Scientific-Technical and Economic Aspects For Development Of Innovative Reactor Plants For Small And Medium Nuclear Power Plants

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Abstract. The scientific, engineering and production capability that has been developed in our country in the field of nuclear shipbuilding is of exceptional value. In nuclear shipbuilding technologies, a special concept of a modular reactor plant has been formed, which is characterized by an extremely small footprint required to accommodate a steam generating plant in a limited space of the reactor compartment, enhanced reliability and survivability. Based on the experience in creating and improving marine and naval reactor plants, JSC “Afrikantov OKBM” has developed a number of designs of innovative reactor plants for small- and medium-sized nuclear energy sources. The paper describes the basic scientific, technical and economic aspects of developing such innovative reactor facilities as ABV, KLT, RITM and VBER.

1. Introduction
Small and medium nuclear reactors and NPPs powered by them (SNPPs and MNPPs) attract close attention growing worldwide as an advanced class of energy sources to effectively handle challenging power supply issues.

As a rule, the reduced unit capacity in nuclear power is accompanied by increased specific capital expenses; therefore, the engineering solutions reducing dependence on the scale factor shall be implemented in the reactor plant and power unit designs. In this connection, in most of the designs, the designers take new innovative decisions on the layout, systems, equipment, arrangement, control automation, etc.

Innovative solutions implemented within the frame of proven marine reactor technologies are considered as the most advanced trend ensuring acceptable economic performance and minimized costs for development of small and medium NPPs. Marine reactor technologies are considered as one of the main achievements of the Russian nuclear industry. More than 460 transportable facilities with a total operating experience of ~10,500 reactor-years have been designed based on the designs developed by JSC “Afrikantov OKBM”.

2. Small-sized nuclear reactors
Based on the experience in creating and improving marine and naval reactor plants, JSC “Afrikantov OKBM” has developed a number of designs of reactor plants for autonomous small- and medium-sized nuclear energy sources in the range of 6 to 55 MW(e): ABV-6E, KLT-40S, RITM-200N and
RITM-200M [1]. The main characteristics of the above-mentioned reactor plants are given in Table 1.

The small-sized energy sources imply that a nuclear power facility can be land-based and arranged on a non-self-propelled floating craft.

The design of the small ABV-6E reactor plant incorporates an integral water-water reactor with thermal capacity of 38 MW with coolant natural circulation and an integrated pressure compensation system. The design specific features include operation without refueling during 10 years, passive safety systems and modular design of the power unit ensuring minimum construction time. Two-unit NPP with ABV-6E reactor plants provides the capacity of 2x8.5 MW(e) when operating in the condensation mode and the capacity of up to 2x6 MW(e) generating heat of up to 2x12 Gkal/h when operating in the heat mode.

Table 1. Characteristics of Reactor Plants for SNPP

| Technical Characteristics       | KLT-40S | RITM-200N | RITM-200M | ABV-6E |
|--------------------------------|---------|-----------|-----------|--------|
| 1. Type of steam generating unit (SGU) | Modular | Integral |           |        |
| 2. Rated thermal power, MW, at least | 2x150   | 2x165     | 2x175     | 1x38   |
| 3. Electric power, MW           | 2x38.5  | 2x52      | 2x50      | 1x9    |
| 4. Refueling interval, years    | 2-3     | 6         | 10        | 10-12  |
| 5. Reactor core stored energy, TW-h | from 2.1 to 3.1 | up to 8 | up to 10 | 2.25   |
| 6. Enrichment in $^{235}\text{U}$, % | not more than 20 |        |           |        |
| 7. Number of FAs in the core, pcs | 121     | 199       | 241       | 121    |
| 8. Circulation type             | Forced   | Natural   |           |        |

The design key feature is that an integral RITM-200N reactor plant is used. Its prototype, designed for the multi-purpose nuclear icebreakers (UAL), is reactor RITM-200 which has the necessary analytical and experimental justification and which is manufactured in series. This reactor plant has been selected for SNPPs based on the operating properties which are inherent for the marine reactor technology and important for SNPPs: small footprint, high load follow capacity and small quantity of liquid radioactive waste.

The analysis of an SNPP competitiveness powered by two RITM-200N in comparison with different power sources generating similar power (hydrocarbon fuel, solar and wind power, tidal power) has shown that to enter the market of SNPPs confidently, the target LCOE (Levelized Cost of Electricity) not higher than $90/MW h (5,400 rubles/MW h) at the discount rate of 7% shall be ensured.

Floating nuclear power plants constitute a powerful factor of stability in the development of the regions not covered by the unified energy system. The next trend in development of this business area is the optimized floating power unit (OFPU) design powered by RITM-200M reactor (its prototype is RITM-200 for UAL) with a high stored energy core which meets international requirements for non-proliferation of nuclear materials. In 2020, the development of documentation on the OFPU preliminary design will be completed.

3. Medium-sized reactors

The VBER modular reactor developed by JSC “Afrikantov OKBM” and NRC “Kurchatov Institute” is one of the most elaborated medium-sized reactors to be implemented in the nearest future. Its concept is based on a combination of technologies: nuclear propulsion steam supply facilities and proven solutions in civil nuclear industry concerning the core and fuel cycle [1, 3].

The design distinctive feature consists in the use of a unified heat exchange loop which is a technological platform aimed at implementing the power range of power units (see Figure 1). The power range of VBER 600–450–300 MW(e) is provided based on the standard four-looped option of VBER-600 reactor and application of a unified heat exchange loop.
The process of developing new reactor plants for small and medium NPPs comes along with developing and implementing innovative engineering solutions and approaches aimed at enhancing technical and economic performance and safety of the station. Let us consider some of them.

4. Reactor Plant Layout

Selecting the layout solutions is of particular importance, since the layout scheme of reactor plants determines much in the safety approaches and features, construction solutions, operating conditions and, ultimately, in economic indicators.

Three types of reactor layout schemes have been identified: looped, modular and integral layouts (see Figure 2). These schemes are acceptable for all types of reactors. The best possible choice in each individual case is defined based on various factors; therefore, it is impossible to talk about common recommendations.

The looped reactor plants are characterized by significant spatial distribution and primary circuit large volume, large diameter pipelines connecting the main equipment: steam generators, pumps, heat exchangers, pressurizers, etc. For this scheme a serious problem is the organization of protection in case of large-break loss-of-coolant accident (LBLOCA). Most of the operating NPPs use VVER and PWR facilities with looped diagram. The same diagram was applied in the OK-150 reactor of the nuclear icebreaker Lenin.

Loop (SG + MCP + vessel) - Factory fabricated module

Four-looped reactor
N=600 MW(e)

Three-looped reactor
N=450 MW(e)

Two-looped reactor
N=300 MW(e)

Figure 1. VBER Reactor Power Range

Looped layout OK-150 Reactor

Modular layout KLT-40S Reactor

Integral layout of RITM-200 Reactor

Figure 2. Types of Reactor Layout
The obvious advantage of the integrated layout (ABV-6E, RITM-200N, RITM-200M) is the localization of the first circuit coolant in one volume (in the vessel), the absence of nozzles and pipelines of large diameter, which reduces the probability of a large-break loss-of-coolant accidents.

On the other hand, in the integrated layout it is difficult to access the equipment located in the reactor, which limits or complicates the repair service. Therefore, the integrated layout requires the use of highly reliable equipment, which is based on solutions proven in operation and has passed a representative life test under the laboratory conditions.

The modular layout (KLT-40S, VBER) occupies essentially intermediate position between loop and integrated circuits. Instead of long pipelines of the primary circuit there are short pipes of large diameter connecting the main equipment of the unit (reactor, steam generator and pumps).

Comparison of weight and size characteristics of KLT-40S and RITM-200 steam-generating units is given in Table 2.

| Technical Characteristics       | KLT-40S | RITM-200 |
|---------------------------------|--------|---------|
| 1. Type of steam generating unit (SGU) | Modular | Integral |
| 2. Height, m                    | 7.5    | 11.6    |
| 3. Length, m                    | 6.1    | 4.5     |
| 4. Width, m                     | 5.1    | 3.4     |
| 5. Dry weight of SGU, t          | 211    | 245     |

The unit layout reduces the unit height and makes it accessible for repair activities. Absence of large-diameter piping in the integral and modular layouts excludes the large-break loss-of-coolant accidents and reduces the possibility of a severe accident. For example, in the modular VBER reactor plant there is no core dryout, heatup and depressurization of fuel rod cladding under maximum design-basis accident (MDBA) conditions which occur in VVER reactor plants. At the 10th second of MDBA in the looped VVER of Novovoronezh NPP-2, the reactor is almost completely dried out and the temperature of the claddings of the most heat-stressed fuel rods reaches 1,050 °C.

5. Fuel improvement

The design of a fuel assembly intended for the VBER-600 core has been developed based on the design of TVSA fuel assembly and its modifications intended for the VVER-1000 reactor plant cores. The VBER-600 fuel assembly design incorporates the technical decisions and structural elements proven by operating experience of such fuel assemblies as: TVSA, TVSA-12, TVSA-PLUS, TVSA-ALPHA and TVSA-5M.

The given design provides fuel assembly geometrical stability and, accordingly, stability of the core thermophysical and neutronic characteristics, and also excludes jamming of CPS absorber rods in guide thimbles that, in its turn, ensures core reliability and safety during operation.

To substantiate the operability of the VBER-600 fuel assembly design and to confirm its concept, the results of a set of pre-irradiation tests have been used, including strength, vibration, thermal and hydraulic tests performed using TVSA fragments and full-scale mockups in the test facilities of JSC “Afrikantov OKBM” and JSC MSZ.

Feasibility of the TVSA design, its resistance to deformation is confirmed by the successful operational experience obtained at the Kalinin NPP, NPPs of Ukraine and Bulgaria.

The design of VBER reactor plant excludes the risk of vapor-zirconium reaction in the scenario of maximum design-basis accident and, accordingly, the necessity of applying materials not inclined to vapor-water reaction (tolerant fuel) in the reactor core. The given quality of the VBER reactor plants considerably increases their technical and economic attractiveness and, taking into account the predicted duration of R&D on the tolerant fuel (10 years), determines their implementation possibility in the nearest future.

The experience and operation results of the reactor cores being part of the operating nuclear icebreakers is widely used in the process of SNPP reactor core development (ABV-6E, KLT-40S,
RITM-200N and RITM-200M). During the last twenty years, their high level of reliability, radiation and environmental safety and economic efficiency have been achieved and confirmed, including:
- not any core failure within the assigned lifetime have been detected;
- the exposure doses on the personnel have been reduced by two-orders-of-magnitude as compared to the previous period;
- the state of all cores at the moment of termination of operation does not exceed the "gas leakage" level;
- based on the operating data of 20 reactor cores (accommodating ~250,000 fuel rods), "zero fault level" has been most nearly provided;

These parameters have been achieved under the conditions of rigid load follow modes of nuclear icebreakers, significantly different from the modes of VBER fuel operation, which determines the specific features of the design and manufacturing technology of fuel rods for propulsion plants.

The activities related to the reactor cores are aimed at increasing the stored energy up to 8.0–10 TW h, improving the fuel composition and materials used in fuel rod claddings, the inventory of fuel rods in the core - fuel rods, disperse burnable absorbers, absorber rods and safety rods accompanied by the necessary set of R&D activities, and verification and certification of neutronic analysis codes and thermal-hydraulic codes.

6. Development of innovative passive safety systems
The research work of passive safety systems is aimed at:
- ensuring a high level of SNPP nuclear safety of under accident conditions with blackout, including LOCA and a severe accident;
- ensuring operation without limitations on the duration of operation and without the need for personnel intervention;
- eliminating a severe LOCA accident accompanied by blackout of at least 72 hours (Fukushima scenario) without control activities and external energy sources;
- performing both emergency and normal operation functions, simplifying the structure and composition of safety systems;
- ensuring high fail-safety of passive systems due to independence and redundancy of equipment operation.

Taken as a whole, at present none of the existing systems used in nuclear power engineering has such properties.

Provided that such a system is developed, it will impart to reactor facilities the properties of increased safety and the capability to "actually exclude" severe accidents

7. Increase in the reactor lifetime
At present, the design lifetime of the operating reactor plants installed on nuclear icebreakers is 30 years. Increased service life of non-replaceable equipment up to 40 years and more up to 60 years, with corresponding increase of replaced equipment service life, contributes to significant improvement of SNPP economic performance.

Nowadays, based on the operating experience of the nuclear icebreakers, there is every reason for this:

- Reactor vessel: Achieved service life: 33 years; operating time: 182,000 h at the fluence of 4.5x10\(^{20}\) neutrons/cm\(^2\).
- Steam generator: Achieved service life: 33 years; operating time: 177,000 hours.
- Primary Circuit Circulation Pump (PCCP): Achieved service life: 33 years; operating time: 185,470 hours.
- Control rod drives: 33 years, operating time: 182,000 hours.

At present, JSC "Afrikantov OKBM" is carrying out R&D activities to substantiate the increase of the specified lifetime characteristics of the main equipment of an SNPP with RITM-200 reactor provided that the reactor plant lifetime is 60 years.
The technology of numerical experiment (instead of a physical experiment) based on digital twins of equipment is applied for validation. Lifetime characteristics of equipment are justified so that their application in individual designs of various SNPPs will not require changes to be introduced in the basic conceptual, constructive and layout decisions.

8. Development of a Digital Twin of a Nuclear Propulsion System

Development of advanced small- and medium-sized reactor plants demands a new approach to the design analytical validation, introduction of modern means of digitization, complex systems of computer designing, the design analysis and production process substantiation and preparation. For this purpose, JSC “Afrikantov OKBM” has developed the technology of creating a supercomputer digital twin of a nuclear propulsion system for various purposes. The supercomputer digital twin of a nuclear propulsion system can be used at all stages of the product life cycle and contributes to:

- Improving the quality and safety of newly developed designs;
- Reducing the number of expensive tests;
- Shortening the timeline and cost of design development of new facilities.

9. Training of personnel and scientific cooperation with higher educational institutions

JSC “Afrikantov OKBM” closely cooperates with Nizhny Novgorod State Technical University n.a. R.E. Alekseev (NNSTU). This cooperation started in 1961 when the Physics and Technology Faculty (PTF) was established in Gorky Polytechnic Institute on the initiative of I.I. Afrikantov, OKBM’s founder, Head and Chief Designer, with the support of Academician A.P. Alexandrov and Academician A.I. Leipunskiy. In 1962, the faculty began its first academic year, three specialized departments were formed in order to organize the educational process. The joint scientific research activities performed by OKBM and NSTU formed the basis for establishing and developing scientific schools and creative teams capable of performing research work at the state-of-the-art level. Improvement of the training of specialists in engineering and scientific qualification is one of the central tasks, which is currently aimed at mutually beneficial cooperation between OKBM and NSTU in the area of education, science and innovations. Under the conditions of the dynamically developing market of reactor technologies, such cooperation enables continuous and prompt improvement of design solutions taking into account changes in the market situation and customer requirements.

10. Conclusion

The marine pressurized water reactors developed by JSC “Afrikantov OKBM” along with power reactors of VBER-PWR type are regarded as the most mature reactor technology confirmed by successful operating experience. The design of innovative reactor facilities for small and medium nuclear power sources such as ABV, KLT, RITM, VBER, implements a unique scientific, technical and production potential of nuclear marine technologies aimed at solving critical issues of nuclear industry related to developing small and medium nuclear power sources and floating power units with short implementation timeline and attractive technical and economic indicators. The developed capacity range of facilities contributes to developing nuclear power plants on the basis of unified designs to meet the expected regional and export needs.
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