

Analysis of advanced nuclear technologies applicable in the Russian Arctic

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Abstract. The main areas and developmental prospects of nuclear technologies used in the Arctic Zone of the Russian Federation are considered in the article. The main directions of the key Russian nuclear research centres and development are discussed. An analysis of advanced nuclear research and development aimed at the development of the Arctic is carried out. The following advanced technologies applicable in the Russian Arctic were described in the article: low-power nuclear power plants; an autonomous automated nuclear power plant for the power supply of subsea and sub-ice drilling and oil and gas production complexes on the shelf of the Arctic seas; a transportable nuclear power plant with a VBER-300 reactor facility based on a stationary ice-resistant platform for power supply of the gas production and processing centres in the Arctic; a system of autonomous power supply of the remote control centre of the prospective hydrocarbon deposit of the Arctic shelf on the basis of an autonomous nuclear power unit; nuclear power modules for power supply of subsea and sub-ice facilities of the Arctic offshore fields; a nuclear subsea gas pumping station; the atomic icebreaker project 10510 – “Leader”. Conclusions about priority areas of development for nuclear technologies in the Russian Arctic are formulated.

1. Introduction

In the present context of the intensive development of the Arctic Zone of the Russian Federation, the problem of ensuring fail-safe power supply becomes especially urgent. In a number of energy-deficit areas, electricity and heat supply problems can be solved by using currently available alternative energy sources. However, the severe natural and climatic conditions characteristic of the northern regions of Russia make it difficult to implement electricity generation solutions based on the transformation of solar, wind, wave or tidal energy. Conversely, the deployment of local generating facilities based on nuclear reactor facilities presents itself as a reliable, safe and cost-effective solution to the problem of maintaining electricity supply. At present, there are two nuclear power plants operating in the Russian Arctic – the Kola (1760 MW) and Bilibino (48 MW) facilities.

The year-round navigation through the Northern sea route by means of a fleet of nuclear icebreakers is a very important aspect of development of economic activity in the Russian Arctic. The development of new nuclear icebreaker projects will make it possible for ships having a larger deadweight and hull width than is currently possible to navigate the Arctic ice seas, as well as to increase the speed of vessels currently navigating severe ice situations.

2. Research and development centres of nuclear technologies applicable in the Russian Arctic



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Among technological leaders in the field of nuclear research and development technologies for the Russian Federation are the following companies: JSC “Afrikantov OKBM”, JSC “NIKIET”, National Research Centre “Kurchatov Institute”, JSC “Atomenergo”.

2.1. JSC “Afrikantov OKBM”

JSC “Afrikantov OKBM”, a large scientific and production centre of the “Rosatom” state corporation, is capable of full-cycle development: the manufacture and delivery of reliable, safe and efficient reactor plants of military and commercial applications, equipment and systems for reactor units and nuclear power stations, as well as their maintenance. Thus, Afrikantov OKBM is capable of carrying out a complete range of works to produce reactor units of various types and equipment for nuclear power plants, including the development of engineering documentation and associated calculations, research and development activities, manufacturing and testing of pilot items with serial improvement of production technology, supervision of the manufacture and assembly of standard equipment, commissioning and starting, maintenance and decommissioning.

For the market sector of regional electric power industry and the thermal power industry, Afrikantov OKBM has developed designs of reactor plants of VBER type (water-cooled modular power reactor) with a power rating from 100 to 600 MW(e). VBER reactor units incorporate an optimal combination of the latest achievements in marine reactor technologies together with proven solutions for the core and fuel cycle VVER-1000 and meet all basic safety, reliability and efficiency requirements for the prospective next generation of nuclear stations.

The list of advanced Arctic research and development of projects carried out by Afrikantov OKBM includes: nuclear power unit for underwater uninhabited nuclear power modules for underwater and under-ice supply of electricity to drilling and mining facilities; nuclear power source with electric power up to 6 MW in types of floating and block-transportable power units; transportable nuclear power plant with a VBER-300 reactor facility based on a stationary ice-resistant platform for power supply to Arctic gas production and gas processing centres; development of modern technical and economic requirements of nuclear ship power units based on empirical-numerical supercomputer technology [1].

2.2. JSC “NIKIET”

JSC “NIKIET”, representing a multidisciplinary institute engaged in a number of major nuclear power engineering areas, is one of Russia’s largest nuclear engineering and technology centres. The main areas of activities of the organisation comprise: the development of power reactors for nuclear power plants; the development of advanced power reactors for the nuclear power of the future, new nuclear fuel cycles, including fast reactors with a lead coolant with a closed-loop fuel cycle; the development, manufacture and testing of nuclear research facilities; starting, operation, decommissioning and utilisation of nuclear power plants, military and civil reactors and their ground-based prototype stands; operation of research nuclear reactors and facilities; research works in the areas of reactor physics, thermal physics, hydrodynamics, reliability, strength, materials science and corrosion; research and development, calculation and experimental, engineering and other works for ensuring the safety of nuclear power plants and research reactors, etc.

The list of NIKIET’s advanced Arctic research and development projects includes: a power unit for a low-power nuclear power plant with a Unitarm-30 reactor unit; a power unit for a low-power nuclear power plant with a NIKA-330 reactor facility; a VRK type boiler reactor power line and designs of power units for low-power nuclear power plants based thereon; power unit of a low-power nuclear power plant with an installed SHELF reactor [2].

2.3. NRC “Kurchatov Institute”

The National Research Centre “Kurchatov Institute” is one of the leading research centres in the world and the largest interdisciplinary laboratory in Russia. A substantial number of Russian nuclear physics facilities have been consolidated in the Kurchatov Institute.

The main areas of activities of the organisation comprise: the organisation of research, development and engineering works in the fields of nuclear power, controlled thermonuclear fusion and plasma processes; participation in the engineering, construction, deployment, operation and decommissioning of nuclear and thermonuclear facilities and radioactive waste storage facilities; participation in the engineering and manufacture of equipment for nuclear and thermonuclear facilities, radiation sources, storage facilities for nuclear materials and radioactive substances.

The list of advanced Arctic research and development projects undertaken by the Kurchatov Institute includes: simulation model of power supply of the underwater complex of development of the gas condensate field of the Arctic shelf; an autonomous power supply system for a remote control centre for the development of a hydrocarbon field on the Arctic shelf on the basis of an autonomous nuclear power unit; atomic energy modules for power supply of subsea and sub-ice facilities for the Arctic offshore fields; scientific and technical problems of integrated environmental monitoring and forecasting of the state of the environment and objects in relation to promising deserted oil and gas production technologies in the Arctic and on the continental shelf [3].

2.4. JSC “Atomenergo”

JSC “Atomenergo” is a leading Russian engineering company in the field of civil nuclear power shipbuilding. The main areas of activities of the organisation include: creation of floating nuclear power plants; creation of means for handling spent nuclear fuel; engineering for nuclear technology service vessels; development of engineering documentation and supply of equipment for water treatment of nuclear power plants.

The list of advanced Arctic research and development projects by Atomenergo includes: the project of a Floating Nuclear Power Plant (FNPP) based on the ABV type reactor installation designed to provide coastal inaccessible areas with electric and thermal energy; a floating low-power nuclear power plant with KLT-40S reactor installations (Akademik Lomonosov FNPP); the transportable nuclear power plant project with a VBER-300 reactor facility based on a stationary ice-resistant platform for power supply to Arctic gas production and processing centres; the project of FNPP on the basis of power unit with RU KLT-40S for the city of Vilyuchinsk in the Kamchatka Region [4].

3. Analysis of advanced nuclear technologies for the development of the Russian Arctic

3.1. Low-power nuclear power plants (LPNPP)

In the medium-term, the role of low-power nuclear power units is the replacement of existing nuclear power generation capacities, also based on traditional types of fossil fuels, as well as the construction of local electricity generation centres for newly-created production and processing facilities in remote Arctic areas.

To date, NIKIET has developed a line of modern power units in the range of 0.2-100 MW of electric power. Among them are the following projects, which are currently at different stages of development: transportable low-power plant with a water-cooled Vityaz reactor with an electric capacity of up to 1 MW; transportable low-power plant on the basis of an innovative gas-cooled reactor of electric power up to 3.2 MW; UNITERM reactor facility for a stationary low-power plant [8]; a power unit with a SHELF reactor facility engineered as a power capsule with built-in reactor and turbo generator sets [5]; installation of integrated NIKA reactor for an LPNPP with an electric power of 100 MW. A pressure compensator placed in the reactor vessel at the station having a NIKA reactor minimises the risk of a LOCA type accident [8]; a line of hull boiling devices developed by NIKIET for stations with electric capacity of 45, 100 and 300 MW in single-block design.

In 2016, the feasibility of creating a transportable LPNPP on the basis of water and gas cooled reactor facilities for the purposes of locally-based power supply in remote locations was studied. The transportation is carried out in the form of transportable modules on a wheel-based platform. Engineering documentation of the water-cooled nuclear unit Vityaz was developed in 2016.

The concept of the transportable LPNPP with ATGOR gas-cooled reactor was developed using the results of the work on the high-temperature gas-cooled reactor project. The electrical power generated (0.2-8 MW) depends on the delivery set. The energy conversion system based on mass-produced gas turbine engines allows the use of traditional generation on organic fuel during maintenance stop of ATGOR.

The SHELF unified nuclear unit (NU) is developed on the basis of experience in the design, engineering and operation of existing facilities. Here, the type of power unit may either be ground-based or underwater, depending on the location. It is supplied in the form of an energy capsule with NU or with a compactly positioned NU and Atomic turbo generator located in a single shell. At present, the technical design and preliminary safety report materials (covering the stage of reactor installation) are being developed.

NIKIET is currently working on the formation of cooperation between manufacturers with the aim of producing of the main sample of LPNPP. Agreements on cooperation and interaction on LPNPP have been signed with the Kurchatov Institute [2].

3.2. Autonomous automated nuclear power plant for the power supply of subsea and sub-ice drilling and oil and gas production complexes on the shelf of the Arctic seas.

For the supply of subsea and sub-ice drilling and production facilities, OKBM Afrikantov has developed projects involving automated autonomous nuclear power plants with water-cooled pressure reactors (WCPR) with the use of compact sealed high-power turbine generators and nuclear power units with high-temperature gas reactors (HTGR) and a closed gas turbine cycle with a useful capacity from 8 to 25 MW of electric power. This type of nuclear power plant facility is able to operate for a long time without a human management or direct maintenance presence.

The chief technical characteristics of the nuclear power plant are as follows: electric power – 8 MW; depth of operation— 100-400 below sea level; total service life (without recharging fuel) – 30 years. Dimensions of the energy compartment: a. \varnothing 11×13 m (for nuclear power plant with WCPR); b. \varnothing 11×10 m (for nuclear power plants with HTGR). A block of modules with a total capacity of up to 250 MW or more can be assembled from single modules with a capacity of 8-25 MW of electric power. Reliable WCPRs developed by Afrikantov OKBM are used as nuclear power plants for the Russian sea vessels. Technical WCPR solutions from currently-operating and under-construction transportable nuclear units are proposed for use in drilling and subsea production complexes.

The proposed installations are engineered taking into account the use of a unified element base for equipment (active zones, steam generating elements, body equipment, pumps, CPS actuators, fittings, heat exchange equipment, etc.). Completed R&D and long-term operational experience of installations of this type at various transportable objects of energy ensure the reliability and resource characteristics, as well as the safety of the installation as a whole. In the proposed nuclear power plants, principles of self-management and self-protection, passive safety and autonomous responses in the case of accidents are developed to the maximum possible extent.

Nuclear power plants having a high-temperature gas reactor (HTGR) comprise an innovative technology, the main technical solutions of which are demonstrated in the work carried out by Afrikantov OKBM within the framework of certain programmes of the Rosatom state corporation. It should be noted that one distinguishing feature of nuclear power plants with HTGR is their high efficiency in comparison with water technologies, which makes it possible to increase the capacity of the unit within the limits of the specified overall characteristics of nuclear power plants. The development of gas technologies in the transport reactor building requires an expansion of the R&D complex including the creation of a domestic ground nuclear test facility for testing high-temperature gas coolant technology. According to preliminary estimates, a pilot plant with HTGR can be created within 8-10 years. Taking into account the innovations used in nuclear power plants with HTGR, this direction of NPP use in the objects of offshore zone development has priority in the long term [8].

In addition to the submarine modules intended for power supply of drilling and production complexes, high-temperature gas coolant technologies can be used for other underwater objects serving

the shelf zone, for example, robotic autonomous units (observation and repair of drilling equipment, etc.), as well as low-power, deep-sea nuclear power plants.

3.3. Transportable nuclear power plant with a VBER-300 reactor facility based on a stationary ice-resistant platform for power supply of gas production and processing centres in the Arctic

The production of liquefied natural gas (LNG) requires significant energy supply. Here, electricity is utilised to satisfy technological requirements for the separation of produced gas into fractions and bringing methane – the main component of natural gas – into a liquefied state at atmospheric pressure and a temperature of minus 163 °C, in which state it is stored and transported by gas carriers. Traditional sources of energy in the LNG cycle include a gas turbine-generator, in which part of the produced well production is consumed.

Energy supply of LNG production capacity of 10 million tons requires the burning of approximately 1 billion m³ of gas per year. Corresponding to this volume, the lost profit from the sale of such a volume of gas in the world market will be up to \$ 180 million per year at a market price for natural gas of \$ 200 per 1000 cubic meters, or \$ 5.4 billion over 30 years. Concerning this issue, there is a question as to what extent it is reasonable to replace gas for internal technological needs of LNG with an atomic energy source. This circumstance indicates the need for a search for alternative sources of energy supply for satisfying the needs of offshore gas fields and for LNG production.

As such an alternative energy source, transportable nuclear power units are developed on the basis of a stationary ice-resistant platform with a VBER-300 reactor facility. Engineering of this type of nuclear power plant (NPP) (transportable, based on a stationary ice-resistant platform) is caused by a reduction in the cost of the facility in comparison with other options for nuclear power generation and takes into account the current trends in the organisation and location of LNG production. The electrical capacity of the NPP (300 MW) corresponds to the energy consumption of the LNG plant in the amount of approximately 5-5.5 million tonnes of LNG per year. As a rule, for large deposits, LNG plants are planned to be constructed in lines with a total capacity of 10-16.5 million tons. As a power source at NPPs, a compact reactor unit VBER-300, developed by Afrikantov OKBM based on shipboard nuclear power engineering technologies, is used [6].

Engineering the NPP to be based on a stationary ice-resistant platform has a number of advantages in comparison with execution in the form of floating nuclear power plants or a ground power unit: the use of floating NPPs limits the geographic location and requires the construction of protective hydraulic structures; the construction of a 300 MW nuclear power plant on the shore, even with the use of floating technology, is not optimal due to the large amount of construction and installation work performed directly on the site of the NPP, which, due to the inaccessibility of the construction site (the Arctic coast), leads to a significant rise in cost of project. The main dimensions of the stationary ice-resistant platform are: length – 132m; width – 132m; height – 24m; mass about 80,000 tons.

In case of the high market prices of gas and increase in gas extraction costs in extreme natural and climatic conditions at distant Arctic areas the use of the proposed transportable nuclear power plant for powering LNG facilities may be more beneficial than burning of expensive hydrocarbon fuel.

3.4. System of autonomous power supply of remote-control centre of prospective hydrocarbon deposit of the Arctic shelf on the basis of autonomous nuclear power unit

The remote-control centre of prospective oil and gas field is a highly effective system for monitoring and managing the development of the field. It takes into account the structural features of a field that provides a significant increase in the level of oil and gas output.

Such a remote-control centre presupposes the availability of all necessary equipment for remote monitoring and management of facilities for the development of subsea ice production. This approach is formed on the basis of advanced solutions used in contemporary Russian and foreign projects for transitioning to autonomous technologies in order to minimise the number of personnel employed directly at the field site with the use of highly automated and robotic technological systems and subsea and sub-ice production devices [7].

The distances to which subsea control cables along the shelf bottom can be laid today reach values of more than 200 km. The high-speed transmission of monitoring and control information using communication and power transmission technologies allows the power supply for offshore field development and production facilities to be carried out at high speed. This concept of autonomous power supply to subsea production facilities is possible due to highly automated underwater power systems that can be in close proximity to consumers for the implementation of their reliable and uninterrupted power supply. The use of an autonomous nuclear power unit with a capacity of 250 KW is proposed for providing power to the remote-control centre of the prospective North-Wrangel deposit [3].

3.5. Nuclear power units for power supply of subsea facilities of the Arctic offshore gas fields

The Kurchatov Institute has carried out the development of a nuclear power plant for direct energy conversion for a submersible power module within the framework of cooperation with JSC “SPMBM” Malachite”. SPMBM Malachite proposed the concept of using a nuclear power plant for direct energy conversion (NPP DEC) as part of a submersible energy module (SEM) designed for servicing the power supply requirements of a complex of subsea and sub-ice facilities for oil and gas fields on the Arctic shelf. The design of the SEM with NPP DEC is proposed to be presented in the form of a permeable frame structure installed on the bottom of the platform base with ten “sockets” for the placement of the NPP PES. A robust, dry electro-technical compartment with electrical panels, transformers, control panel is installed on the platform base. The platform is located on supports above the ground bottom to prevent the bottom hydrants from moving out. The electrical compartment is equipped with unified international standard coamings to ensure the docking of habitable underwater vehicles. The premises and equipment of the electrical compartment on the SEM do not require long-stay personnel.

This approach is formed on the basis of promising future solutions used in modern Russian and foreign projects for the transition to autonomous technologies in the development of the field in order to minimise the number of personnel working directly at the field site with the use of highly automated and robotic technological systems and subsea mining devices. The SEM with NPP DEC can be installed at a depth of up to 400 m and provide power supply for technological systems and underwater ice facilities with a capacity of up to 10 MW.

For safe and reliable power supply, a SEM with a NPP DEC includes in its project technical solutions and measures based on the principles of natural safety (natural circulation of coolants in all circuits, self-regulation due to inverse physical connections, thermoelectric energy conversion), which also takes into account the necessity of reserves. The project meets modern nuclear energy safety requirements and is based on the experience of creation and scientific management of atomic energy units and spent fuel elements solutions of nuclear power engineering [6].

3.6. Nuclear subsea gas pumping station

A subsea autonomous nuclear gas pumping station for underwater gas pipelines was laid from the places of offshore natural-gas production to the continent was engineered by JSC CCB ME “RUBIN”. The project was developed using the results of research and development performed by corporations of the military-industrial complex of Russia during engineering of main power units of nuclear submarines and surface ships of the Navy. Multiyear experience in the operation of nuclear submarine equipment was additionally used in the course of the project to provide extra safety and ensure the reliability of the facility.

Technical solutions used in the project provide the opportunities for: transportation of the station to the place of installation and operation in the above-water position; immersion of the station at the depth of the main gas pipeline; plugging the station into the gas pipeline through the gas pipeline support and landing platform; long-term and reliable operation (in automatic control mode) as part of the main gas pipeline, creating and maintaining a degree of compression of the pumped gas to ensure the required productivity of the gas pipeline; unplugging of the station from the main gas pipeline and replacing it with a similar one in the event of an failure or after the end of service life; periodic visits to the station

by support personnel using an underwater transport vehicle for service of its mechanisms and change of consumables (oil).

The project includes systems and mechanisms that ensure the possibility of a long-term operation of the station in autonomous mode, as well as propulsion systems that provide the station the ability to manoeuvre in an underwater position after bringing it to zero buoyancy. The staff is provided with the possibility to periodically visit the working station for service maintenance. There are living and service rooms for the staff during their stay at the station.

3.7. The atomic icebreaker project 10510 – “Leader”

The 10510 “Leader” nuclear icebreaker is designed for year-round navigation of large-capacity transport vessels with a deadweight of more than 100,000 tons and a width of more than 50 metres all along the Northern Sea Route at an economically effective speed of about 15 knots with an ice thickness of about 2 metres. The unique design of the newest Russian nuclear-powered vessel will support the navigation along the Northern Sea Route even by large-tonnage tankers and dry cargo vessels, which cannot currently use this route. The hulls and the power of 120 MW screws will provide the icebreaker with unprecedented navigation capability in sea ice.

For the “Leader” icebreaker project, Afrikantov OKBM offered a conceptual design for the RITM-400 reactor with a thermal capacity of 315 MW, twice as powerful as the RITM-200 reactor facility installed on the icebreaker project 22220. The required capacity of the nuclear-powered icebreaker “Leader” will be two RITM-400 installations.

4. Conclusion

Based on the overview and analysis, it is possible to draw the following conclusions about the development of nuclear technologies applicable in the Russian Arctic:

1. The key area in the development of nuclear technologies in the Russian Federation is the development of efficient, highly automated reactor facilities for nuclear power plants of small and medium electric power in the range from 6 to 100 MW. Their usage in the Russian Arctic allows providing electric and heat supply to residential and industrial facilities in distant Arctic areas that do not have centralized power supply and have expensive far distance supply of fuel.

2. The early commissioning of the already built floating nuclear power station “Akademik Lomonosov” will significantly increase the energy supply to objects in the town of Pevek in the Chukotka region of Russia. At the same time, an analysis of the overall budget and long-term construction is needed. The design of the station began in 2008, with commissioning planned for 2019. When implementing the subsequent projects of the Floating nuclear power station, all involved organisations should make maximum efforts to shorten the terms of design, construction and commissioning. It is possible to implement the previously developed FNPP project based on the ABV-type reactor facility, as well as the project of a transportable nuclear power plant with the VBER-300 reactor facility based on a stationary ice-resistant platform for power supply of gas production and processing centres in the Arctic.

3. One of the promising areas for the development of nuclear technologies in the Russian Federation is the implementation of high-temperature gas-cooled reactor projects aimed at expanding the energy market in the sphere of heat supply. Produced heat can be used for various industries, including the intensification of oil production, petrochemicals and refining. According to the vision of the developers, it is possible to implement a high efficiency direct gas turbine cycle (~ 50%) with simultaneous use of waste heat for municipal heat supply. Installation of a single reactor unit and helium-cooled gas turbine plant is used to provide a compact self-contained power source for the surface, underwater and ground objects of the Russian Arctic separated from external infrastructure [9].

4. Russia is the undisputed world leader in the construction of civilian nuclear ships. Icebreakers powered by nuclear power plants have been successfully operating in the Arctic Zone of the Russian Federation for a long time, ensuring the safe passage of transport vessels through the Northern sea route. The current practice of the icebreaker fleet involves navigation of vessels on deep water with linear

icebreakers. Icebreakers with limited draft are used in shallow water areas. This requires the transfer of caravans from the linear icebreaker to the icebreaker with a small draft and vice versa, leading to delays and negatively affecting the economic efficiency of cargo transportation. In order to improve the efficiency of the nuclear icebreaker fleet, a project for the construction of a new-generation universal two-vessel nuclear icebreaker (project 22220) is currently being implemented. This will be capable of combining the functions of both linear icebreakers and icebreakers supporting limited-draft shipping. Icebreakers of this type incorporate two of the latest RITM-200 175 MW reactor units each. The inventions, utility models, software and know-how obtained during the development of this reactor system will allow the construction of RITM-400 reactor units with 110-130 MW capacity for the icebreaker (project 10510), which will be able to provide year-round navigation on the NSR.

Intensive research and development in the above areas will preserve and consolidate Russia's position as a leader in the production and use of nuclear reactor facilities. The Russian Arctic has become a testing ground for the application of the most advanced technologies and scientific research, providing a long-term basis for technological development of the whole country and forming scientific and technical grounds for securing of the actual sovereignty of the Russian Federation in the Arctic [10].

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