Research on the versatility of Arctic marine nuclear power plant

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Abstract. Research on the versatility of nuclear power plants can increase the utilization rate of nuclear power plants and reduce the development cycle and cost. By comparing the power requirements of Russian nuclear power icebreakers, polar transport ships, and floating nuclear power plants, and combining the development status of Russian marine reactor devices and steam turbine generator sets, the analysis shows that marine nuclear power plants can be based on low (38tMW), the three-level benchmark reactor devices of medium (175tMW) and high (350tMW) and the two-level benchmark steam turbine power plants of low (6~8 eMW) and medium (35-40 eMW) are designed for multi-scheme combination.

Keywords: Arctic marine, nuclear power plant, versatility

1. Introduction
The development of a new generation of marine nuclear power plant is an important way to safeguard Russia's energy security in the Arctic region by protecting Russia's geopolitical interests in the Arctic region and solving the core factors of industrial, economic and social sustainable development in Russia's Siberia and the Far East[1]. At present, the Russian civil nuclear power plant is mainly used in three aspects:

Nuclear-powered icebreaker, used to ensure the Arctic routes throughout the year transit cargo transport, Yamal and other oil and gas resources development. Among them, nuclear-powered icebreakers are divided into three categories: pilot or general-purpose ice-breakers. With the expiration of the service life of the reactor unit, the active nuclear-powered ice-breakers will gradually retire and only the "50th Anniversary of Victory "will continue to operate by 2025[2]. The general-purpose nuclear-powered ice-breaker (Project 22220), which is currently under construction, can operate both on Arctic routes and in shallow waters of the Arctic coastal shelf and at the mouth of the Siberian River; one is a multi-purpose nuclear-powered ice-breaker (Project 10570) with shallow draft water, designed to work in shallow water areas along the Russian Arctic Mainland shelf, including providing ice-zone safety and operational technical support for drilling platforms, oil and gas production facilities; One is that the leader-class icebreaker ensures annual navigation throughout the north-east Arctic route and stays ahead of the high-latitude pilotage period for large-tonnage carriers, securing the supply of fossil energy from the Yamal Peninsula oil fields to countries in the Asia-Pacific region[3].

The high power density of the nuclear power plant in the polar nuclear-powered transport
vessel can provide the Arctic transport vessel with sufficient ice breaking shaft power, unlimited endurance, high speed navigation of open water, and no discharge of harmful substances, which is particularly important to protect the polar environment and meet the requirements of polar regulations. Experience in the operation of Sevmorput light nuclear-powered container ships has confirmed the considerable economic benefits of Arctic nuclear-powered carriers. By comparing transport costs of nuclear-powered container ships from Europe to Asia via the North-East Arctic route and ordinary container ships via the Suez Canal, nuclear-powered container ships have a greater competitive advantage, taking into account environmental pollution control costs. At present, the prerequisite for the wide application of nuclear-powered merchant ships is that all countries reach a consensus on the regulations governing the design, construction and operation of nuclear-powered ships, in particular by determining the regulations governing the operation and maintenance of nuclear-powered ships in ports.

Floating nuclear power plant, mobile, miniaturized nuclear power plant is an important means to solve the energy supply in remote areas of the Arctic, and mobile small nuclear power plant decommissioning will not leave radioactive material in the application site, conducive to the protection of the Arctic fragile environment. Currently, the KLT-40S reactor "Academician Romonosov" floating nuclear power plant (20870 project) has docked in the port of Perwick (Pevek), and as part of the Chawonsk-Bibibinsk region energy center. Through a comprehensive study of the energy demand of the ports and cities along the north-eastern Arctic route, it is found that the demand for 6-12 MW floating nuclear power plants in the Arctic and Far East marine coasts, such as the northern Yakut, Murmansk, Kamchaga, Magadan region, Tamil, Chukchi and the Autonomous Region of Koryak, is much greater than that of 70 floating nuclear power plants similar to MW 20870 project. Because the marine nuclear power facilities are built in small quantities or even only one, it is of special significance to ensure the versatility of the main supporting equipment of all kinds of nuclear power marine engineering facilities in the design of nuclear power plants. It can reduce the development cost and shorten the development cycle.

2. Power requirements analysis for marine reactors
With the expansion of the task of nuclear-powered ice-breaking fleet, new technical requirements for nuclear-powered ice-breaking ships are put forward:

1) Increase the width of the pilot icebreaker to escort large carriers;
2) Increase ice breaking shaft power to ensure greater ice breaking capacity;
3) Increase propulsion power to ensure higher escort speed;
4) Extend the service life of nuclear power plant to improve economic efficiency;
5) Strengthen the plasticity of modular combination between main equipment to reduce development cost and shorten R & D cycle.

The main requirements of the new generation of marine nuclear power plants compared with the existing ones are to extend the service life of the equipment and improve the reliability of the equipment: the ≥ of the main equipment is 320,000 hours; the ≥ of the replaceable equipment is 160,000 hours; the service life is 40 years; and the interval between the refuelling of nuclear fuel ≥7 years.

The operation experience of marine nuclear power plant shows that the OK-900 reactor with rated thermal power of 171 MW can be used in both double and single reactor ice breakers, and can also be used in "Sevmorput" container ships with rated thermal power of 135 MW. Therefore, a reference reactor unit can be established for various marine engineering facilities through an analysis of the power required for the various types of marine engineering facilities, combined with the impact on the number of reactors in marine engineering facilities, the efficiency of nuclear power plants, the acceptable steam reserve allowance on the variation (increase and decrease) of the thermal power of the reactor, which can be optimized to suit a wider range of applications.

Though Lenin's icebreaker had three OK-150 reactors with 90 MW single reactor power, Two of
these reactors operate at about 80% power. To ensure the full force of the icebreaker, the third reactor is in standby. The installation of three reactors is due to a lack of experience in operating the reactors on ice-breaking ships. The reliability of its fault-free operation can not be evaluated. in 1959-1966. The icebreaker Lenin sailed six times. The actual operation shows that the reactor has sufficient reliability. After the main equipment of the OK-150 reactor unit has run out of service life, To modernize Lenin’s icebreaker, Two OK-900 new reactor units with 159 MWt thermal power are installed on them.[15-16]. Subsequently, two reactor units were installed on pilot nuclear-powered icebreakers, one reactor unit was installed on shallow nuclear-powered icebreakers and one reactor unit was installed on the light nuclear-powered container ship Sevmorput’. The development experience of civil nuclear power vessels shows that no more than two reactors are installed on civil nuclear power vessels.

The thermal power of the reactor should be determined taking into account both the efficiency of the nuclear power plant and the steam reserve allowance. Both pilot and universal ice breakers carry two reactor units and adopt a "steam-condensation" circulation scheme. One reactor unit can provide steam to all main turbine generators and other users of the secondary circuit system. Two reactor units can also operate jointly at different power levels. In principle, the scheme can "flexibly" utilize the energy reserve of the reactor core and make full use of the steam output of each reactor, but the steam reserve allowance is usually set to 15% in actual operation.[17]. In icebreakers, polar carriers and floating nuclear power plants carrying a single reactor unit, the steam load of the nuclear power plant (each series, including the reactor unit and the secondary circuit system operating independently) does not change significantly, and the steam reserve allowance is assumed to be 3 per cent when estimating the thermal power of the reactor.[18].

Based on the analysis of the power requirements for nuclear-powered icebreakers, polar carriers and floating nuclear power plants, combined with the impact of the number of reactors, the efficiency of nuclear power plants and the steam reserve allowance on the thermal power of the reactors, the requirements for reactor power for various marine engineering facilities are shown in Table 1[19].

Table 1 Power characteristics of nuclear power ice breakers, transport vessels and floating nuclear power plant reactor installations

| Application object         | Power requirements, MW | Efficiency | Number of reactors | Steam reserve allowance, % | reactor thermal power, MWt |
|----------------------------|------------------------|------------|--------------------|-----------------------------|-----------------------------|
| Universal Icebreaker       | 60-70                  | 0.2        | 2                  | 15                          | 173–202                     |
|                            |                        |            | 1                  | 309–361                     |
| Leader icebreaker          | 110-130                | 0.2        | 2                  | 15                          | 315–374                     |
|                            |                        |            |                    | 3                           | 283–335                     |
| Shallow draft icebreaker   | 30–40                  | 0.2        | 2                  | 1                          | 155–206                     |
| Arctic Icebreaker          | 30-50                  | 0.24       | 1                  | 3                           | 129-215                     |
| Floating nuclear power plant | 60^a, 60^b+57^t        | 0.24       | 2                  | 3                           | 129                         |
| Floating nuclear power plant | 6^c, 10^d, 12^d, 28^t | 0.24       | 1                  | 3                           | 26                          |
|                            |                        |            | 1                  | 43                          |
|                            |                        |            | 2                  | 40                          |

Note: a means electric power, t means thermal power

On the basis of the data analysis in Table 1, it is concluded that for the possible application scenarios of nuclear power plants in the field of marine engineering, the power of the reference reactor can be divided into three levels: 40 MW (low power), 175 MW (medium power) and 350 MW (high power):

1) Reactor devices with thermal power of 25~45 MW can be developed on low power basis and used in single-stack floating nuclear power plants with 6~10 MW and double-stack floating nuclear power plants with 12~20 MW.
2) Reactor units with thermal power of 130–215 MW can be developed on a medium power basis and used for propulsion of 30–40 MW single reactor icebreaker and transport ship, propulsion of 50–70 MW double reactor icebreaker and floating nuclear power plant with power of 30–70 MW.

3) Reactor devices with a thermal power of 220–360 MW can be developed on a high power benchmark and used for single-heap icebreakers and transport vessels with a propulsion power of 50–70 MW and two-heap leader-class icebreakers with a propulsion power 100–130 MW.

3. Marine integrated reactor units
The integrated reactor unit has great application prospect in the field of marine engineering. Its advantages are that it increases the irradiation life of the reactor pressure vessel, reduces the weight and size of the reactor equipment in the containment vessel, reduces its own energy consumption demand and improves the natural circulation capacity to ensure the safety of the whole reactor unit.[20]

The following reactors developed by the Mechanical Manufacturing and Design Agency of the Russian "Afrikantov" may be considered as reference reactor installations for marine engineering facilities (see Table 2 for technical parameters):

1) Thermal power about 40 MW integrated reactor plant ABV-6M, suitable for 6–10 MW of single-stack floating nuclear power plant and 12–20 MW of double-stack floating nuclear power plant;

2) RITM-200, MW compact reactor units with thermal power of about 150–175MW Suitable for single pile icebreaker and transport ship with propulsion power of 30–40 MW, double pile icebreaker and polar transport ship with propulsion power of 50–70MW, and floating nuclear power plant with power 30–70MW. RITM-200 reactor units such as nuclear-powered icebreakers with typical feedwater temperatures of 105°C, rated thermal power up to 175 MW; For floating nuclear plants with a typical feedwater temperature of 170°C, Heat rating reduced to 150 MW;

3) The RITM-400 reactor unit with a thermal power of about 300-350 MW can be used for single-heap icebreakers with 50–70 MW propulsion power, polar transport ships and two-heap leader-class icebreakers with 110–130 MW propulsion power.

The technical parameters of the above reactor units are shown in Table 2.[16]

| Table 2 Technical parameters for nuclear reactors (RITM-200, RITM-400, ABV-6M) |
|---------------------------------|-------------------------------|--------------------|-------------------|
| Heap power, tMW                | RITM-200                      | RITM-400           | ABV-6M            |
| Steam, t/h                     | 175                           | 315                | 38                |
| Steam parameters               |                               |                    |                   |
| Temperature, ºC                | 295                           | 295                | 295               |
| Pressure, MPa                  | 3.82                          | 3.83               | 3.82              |
| ºC feed water temperature      | 105                           | 105                | 105               |
| Primary circuit Pressure, MPa  | 15.7                          | 15.7               | 15.7              |
| Entrance, outlet temperature, ºC| 276/314                      | 281/318            | 288/313           |
| Quantity and power of main coolant pump, kW | 4×98                          | 6×128              | —                 |
| Reactor unit weight, t in containment | 1100                          | 1920              | 950               |
| Holistic dimensions, m of containment | 6×6×15.5                    | 9×8.2×17           | 5×5×13            |

4. Marine Turbine Generator
The analysis of the parameters of the secondary loop system shows that it is recommended that the main turbogenerator with a power of about 40 MW be installed on nuclear-powered ships. It can be used both on ice-breaking ships with electric propulsion and renewable preheaters (feed water temperature is about 105°C), and on floating nuclear power plants with good heat recovery capacity (feed water temperature is about 170°C) and as part of the propulsion turbine of polar transport ship owners.
JSC "Kirov Energomash" developed dual-cylinder PTU72 main turbine generator, installed on a general-purpose nuclear-powered icebreaker (Project 22220) with two main turbine generators. And plan to install leader-class icebreaker (10510 project) (carrying two main turbine generator sets) on. JSC "KTZ" K-35-3.4 main turbine generator set developed for the floating nuclear power station (20870 project) of Academician Romonosov[14].

The steam pressure at the outlet of the steam generator of the RITM-200 and RITM-400 reactor units is 3.8 MPa, higher than that of the previous nuclear power plant 3.4. The increase of the steam pressure at the inlet of the main steam turbine leads to the need to take measures to reduce the erosion and wear of the turbine blade. To ensure the service life of the blade. The PTU72 type main steam turbine generator is provided with a steam separator after the high pressure cylinder, K-35-3.4 is a built-in steam separator[21]. The technical parameters of PTU72 type and K-35-3.4 type main turbine generator set are shown in Table 3.

| Technical indicators | K-35-3.4 | PTU72 |
|----------------------|----------|-------|
| rated power, eMW     | 35       | 35    |
| Steam inlet parameters: |         |       |
| - Pressure, MPa       | 3.4      | 3.4   |
| - Temperature, °C     | 285      | 285   |
| Nominal pressure for main condenser, kPa | 6       | 7.6   |
| External cooling water consumption, for main condenser m³/h | 5400   | 6000  |
| Overall turbine size (length × width × height), m | 7.4×9.1×8.9 | 8.5×5.1×11.0 |

The main turbogenerator with a power of 6 MW, voltage of 6.3 kV or 10.5 kV can be used in floating nuclear power plants with low power or as auxiliary turbine generators on nuclear ships.

5. Conclusion
By comparing the power requirements of nuclear-powered icebreakers, polar carriers and floating nuclear power plants, and combining with the development trend of nuclear power plants for Arctic ships, the following conclusions can be drawn:

1) The general reactor can be divided into three levels: low power (38 MW)-ABV-6E, medium power (175 MW)-RITM-200, high power (350 MW)-RITM-400;

2) Two levels of reference turbogenerator: low power turbogenerator (6~8 MW), medium power turbogenerator (35~40 MW).

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