

Safe development of nuclear power technologies in the Arctic: prospects and approaches*

Ashot A. Sarkisov¹, Sergey V. Antipov¹, Dmitry O. Smolentsev¹, Vyacheslav P. Bilashenko¹, Mikhail N. Kobrinsky¹, Vladimir A. Sotnikov¹, Pavel A. Shvedov¹

¹ Nuclear Safety Institute of the Russian Academy of Sciences, 52 B. Tulkaya st., Moscow, 115191 Russia

Corresponding author: Dmitry O. Smolentsev (dsmol@ibrae.ac.ru)

Academic editor: Georgy Tikhomirov ♦ Received 29 August 2018 ♦ Accepted 19 November 2018 ♦ Published 13 December 2018

Citation: Sarkisov AA, Antipov SV, Smolentsev DO, Bilashenko VP, Kobrinsky MN, Sotnikov VA, Shvedov PA (2018) Safe development of nuclear power technologies in the Arctic: prospects and approaches. Nuclear Energy and Technology 4(4): 235–241. <https://doi.org/10.3897/nucet.4.31870>

Abstract

The demands for nuclear power technologies in the Arctic for solving social and economic problems of the state can only be satisfied if adequate strategies of their safe handling at all stages from design to decommissioning are defined, methodological approaches and mathematical models for predicting and minimizing adverse environmental impacts of potential emergency situations at such facilities are developed, and scientifically-based results yielded within a decision-making support system for the elimination of such emergencies are applied. Special relevance of these requirements is determined by unique features of the Arctic nature and its role in the generation of climatic and hydrological processes in the World Ocean.

Main results and generalized conclusions based on the analysis of radiological consequences of the large-scale application of nuclear power industry for the benefit of economic development of the Arctic region are provided in the present paper. The analysis was performed within the framework of the complex research project “Development of the methodological approaches and mathematical models to assess the environmental impact of the possible accidents at the floating nuclear power objects, model calculations of the radiation propagation in the Arctic aquatic territories in case of emergency situations”. The increasing demand for the low-power nuclear power plants for the benefit of development of remote areas, the technological and economic advantages of such power plants as well as minimal possible environmental consequences of the hypothetical accidents resulted in the qualitative changes in the attitude towards their usage. Estimation was made of the scale of application of nuclear power and results were obtained of numerical modeling of distribution of reactivity in case of accidents. The conclusion was drawn on the necessity to adhere to the low-power nuclear energy generation development strategy based on the modular design concept.

Keywords

Arctic region; nuclear icebreaking fleet; Low-Power Nuclear Power Plant; development forecast; radiation safety; sea areas; mathematical modeling

* Russian text published: *Izvestiya vuzov. Yadernaya Energetika* (ISSN 0204-3327), 2018, n. 3, pp. 5–17.

Low-power nuclear energy generation development strategy

With growing need of world economy in the development of natural resources in remote, isolated and scarcely populated regions demand for self-sustainable, environmentally safe and financially efficient plants of energy increases. Low-power nuclear power plants (LPNPPs) will be highly demanded as energy plants for electricity and thermal power supplies, as well as for technological purposes. A number of countries with developed nuclear power generation make practical steps and undertake large-scale efforts for the development of low-power nuclear reactors for a wide range of applications.

Large-scale development and implementation of nuclear power generation technologies for civil applications in the Arctic region of Russia is intended within the framework of realization of the plan of measures under the state programs “Social and economic development of the Arctic zone of the Russian Federation”, “Development of shipbuilding for the period of 2013-2030” and “Development of nuclear power industrial complex”. Nuclear-powered icebreakers, transportable LPNPPs, cogeneration heat and electricity nuclear power plants, submersible LPNPPs for supplying power to shelf oil and gas production complexes, nuclear power plants for supplying energy for maritime and aviation navigation along the Northern Sea Route and other special objects of infrastructural development on the littoral northern territories are referred in the first place to such technologies.

It is evident that nuclear power plants already implemented or currently under development will constitute one of the cornerstones of the transport and energy sectors of the Arctic region in the nearest future. As of today this means wide variety of design and types of such LPNPPs. Efficiency of such scenario of development of low-power nuclear energy generation is far from optimal because operation of such LPNPPs becomes more complicated and development of appropriate infrastructure is required.

Modern requirements on the development of competitive LPNPPs amount to the necessity of batch production of power generating units and of centralized infrastructure for their operation (scheduled major overhauls, handling radioactive wastes (RW) and irradiated nuclear fuel (INF), decommissioning, etc.) (Low-Power Nuclear Power Plants 2015, Sarkisov 2011, The History of Nuclear Power 2004) allowing unifying the chain of technological processes and reducing the cost of ownership of power generation object in case of large-scale development along the chosen direction. Organization of the system of types and performance characteristics of nuclear power units used or planned to be used in the Arctic, technologies applied for their operation, as well as quantitative estimation of the impact on the environment in case of potential accidents result in the need to select such LPNPPs development strategy based on the implementation of modular principle in designing nuclear power plants providing for the development units of different power capacity due to the combination of several units of the same type.

Following the above logic, it is reasonable to address design of modular transportable fully factory-assembled nuclear power units as the first priority projects.

At present the application of nuclear power units in the Arctic and its future potential appear to be as follows.

Nuclear powered ships

Four nuclear powered icebreakers are under operation: two Design 10521 icebreakers (Yamal and 50 Years of Victory with two OK-900A nuclear steam-generators (NSGs)), two Design 10580 shallow draught icebreakers (Taymyr and Vaygach with one KLT-40M NSG). Taking into consideration the possibility of extension of service life of the nuclear power units three out of currently operated icebreakers will be decommissioned by 2025-2026 and the only 50 Years of Victory icebreaker will remain in operation by 2030. Thorough qualitative re-equipment of the fleet of nuclear-powered icebreakers is planned for the purposes of providing support to the implementation of state tasks on the maintenance of pilotage of sea vessels along the Northern Sea Route (Ruksha et al. 2016, Kashka et al. 2016, JSC “Afrikantov OKBM” 2018, Kudinovich 2016). Three universal nuclear-powered Design 22220 icebreakers are under construction at the Baltic Shipyard in order to maintain the functions and expand the scope of tasks performed by the fleet of nuclear-powered icebreakers: Arctica (was launched in June, 2016, operational commissioning is planned for 2019), Sibir (was launched in October, 2017, operational commissioning is planned for 2020) and Ural (keel laying ceremony took place in July, 2016, operational commissioning is planned for 2021). Two RITM-200 reactor units (RU) will be included in the composition of NSGs of this design of icebreakers.

Search for investors is ongoing and design projects of construction of icebreakers in the long-term perspective until 2030 are explored:

- Two universal nuclear-powered Design 22220 icebreakers (to be added to the three vessels indicated above);
- Leader icebreaker with two RITM-400 NSGs for all-year round navigation;
- Multi-functional nuclear icebreaker of off-shore type with RITM-200B NSG for solving tasks of sea shelf development.

The only nuclear-powered Sevmorput icebreaking cargo LASH vessel with KLT-40 NSG is in operation besides the icebreakers.

Transportable and stationary lower-power nuclear power plants

According to NEA OECD and IAEA estimations, installed capacity of LPNPPs in the world will reach 21 GW

by the year 2035. Commissioning from 2 to 10 GW(e) of new capacities will be required for supporting the development of social and industrial infrastructure in the Arctic region of Russia until 2030 with total fraction of nuclear energy plants reaching 30% under the condition of complex development of this direction.

Floating Design 20870 power unit with two KLT-40S (floating nuclear cogeneration heat and electrical power plant - FNPP) is currently in the later stages of practical implementation. Beginning of test operation of this power unit is expected in near future. The Town of Pevek in the Chukotka Autonomous Region was chosen as the location site for the first FNPP, beginning of operation was synchronized with shutting down the Bilibino NPP and is planned for 2019. Construction of a series of power plants of this type is necessary for ensuring continuous power supply in the target region taking into consideration the specific features of the FNPP design (factory repair after each of two 12 year-long operational cycles). Thus, construction of one or two more FNPPs optimized cost-wise as compared with the pilot power plant for achieving competitiveness can be expected before 2030 after thorough fine-tuning of the technology in real operational conditions.

For power supply of coastal consumers, as well as consumers removed from the sea it is advisable to use transportable modular LPNPPs with up to 10 MW(e) power per unit. LPNPPs of SHELF type represented by the series of different configurations of nuclear power plants on the basis of the unified 6.4-MW(e) land-based SHELF reactor unit represent the development effort with the highest degree of substantiation of the technical and financial model of their application. Other promising type of LPNPP is represented by the design project based on the cogeneration 12-MW(th) plus 6-MW(e) ABV-6E reactor unit either land-based or in the composition of a floating power plant. No decision on the starting these projects has yet been made, but, taking into consideration the dynamics of their development and the real existing needs, the beginning of works on the construction of pilot units can be expected within the next six – eight years.

As reported by mass media (for instance, (Compact Nuclear Batteries 2018)), the Defense Ministry design projects on the development of LPNPPs are under realization. As of August, 2017 negotiations with investor are ongoing on the development of pilot samples of 1 MW(e) and 100 kW(e) power units for providing electricity supply to isolated remote consumers. The target objects for application of such power plants in the Arctic can be meteorological and hydrological stations and posts, scientific research bases, radiolocation stations, airfields used for both military and for civil purposes. Unattended LPNPP of megawatt power class will be mounted on tractive vehicles or semi-trailers that can be transported by water routes. Description of the project in open sources is not yet accessible, but the closest in terms of power capacity (Compact Nuclear Batteries 2018) are the LPNPPs with ATGOR gas-cooled reactor unit and LPNPP on the basis of light-water VITY-AZ reactor unit developed by the NIKIET JSC.

Reactors with direct energy conversion of nuclear energy into electricity used for power supply of equipment of space missions, GAMMA pilot demonstration nuclear thermoelectric unit with electrical capacity up to 6.6 kW(e) and ELENA nuclear thermoelectric unit with 68-kW(e) electrical capacity (engineering design), as well as Radioisotope Thermoelectric Generators (RTG) (~ 0.3 kW(e)) earlier applied in navigation beacons, radio beacons and on meteorological stations are the prototypes of unattended nuclear energy units with application of the technology of direct conversion of nuclear energy into electricity (up to 100 kW(e)). Expected lead time for the implementation of power units pilot projects construction with electric power of the order of 1 MW(e) and 100 kW(e) is tentatively scheduled for the year 2023 under the condition of the beginning of investment in 2017-2018 (Compact Nuclear Batteries 2018).

LPNPP application in the Arctic economical aspects

In contrast to nuclear power generation technologies in shipbuilding the scale of application of LPNPPs is determined by their competitiveness (in terms of aggregate costs and cost of generated energy) as compared with other types of power supplies. Implemented technical and financial analysis of options of LPNPP application in the Arctic demonstrated relative efficiency of some of the projects (Low-Power Nuclear Power Plants 2015, Kudinovich 2016, Sarkisov et al. 2018a, Nikitin et al. 2015, Smolentsev 2012, Possibilities for Employment of Low-power NPPs 2016, Small Modular Reactors 2016, Approaches for assessing the economic competitiveness of small and medium sized reactors 2013).

Despite the high relative capital investments (RCI) (for instance specific RCI for nuclear power plants with capacities of the order of 1 MW(e) and 5 MW(e) are estimated to be equal to 3 mln. rubles and 1 mln. rubles, respectively) integral costs for LPNPPs grow slower as compared to conventional energy units operated on targeted sites (diesel electric power plants (DEPP), CCGT plants, coal heat and electricity plants) because of absence or significant reduction of supplied fuel costs, which is reflected, as the result, in the leveled costs of energy (Figs 1, 2).

The drivers of reduction of cost of the LPNPP main production, i.e. electricity, determining LPNPP competitiveness, are the modular configuration of power units and their production in batches. Estimation of LCOE reduction for LPNPP for the case of batch production is presented in Fig. 3.

Increase of scale of LPNPP application can be expected in mid-term perspective taking into account relative competitiveness of LPNPP for the target regions of application in the Arctic. Table 1 contains compilation of the forecasted data on the use of nuclear power units for the purpose of development of Arctic region taking into

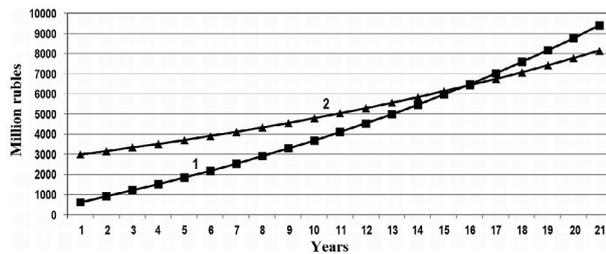


Figure 1. Accumulated integral costs for years of operation of megawatt-class power plants in the Arctic: 1 – 1-MW diesel electric power plant; 2 – 1-MW nuclear power plant.

account the industrial potential and the necessity of development of service infrastructure, economical efficiency, as well as certain known parameters of reactor units which can be used during subsequent stages of work during implementation of a scenario modeling and assessment of risks of development of emergency situations.

The presented materials clearly illustrate the statement made at the beginning of the present paper on the wide variety of types and design of LPNPPs complicating their operation and increasing expenditures during the whole lifetime. This leads us to the conclusion on the advisability of examination as the first priority the unified design projects of fully factory assembled modular LPNPPs.

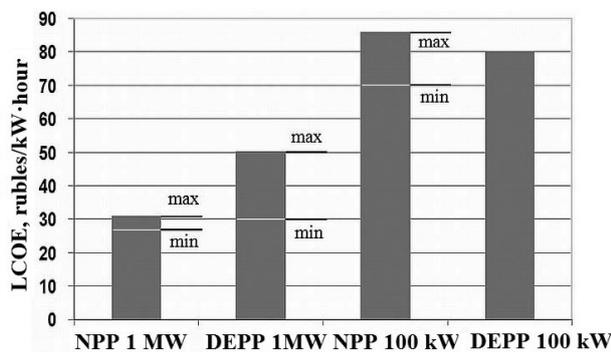


Figure 2. Estimated Levelized Cost of Energy (LCOE) for megawatt-class power plants in the Arctic (NPP – nuclear power plant).

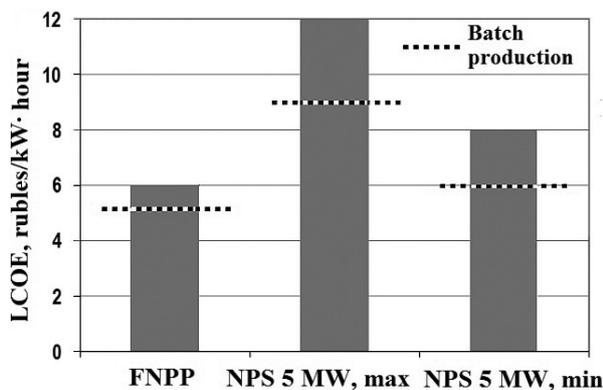


Figure 3. Estimated LCOE for batch production (NPS – nuclear power source).

Safety of LPNPPs application in the Arctic

Transfer of the most dangerous operations, both nuclear and radiation, associated with repairs, fuel reshuffling and decommissioning from the LPNPP site to the factory shops will allow ensuring high level of safety and quality of the performed procedures and minimizing environmental consequences (Low-Power Nuclear Power Plants 2015, Sarkisov 2011).

The main method for delivering modules of LPNPPs, as well as nuclear fuel (including INF) to the regions of their operation or to the objects of centralized infrastructure are towing or transportation along the Northern Sea Route. Transportation of certain power units (except unattended) is planned to be performed together with reactor cores for subsequent fuel re-loading. For example, four sets of reactor cores for each of the reactor units, as well as INF storage unit for the return trip will be loaded on board the FNPP. Factory testing (mooring testing, fuel loading, reactor start-up, test operation, shutdown) will be performed before shipping LPNPPs to the place of their operation. For ensuring compliance with legal requirements reactor units will be shipped in the cooled-down mode after isolation. Thus, at the moment of transportation structural elements of cooled-down reactor units will contain, in addition to the reactor cores, radioactivity accumulated in the process of testing. Activity during the return trip to the production facility upon completion of the fuel irradiation cycle will be significantly higher. Therefore, thorough safety analysis of the objects during all phases of their life-cycle is necessary.

The following navigation accidents with possible release of radionuclides in the environment in case of fracture of pipeline or damage of storage facilities for spent nuclear fuel or solid radioactive wastes are examined as the main events for transportable power units and icebreakers: ramming by other sea vessel, sinking in shallow or deep waters, taking the ground. These accidents refer to beyond design-basis accidents with probability not higher than 10^{-6} year⁻¹ (Kudinovich 2016, Kuznetsov et al. 2014).

Nevertheless, for substantiating safety of transported objects it is also necessary to examine consequences of their extended presence at the sea floor in case of potential accidental sinking. This is also necessary because preparation of projects of submersible capsular LPNPPs is ongoing including the following: Project AISBERG, SHELF type submersible unit, submersible power module with SVIR reactor unit on the basis of lead-cooled fast reactors.

Investigation under the research project “Development of methodological approaches and mathematical models for forecasting environmental impacts in case of accidents on nuclear floating objects, modeling spread of radiation on Arctic sea areas in case of accidents” conducted by the team from the Nuclear Safety Institute of the Russian Academy of Sciences are intended to make contribution

Table 1. Parameters of reactor units operated (planned for operation) in the Arctic.

Type of reactor unit	Reactor unit in operation (forecast)		Configuration ^{*)}	Thermal capacity, MW	Fuel composition	Fuel enrichment, %	Fuel irradiation time, years	Fuel load ²³⁵ U, kg
	2020	2030						
PK-900A	4	2	1	171	Intermetallide	≥ 40	5–6	207
KLT-40M	2	0	1	171	Intermetallide	≥ 89	10	Up to 200
KLT-40	1	0	1	135	Intermetallide	≥ 89	10	151
RITM-200	4	10	2	175	Ceramic metal	≤ 20	7 (10–12)	438
RITM-200B	0	1	2	209	Unified with RITM-200 reactor unit			
RITM-400	0	2	2	315				
KLT-40S	2	4–6	1	150	UO ₂	≤ 20	3	290
ABV-6M	0	1–2	2	38	UO ₂	≤ 20	10–12	190
SHELF			2	38	Intermetallide	≤ 20	4–6	–
VITYAZ	0	1–4	2	6	–	≤ 20	6	–
ATGOR			2	3.5			10	

^{*)} Modular configuration; 2 – Integrated configuration.

in obtaining scientifically substantiated estimation of the level of threat and risks in making decisions on the future development of the direction in question.

Nuclear reactors, reactor compartments of nuclear submarines and screen assembly of the Lenin nuclear icebreaker (Sarkisov et al. 2015) sunken at the bottom of the Arctic Ocean in the Kara Sea in 1960-70-ies were examined as model cases in the course of studies and assessment of risk of environmental impact in case of sinking nuclear and radiation dangerous objects. Model and software means were developed for estimating time of expected destruction of protective barriers of such objects by corrosion (Sarkisov et al. 2018). Data on the multi-layer shielding (protective containment, physical boundaries of the cooling loop, fuel pin cladding, fuel composition), accumulated activities, outside dimensions and structural materials corresponding to the sunken object were used as the input information. Here, the algorithm for calculation of corrosion destruction of protective barriers for simple objects (steam generators, reactor vessels and lids, etc.) amounted to the calculation of the time for the development of penetrating holes and complete dissolution of objects, while that for complex objects (sealed reactor vessels and reactor compartments) amounted to the analysis of possible ways for penetration of sea water and stage-by-stage corrosion destruction of all encountered barriers (Sarkisov et al. 2015, Sarkisov et al. 2018, Sivintsev et al. 2005, Reistad Ole and Ilgaard Povl 2006). Quantitative estimation of consequences from the object residing on the sea bottom is based on the modeling of each of the stages of degradation: corrosion process – penetration

of radionuclides in the marine environment – spread of radioactivity and isotopic composition of the contaminants.

It was demonstrated that the rate of release of radionuclides beyond the limits of corroding materials, their penetration and spread in the environment are described by the following equations:

$$Q(t) = \frac{Smv}{V_0} \sum_i^l q_i(0) f(t) \exp(-\lambda_i t)$$

$$C(x, y, z) = \frac{Q}{2\lambda \sigma_y \sigma_z U} \exp\left\{-\frac{1}{2} \left[\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right]\right\}$$

$$\sigma_i(x) = \sqrt{2k_i t} = \sqrt{2 k_i x/U}, i = y, z$$

with the following boundary conditions:

$$\begin{cases} C = 0 & \text{for } t = 0, \\ C = 0 & \text{for } t = -\infty, \\ \frac{\partial C}{\partial y} & \text{for } y = 0. \end{cases}$$

Here, t is the time of corrosion, years; $Q(t)$ is the rate of release of radionuclides in the sea water, Bq/yr; S is the surface area of the corroding material, m²; m is the mass of the corroding material, g; v is the corrosion rate, mm/yr; V_0 is the initial volume of the corroding material, m³; λ_i is the decay constant of the i -th radionuclide, yr⁻¹; l is the number of nuclides under examination; $q_i(0)$ is the specific activity of i -th radionuclide at the moment of sinking ($t = 0$), Bq/g; $f(t)$ is the function taking into account the variation of activity on the corroding surface due to the non-uniform distribution of activity over the thickness of the structural element; for instance, reactor vessel or lid; C is the volume activity at the point with coordinates (x, y, z) , Bq/m³; U is the flow rate along x -axis, m/s; k_y, k_z are the coefficients of turbulent diffusion, m²/s; σ is the dispersion in lateral directions, m; z -axis is directed from the bottom to the surface, with x, y and z axes forming a right-handed coordinate system.

Results of investigation demonstrated that in case of residence of the object at sea bottom release of radionuclides in the marine environment due to corrosion destruction of protective barriers can take place not earlier that after 300 – 400 years. Methods for salvaging and bringing nuclear-hazardous objects from the sea bottom can be and will be found and implemented during this period.

Increase of concentration of technogenous radionuclides in bottom sediments in the vicinity of sunken objects as compared to the background will occur in case of release of radionuclides in the marine environment. However, concentration of radioactive substances at the distance of over 1000 m from the sources of release will not be

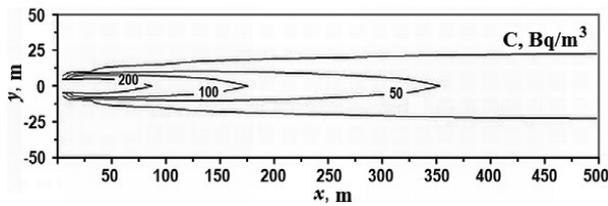


Figure 4. Isolines of concentrations of radionuclides (C , Bq/m^3) in sea water one year after loss of sealing of the radiation source. The source is located in the origin of coordinates.

significantly different from the concentrations induced by global fallout (Fig. 4) (Sarkisov et al. 2018).

Results of computer modeling of spread of activity over the water area for the case of maximum possible burst release or of protracted slow effluence in the environment beyond the limits of protective barriers for different scenarios up to the complete destruction of the reactor and fuel assemblies conducted using the combined model of marine dynamics and particle transfer on the basis of IVM-IO ocean dynamics model (Ibrayev et al. 2012) demonstrated that for maximum hypothetical accidents regions of radioactive contamination of sea water with ^{137}Cs in excess of concentrations permissible according to Russian regulations are localized in the vicinity of places of sinking of nuclear objects. The highest concentrations of ^{137}Cs will be detected in sea water during the initial stages (up to 20 days after the accident) at the distances up to 10 – 20 km from the source. Concentration of ^{137}Cs within this sea area can reach 0.1 – 10 of the permissible concentration. Concentration of the radionuclide will decrease in these regions within one – two months as the result of its diffusion and will become comparable to the background after three months.

The developed models and software solutions make contribution in the development of understanding about the safety of sunken objects, because modeling can be regarded as the method for preventing emergency situations and for estimation of their consequences for the marine systems. The developed computer codes allow obtaining prompt assessment of the degree of hazard of the object and only after that making decisions on the necessity or impracticality of attraction of additional computer, financial or human resources for subsequent detailed study of the risks. The above mentioned mathematical models and software complexes can be extended

on any offshore based objects creating threat of development of emergency situations.

Conclusions

Taking into account the increased demand in LPNPPs for the purposes of development of remote regions, the above mentioned financial and technological advantages of these energy plants, as well as minimum possible environmental consequences in case of hypothetical accidents qualitative change of attitude towards the use of such energy plants can be expected. For optimistic scenario of development of nuclear power technologies (see Table 1) up to 26 reactor units will be in operation in the Arctic by 2030 including icebreakers NSG, floating and land based power plants. The number of transportable and operable reactor cores will amount to several dozens. Such scale of use of nuclear power is possible only under the condition of accelerated development of the associated infrastructure, including that pertaining to ensuring safety and protection of personnel, population and environment in cases of deviations from normal operational modes of radiation-hazardous objects and penetration of radioactive materials in Arctic sea areas. In support of importance of the topic under discussion let us notice that the “General provisions on ensuring safety of sea vessels and other floating craft equipped with nuclear reactors” (NP-022-17) approved during the period of preparation of the present paper makes provisions, as pertains to the measures for ensuring safety (Level 5 Anti-accident planning), for the implementation of realistic (non-conservative) analysis of beyond design-basis accidents containing estimations of probabilities for accident propagation paths and consequences for preparing emergency response plans (Ristekhnadzor Order of 09.04.2017).

Creation of the system of types and performance characteristics of nuclear power units used or planned to be used in the Arctic, technologies for handling these units, as well as quantitative estimation of environmental impacts in case of potential emergency situations lead to the conclusion on the necessity of LPNPPs development based on the implementation of modular principle in their design providing for the possibility to develop units with different power capacities due to the possibility to select configurations with power units of the same type.

The research was funded from the grant of the Russian Science Foundation (Project no. 17-19-01674).

References

- Approaches for assessing the economic competitiveness of small and medium sized reactors (2013) Vienna: Intern. Atomic Energy Agency, 271 pp.
- Compact Nuclear Batteries for Arctic are to be Constructed for Ministry of Defense by 2023 (2018) Available at: <http://tass.ru/armiya-i-opk/4508435> [Accessed Feb. 7, 2018]. [In Russian]

- Ibrayev RA, Khabeyev RN, Ushakov KV (2012) Eddy-resolving 1/10° Model of the World Ocean. *Izvestiya Rossiyskoy akademii nauk. Fizika atmosfery i okeana*, 48(1): 45–55. [In Russian]
- JSC “Afrikantov OKBM” [2018] Reactor Facilities for Nuclear Icebreakers and Optimized Floating Blocks. Available at: http://www.okbm.nnov.ru/images/pdf/ritm-200_extended_ru_web.pdf [Accessed Feb. 7, 2018] [In Russian]
- Kashka MM, Smirnov AA, Golovinsky SA, Vorobyev VM, Ryzhkov AV, Babich YeM (2016) The prospects for development of nuclear-powered icebreaker fleet. *Arctic: ecology and economy* 3(23): 98–107. [In Russian]
- Kudinovich IV (2016) Nuclear Power Facilities of the Prospective Objects of Civilian Marine Machinery and Justification of Their Safety. Dr. Tech. Sci. diss. St. Petersburg. Krylov State Research Centre Publ., 292 pp. [In Russian]
- Kuznetsov VP, Demin VF, Makarov VI, Molchanov AS, Solonyuk VA, Shmelev VM (2014) Aspects of Liability Insurance of Nuclear Risks from the Low-power Nuclear power plants. *Izvestiya Rossiyskoy akademii nauk. Energetika*, 2: 88–95. [In Russian]
- Low-Power Nuclear Power Plants – A New Line in the Development of Power Systems (2015) Vol. 2. Ed. by Acad. RAN A.A. Sarkisov. Moscow. Akadem-Print Publ., 387 pp. [In Russian]
- Nikitin VS, Polovinkin VN, Simonov YuA, Ustinov VS, Kuznetsov VP, Makarov VI (2015) Nuclear Energy in the Arctic Region. *Arctic: ecology and economy*, 4(20): 86–95. [In Russian]
- Possibilities for Employment of Low-power NPPs for providing Power Supply to Civilian Customers (2016) Results of the Scientific and Technical Board of the Unified Energy System and the Section on the Problems of Reliability and Safety of Large Energy Systems of the Scientific Council of the Russian Academy of Sciences on Electric Power Systems Research. *Vesti v Elektroenergetike*, 6(86): 33–44. [In Russian]
- Reistad Ole, Ilgaard Povl L (2006) Russian Nuclear Power Plants for Marine. NKS-138 (ISBN 87-7893-200-9), 92 pp.
- Rostekhnadzor Order of 09.04.2017 No. 351. Available at: <https://rg.ru/2017/09/29/rostekhnadzor-prikaz351-site-dok.html> [Accessed Feb. 7, 2018]. [In Russian]
- Ruksha VV, Golovinsky SA, Belkin MS (2016) Icebreaker support for the largest national Arctic hydrocarbon projects. *Arctic: ecology and economy*, 4(24): 109–113. [In Russian]
- Sarkisov AA (2011) Introductory Paper of the Chairman of the Conference Scientific Committee. *Low-Power Nuclear Power Plants - A New Line in the Development of Power Systems*. Moscow. Nauka Publ., 1: 7–12. [In Russian]
- Sarkisov AA, Antipov SV, Bilashenko VP, Vysotskiy VL, Ilyushchenko GE, Kalantarov VYe, Kobrinsky MN, Smolentsev DO, Sotnikov VA, Khokhlov IN, Shvedov PA (2018) Mathematical Model for Evaluating the Technical Condition and Predicting Collapse of Protective Barriers on Flooded Radiation-Hazardous Sites. *Atomnaya Energiya [Atomic Energy]*, 124(2): 99–104. <https://doi.org/10.1007/s10512-018-0385-6> [In Russian]
- Sarkisov AA, Smolentsev DO, Antipov SV, Bilashenko VP, Shvedov PA (2018a) Economic Efficiency and Possibilities of Using Megawatt-class Nuclear Power Sources in the Arctic. *Arctic: ecology and economy*, 1(29): 4–14. [In Russian]
- Sarkisov AA, Vysotskiy VL, Sivintsev YuV, Nikitin VS (2015) Nuclear Legacy of the Cold War at the Arctic Seabed. *Radiological and Technico-Economical Issues of the Sea Radiological Remediation*. Moscow. IBRAE RAS Publ., 699 pp. [In Russian]
- Sivintsev YuV, Vakulovsky SM, Vasilyev AP, Vysotskiy VL, Gubin AT, Danilyan VA, Kobzev VI, Kryshev II, Lavkovskiy SA, Mazokin VA, Nikitin AI, Petrov OI, Pologikh BG, Skorik YuI (2005) Technogenic Radionuclides in the Seas Surrounding Russia. *Radioecological Consequences of Radioactive Waste Dumping in the Arctic and Far Eastern Seas (“The White Book-2000”)*. Moscow. IzdAT Publ., 624 pp. [In Russian]
- Small Modular Reactors: Nuclear Energy Market Potential for Near-Term Development (2016) [S.I.]: OECD. [NEA No. 7213]
- Smolentsev DO (2012) Development of the Arctic energy sector: problems and capabilities of low-power generation. *Arctic: ecology and economy*, 3(7): 22–29. [In Russian]
- The History of Nuclear Power of the Soviet Union and Russia: A Collection of Articles (2004) iss. 1–5, iss. 5: *History of Low-Power Nuclear Power Plants*. Ed. by V.A. Sidorenko. Ros. Nauch. Tsentr “Kurchatovsky Institut”. Moscow. IzdAT Publ., 168 pp. [In Russian]