and high cost of energy generation has created favorable conditions for the priority use of SMRs. Intensive research and development work was deployed to reconsider the approaches used for construction of the reactors of large capacities in order to find new solutions to meet specific requirements of today for small reactors. Comparison of the feasibility of these requirements for small PWRs of Generation III + and Generation IV reactors is provided in the paper. The discussion on the requirements to SMRs and some ways for their implementation is supplemented by consideration of their role as a large sustainable component of the future national and global energy sector.

Keywords: Nuclear Energy Systems, Generation IV Reactors, Lead–Bismuth Coolant, Sustainable Energy, Decentralized Energy Supply.

Introduction

Currently, an increased interest in nuclear plants with small modular reactors (SMRs) is observed and a large number of designs of these reactors have been developed while the role and prospects of SMRs are still being discussed, and their deployment is very low. The paper provides a vision of the Institute for Physics and Power Engineering (IPPE) on the status and future of SMRs and small NPPs with SMRs. Special attention is focused on the analysis of impediments slowing down the development and on finding the driving forces for deployment of SMRs as a component of a sustainable nuclear energy system (NES). The IPPE was one of the pioneers in the development and deployment of small NPPs in the USSR/Russia and in the world. The paper is divided into three parts: a motivation for deployment of small NPPs with SMRs in the past and now, the role of technical innovations in the acceleration of the SMRs penetration into the energy sector of the country, and consideration of institutional innovations as a supplement to the main stream of R&D activities aimed at enhancing SMRs competitive abilities.

The analysis of the SMRs penetration phase is made with consideration of specific economic and geographical conditions of Russia. Technical innovations under investigation in the IPPE are within the framework of fundamental developments carried out towards the development of Generation IV reactor systems. The prospects for large-scale deployment of SMRs as a sustainable component of the world nuclear power are discussed in the paper in a broad context without reference to the specific conditions of any country. Some of these ideas were discussed with foreign participants of the IAEA/ INPRO ASENES project "Scenarios for the Sustainable Development of SMRs" during implementation of the project.

Contribution of the Institute for Physics and Power Engineering to The First Phase of Smr Development and Evaluation of the Experience Gained

Leypunsky Institute for Physics and Power Engineering (IPPE) is one of the founders of the direction related to the development of the NPPs with small reactors (NPP-SMR) in the USSR /Russia and in the world. In cooperation with other organizations, the following small NPPs were developed in IPPE and built as part of the initial phase of nuclear power development in the country:

- The world's first NPP in Obninsk of 5 MW(e) that was built during 5 years and operated from 1954 to 2002;
- The transportable small NPP TES-3 of 1.5 MWe operated from 1961 to 1969;
- Shipboard nuclear power facilities for submarines with lead-bismuth coolant;
- The Bilibino NPP in Arctic of 48 MW(e) and 25 Gcal/h of heat launched up in 1974;
- The Beloyarsk NPP with two units of 150 MW(e) operated from 1964 to 1989.

The first phase of small NPPs deployment allowed us to get valuable experience that was used in designing and construction of subsequent NPPs. The Obninsk NPP has demonstrated the fundamental possibility of safe electricity generation and thus opened the way to larger NPPs. The Arctic Bilibino NPP has confirmed the efficiency of small NPPs for electricity and heat supply to the settlements and mining enterprises in the remote regions where the energy price is much higher than in the central part of the country. At the same time, the need for a lower capacity and less number of staff was identified from the experience of the Bilibino NPP operation. The transportable TES-3 and other transportable NPPs of the type constructed a little later have shown possibility of implementing practically unmanned operation, at the same time identifying the need for strengthening radiation protection due to tightening radiation safety standards.

After the completion of the first phase of SMRs building, only nuclear power facilities for marine engines were put into operation while in the central parts of the country only large NPPs competitive with other land-based power plants were constructed. SMRs of various types were designed, but not built.

Prerequisites and Ways for Implementation a New Phase in Development and Deployment of Small NPPS

The course towards accelerated economic development of northern, eastern and arctic regions of Russia aimed at the growth of mining and processing plants production, modernization of ports of the Northern Sea Route and navigation infrastructure, etc., raised the question of autonomous energy supply for these regions. Therefore, for reliable energy supply to newly constructed facilities in the northeastern regions, it is necessary either to create an infrastructure for providing fossil fuels, or to quickly develop and implement nuclear energy sources capable of operating in autonomous mode for a long time. Energy sources like wind, sun, etc. can serve as part of autonomous networks, only as auxiliary ones.

As shown in Fig.1, the regions of the country that are zones of decentralized energy supply occupy over 80% of the territory of Russia. The power generation is carried out either at the expense of energy resources extracted locally or through the supply of fuel under government programs.

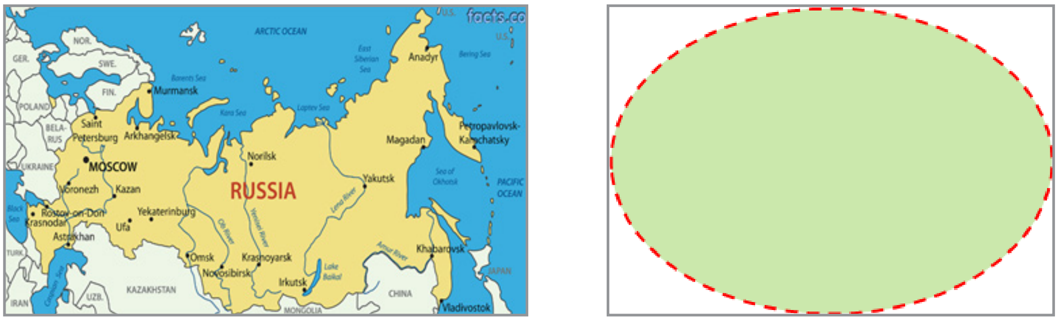

Figure 1: The territory of Russia in the oval is a part of country with decentralized energy supply

The difference between population density and electricity generation prices in two regions of Russia estimated by the authors is shown in Table 1.

Table 1: Population Density and Electricity Generation Cost in Different Regions of Russia

Indicator	European part	Remote regions
Population density, person/km^2	30-80	< 1
Electricity generation cost, RUB/kWh	2-3	14-43

It can be seen that difference between electricity generation prices in two regions of Russia can reach up to 20 times. The cost of organic fuel in the cost of electricity generation for many regions of the country with decentralized energy supply is about half of the full cost of electricity. The state subsidizes the main share of the power plants expenses.

The course towards accelerated economic development of northeastern regions of the country raised the question of autonomous energy supply for these regions. At present and in the near future, respond to this request can be only mastered in the country technology of light water reactors, most probably PWR/VVER reactors with steam turbine. SMRs of the type are successfully exploited as shipboard nuclear power facility in the naval and civil fleets. 12 nuclear icebreakers were designed and operated in the Soviet Union and Russia. 7 of them are in service, why several more are under construction. In 2010, the 'Academic Lomonosov' floating NPP (70 MW-e) was launched, which became the northernmost NPP in the world. A license was obtained to construction of the first land-based small NPP in Yakutia. Negotiations regarding construction SMRs of Russian design for small NPPs are underway with some countries of the world.

However, a PWR with a steam turbine has physical and technological features that to some extent limit its adaptation to the specific conditions of remote, hard-to-reach regions with decentralized energy supply. Russian scientific and design organizations are developing tens of prospective designs of SMRs for small NPPs of PWR type based on new technical solutions.

R&D on Generation-IV smrs with Metal Coolants

The focus of R&D activities of the Institute for Physics and Power Engineering (IPPE) in the area of small reactors is SMRs with metal coolants. Despite Russia's scientific leadership in the creation and operation of fast reactors with sodium coolant, there is only one project of small NPP with a fast sodium reactor - the BN GT-300 project proposed by IPPE. The project has not demonstrated the break-through characteristics necessary for the construction in the near prospect and is currently frozen. The IPPE for a long time was the scientific supervision of the development of SVBR-100 multi-purpose modular fast reactor based on the experience in the development and operation of lead-bismuth cooled shipboard reactors. The SVBR-100 meets the safety requirements of generation IV reactors. The project of SVBR-100 reactor plant includes the following characteristic features:

— Fast neutron reactor with a chemically inert lead-bismuth coolant (SBT) of the primary circuit;
— Integral reactor layout, in which all equipment of the primary circuit is placed in a reactor vessel;
— Double-circuit heat removal scheme from the core;
— Natural circulation in the first and second circuits of the reactor plant coolant sufficient for passive cooling of the reactor without overheating of the core;
— Significant reduction in the number of safety systems in comparison with pressurized water reactors;
— The main components of the reactor monoblock and reactor plant are made in the form of individual modules, which makes it possible to replace them and repair and some other advanced solutions important for safety and economics.

All documentation of the technical design of the reactor plant has passed technological control at potential manufacturing enterprises with confirmation of readiness of production and sufficiency of elaboration of existing requirements. The model of a state - private capital partnership that was approbated in case of SVBR-100 development and deployment assumed financial assistance from a utility that was interested in long-term, reliable and affordable electricity supply along with reducing greenhouse gas emissions by at least 2.5 million tons CO2 per year from 2026. However, the issues of interaction of state and private capital are new for Russian nuclear business and the problems that have arisen are awaiting their resolution.

As a technical solution providing the request from remote northern regions specialists of IPPE have selected and are now developing a nuclear reactor SVGT with lead-bismuth coolant in the primary circuit and an open-cycle gas turbine converter in the second. The project being developed is based on the following basic provisions:

— The experience of operation in nuclear submarines, developing the technical design of the SVBR-100 and developing and operation of the open-cycle aviation and marine gas turbine engines;
— Requirements arising from the conditions of the region where the SMRs has to be located including absence of industrial infrastructure, ambient temperatures down to –70°C, need for the generation of thermal energy for heating industrial and domestic facilities, simple design, etc.;
— The duration of the campaign without on-site fuel reloading should be ensured for at least 15-20 years, transportation of the reactor with loaded fuel and coolant in a "frozen" state to the placement site, relocation to another site and its removal at the end of its service life to the supplier plant along with the spent fuel;
— The use of air as the working fluid of a gas turbine;
— The elimination of the hydrogen release in the most severe accidents, increasing the pressure in the primary circuit above the free level of the coolant above atmospheric pressure, loss of coolant accident and high-pressure radioactive releases.

Table 2: Comparison of characteristics of SMR VVER and requirements for the SMR SVGT

Characteristics / requirements	SMR VVER	SMR SVGT
Electrical power, MW	20-50	0.5-1.5
A heating device	yes	yes
Nearly full factory production	no	yes
Delivery to the site by road transport	no	yes
Loss of coolant accident possibility	yes	no
Generation of liquid radioactive waste during operation	yes	no
Safe transportation of the reactor loaded with fuel and coolant	no	yes
Operation without recharging fuel	5 years	20 years
Exclusion of the harmful effects of low temperatures in case of power loss	no	yes
Ability to work in automatic mode without constant maintenance	no	yes
The presence of shut-off and control valves in 1 and 2 circuits	yes	no
The presence of circulation pumps	yes	no
Coolant pressure	15,7 MPa	atmospheric

Comparison of requirements for the development of lead-bismuth SMR SVGT with current characteristics of SMR VVER in Table 2 demonstrates possible improvement in some consumer properties that can be reached by the SVGT reactor. Further research should show whether the significant improvements in the consumer properties of the reactor SVGT indicated in the Table can be achieved in compliance with the main user requirement – acceptable economic characteristics not only in comparison with LWR, but also in relation to other energy sources.

Possible Contribution of the Institutional Innovations to Accelerating Deployment of Smrs

Providing energy supply in isolated regions is an important current motivation for the development of SMRs in specific geographical conditions of Russia but does not exhaust their potential for deployment. As noted by many experts, SMRs can become an overall driver for nuclear power. The conditions and driving forces for the deployment of small NPPs are considered in many national studies and in the IAEA/INPRO ASENES project "Scenarios for the Sustainable Development of SMRs -ASENES SMR" [1], in which Russian specialists from Kurchatov Institute, Moscow Physical Engineering Institute, Centre of Rosatom Analytical Studies, and IPPE are participating. The research in [1] is based on multi-criteria assessments of NES options using KIND, CENESO and other tools developed in IAEA/INPRO and in participating countries. These tools help to understand the state and prospects for the SMRs deployment as a sustainable part of nuclear power.

The results of multi criteria analysis implemented in Russia indicate that estimation of the SMRs perspective critically depends of their economics. Many indicators of large and small reactors are rather similar (nuclear safety, low greenhouse gas emissions and environmental impacts during normal operation, etc.) and they do not prevent widespread implementation of SMRs as a new component of the energy sector. Some factors like compliance with specific energy needs of users, deployment and operational flexibility, economic risks associated with the construction and operation, probability of severe accidents and magnitude of possible damage are strong drivers for SMRs. However, specific cost of electricity that is largely determined in nuclear by unit capital costs closes the decisions in favor of SMRs in case where the criterion of the electricity cost is given a priority. This conclusion from multicriteria analysis is confirmed in practice when decision makers give absolute priority to the option with the lowest cost of electricity. Thus, the R&D efforts on reducing of SMRs capital/operating costs should be recognized as the main way for finding solutions to improving SMRs competitiveness. At the same time, any other ways for accelerating the deployment of SMRs must also take their place. One of them could be an innovative institutional approach based on SMRs specific features.

As it has been established [2] a network structure of several power units with a unified financing can provide reduction of the cost of electricity compared to the cost generated by a single power unit. Due to lower start up investments and shorter construction periods, the SMRs appear to be promising options for the creation of a financially integrated energy cluster [3]. The Fig. 2 shows a diagram of investing in construction of a cluster of 4 SMRs of PWR type with a capacity of 300 MW(e) each and return of invested equity and credit capital.

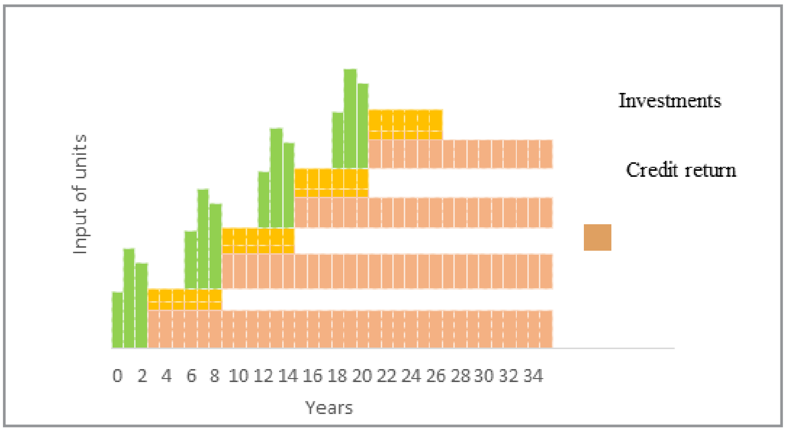

Figure 2: The diagram of investing in construction of a cluster of 4 SMRs and return of invested equity and credit capital.

For simplicity, it is supposed that by the start of a new unit operation, the credit invested in the construction of the previous ones has to be paid off, so the new credit applies not to one unit, but to the entire system. Technical and economic reactor characteristics and parameters of these two systems are in Table 3. Financing conditions are in Table 4.

Table 3: Technical and economic reactor characteristics and parameters of the system

Characteristic	Large unit	Cluster
Installed capacity, MW(e)	1200	4X300
Load factor, %	92	92
Life time, years	60	60
Construction time of a power unit, years	6	3
Specific capital cost, USD/kW(el.)	4000	4000
Operating and maintenance cost, USD/MWh	12	12
Fuel cost, USD/MWh	8	8

Number of power units in the system	-	4
Span between power unit commissioning, years	-	9

Table 4: Financing conditions

Characteristic	Large unit	Cluster
LCOE discount rate, %	8	-
Interest on equity, %		8 (N1) -11 (N4)
Interest on debt, %	8	8
Credit return period, years	-	6
Equity return, years	60	60
Electricity price, $/MW(e)	80	80

Calculated cost of electricity is shown in Fig.3.

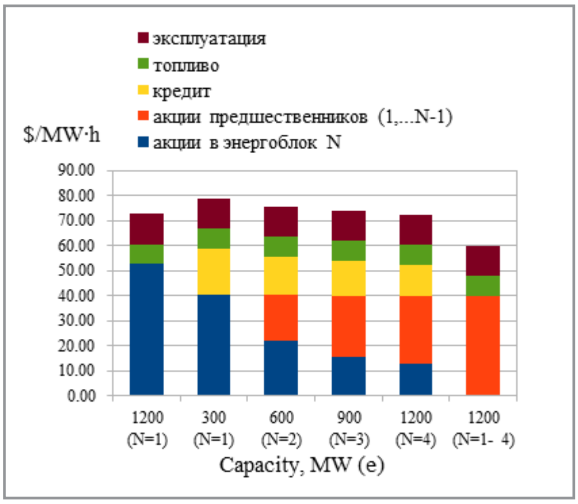

Figure 3: Electricity cost structure of a high-power power unit and a cluster

As can be seen in Fig.3, the financial burden on shareholders is step by step decreasing with the growth of number of units in the cluster thus resulting in essential reduction of the cluster electricity cost after construction of the last its unit. The combination of equity and credit investments creates a financial mechanism that can significantly increase, as can be seen in Fig.4, net present value and other commercial indicators shown in Table 5. Since the units are financially integrated into a united entity with enlarged capacity, it is possible to conclude that the effect received is a sort of a scale effect for SMRs.

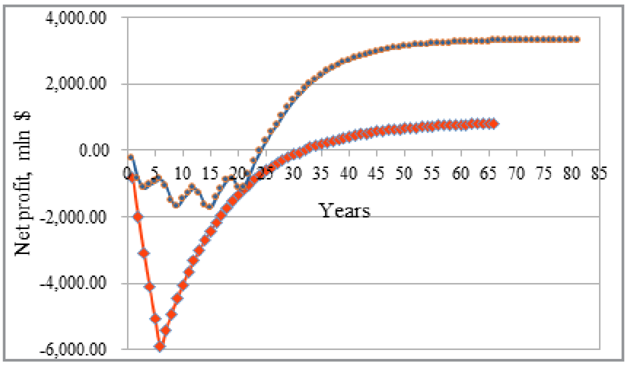

Figure 4: Net present value of a 1200 MW(e) power unit and a cluster of 4x300 MW(e) with the same specific construction and operation costs and the same electricity price

Table 5: Commercial performance indicators

Characteristic	Large unit 1200 MW(e)	Cluster 4x300 MW(e)
Electricity cost, $/MW(e)	78	79 (N1) - 60 (after N4)
Net present value, mln. $.	813	3297
Investment return index, relative units	1.14	1.86

Payback period, years	33	24
Equity productivity, kWh/$.	92	142

Conclusions

At present, there is an increased interest in nuclear plants with small reactors (SMR) and a large number of SMR designs have been developed while the role and prospects of these reactors are still discussed and their deployment is at a very early stage. The presentation provides a vision of authors on the driving forces and impediments on the way to small NPPs wide deployment.

The analysis of the development of the SMR shows that from a technical point of view and in terms of safety indicators, these reactors have reached a certain level of maturity. Thus, nuclear icebreakers successfully fulfill the important task for the state of developing the Northern Sea Route. The problems of SMRs are related to the need to achieve economic competitiveness with well-developed energy sources, including high-power reactors. It is expected that SMRs can produce competitive electricity and heat in northern and arctic regions with high energy cost. However, even in this case, to achieve success, new solutions are required, which, as shown in the paper, are being intensively developed, but do not always satisfy consumers.

It is shown in the last part of the paper that the institutional innovation – organization of a network structure with small reactors can help to solve one of the most pressing problems of the reactors – their commercial attractiveness.

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