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Conceptual design and technical requirements analysis of nuclear-powered icebreaker

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Abstract. As the Arctic's strategic position has become increasingly prominent, China's existing icebreaker fleet has been unable to meet the growing demand for polar affairs such as polar scientific research, Arctic shipping, and polar emergency. From the perspective of route planning, the marine environmental conditions faced by nuclear-powered icebreakers have been sorted out. The research status of domestic nuclear power plant, the selection and design of nuclear power propulsion plant and the main technical requirements were put forward. Finally, the overall plan design was carried out from the aspects of general layout, main dimensions, shaft power, etc., and the main technical requirements for hull design were put forward.

1. Introduction

The north and south poles have important strategic value, especially in recent years, with the global warming, the accelerated melting of sea ice, the rich resources of the polar region and the valuable Arctic waterway make the Arctic region become the hot spot of global geopolitical economy, while the Arctic competition characterized by accelerating the competition for seabed resources and controlling ocean space is becoming increasingly fierce.

Combined with the main activities of countries in the Arctic region, the main needs of polar vessels are divided into four categories: the first is polar engineering vessels, such as drilling, fishing, transportation and security, for the purpose of exploration and development of polar resources; the second is trans-Arctic transit transport vessels; the third is scientific research and research vessels at the north and south poles; and the fourth is polar tourism vessels, polar rescue and military support vessels.

Because of the problems of high technical difficulty, high cost and difficult construction and maintenance, polar ships need to be comprehensively evaluated when designing and constructing polar ships. However, according to statistics, new polar ships in various countries are developing towards comprehensive function, diverse and efficient ice breaking, strong adaptability, scale and power [1].

As a near-Arctic country, China enjoys the rights of scientific research, navigation, fishing, resource exploration and exploitation in the high seas of the Arctic Ocean in accordance with international treaties and general international law. Therefore, China's activities in the Arctic region will rely mainly on international cooperation in resource exploitation, waterway development, Arctic scientific research, polar tourism and polar rescue [2].

However, as an active participant in the development of Arctic resources, China has only two conventional polar ice-breaking ships, the most advanced of which is the Snow Dragon 2, which is far from the Russian and American ice-breaking ships, and can not meet the increasing requirements of polar activities such as polar scientific research, Arctic shipping and polar emergency, and China's polar ship design and construction capabilities and technical equipment are still lagging behind in the world [3-4] has severely restricted the development and implementation of China's Arctic strategy and the Silk Road on Ice.

In order to improve China's ability to open up waterways, develop and utilize resources, travel between the two poles and provide comprehensive supplies in the polar region, China urgently needs to design and build an integrated support ship with strong ice breaking capacity, comprehensive, large-scale, long-term continuation, energy saving and environmental protection, and safety and reliability.

Because of its strong ice breaking capability, lasting endurance and meeting the requirements of polar fragile environmental protection, nuclear-powered ice-breaking ships will be an important technical support equipment to guarantee polar commercial shipping, meet the development and utilization of resources, and support polar military activities.

The marine environment condition of nuclear-powered ice-breaker is combed from the angle of route planning, and the general layout, main scale and shaft power are designed according to the type selection of nuclear-powered propulsion device.

2. Analysis of expected routes and environmental conditions

2.1. Expected route

According to the 2008 U.S. Geological Survey survey on the distribution of Arctic oil and gas resources, Russia's Barents Sea and Kara Sea play an important role in the Arctic oil and gas[5]. The projected destinations of nuclear-powered icebreakers are the Barents Sea, Kara Sea and the Arctic Science Station in Russia.

Nuclear-powered icebreakers mainly sail on northeast routes. And the northeast route also includes the coastal route, the intermediate route, the transit route and the pole-piercing route[6]As shown in Figure 1.

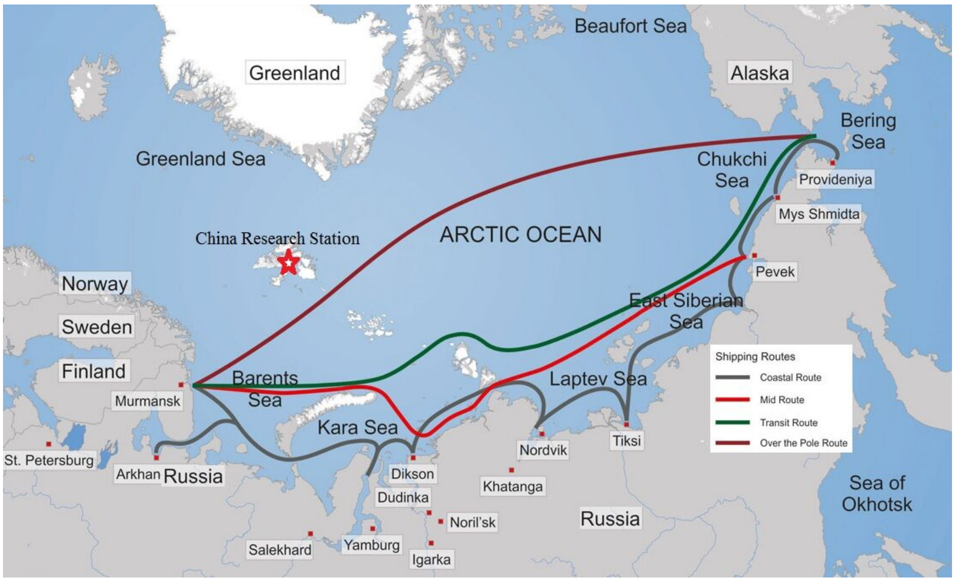


Figure 1. Northeast Arctic Route

For the above four northeast routes, the route of nuclear-powered ice-breaker is initially determined as the northeast transit route, for the following reasons:

1. Transit routes are shorter and shorter than coastal and intermediate routes;

2. There are many shoals and shallow water depth along the Russian coast, and the transit route can avoid the restriction of draught on the coastal route and the intermediate route;

3. Compared with coastal routes and intermediate routes, transit routes can provide margin for the later development of Arctic sea resources;

4. The requirement of ice breaking capacity in transit route is lower than that in polar route, and the nuclear-powered icebreaker is mainly aimed at the guarantee of polar resource development, so it is not necessary to cross the pole;

5. Nuclear-powered icebreaker away from land navigation, can reduce the impact of the public;

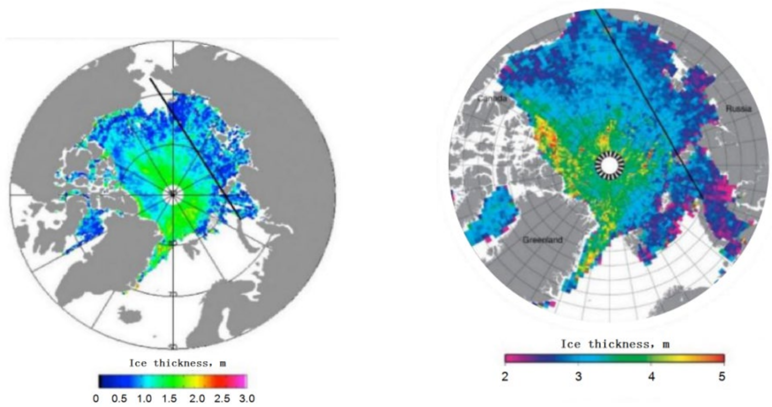
6. Transit routes can weaken the Russian government's regulation of the transit of nuclear-powered icebreakers.

The main transit routes include: Shanghai-Japan Sea-Okhotsk Sea-Bering Strait-Chukchi Sea-Drand Strait-East Berlia Sea-North Siberian Islands-North side of the Barents Sea-Norway Sea-Rotterdam.

2.2. Environmental conditions of transit routes

2.2.1. Ice thickness. At present, the northeast route generally has a navigation period of 2~ and 3 months in summer, so the nuclear power icebreaker mainly considers the ice breaking capacity in autumn and winter, so as to ensure polar commercial shipping, resource development in winter, rescue and material transportation.

Based on observations of Arctic ice thickness by the European Space Agency CryoSat satellite in October or November, January or February 2011 [7] the ice thickness of the northeast transit route is about 1.25 in autumn m, 3 in winter m, as shown in Figures 3.



(a) (b)

Figure 2. Arctic ice thickness observation data in October or November (a).and January or February (b)

As a result, the maximum ice breaking thickness of a nuclear-powered icebreaker should be about 3 m. in winter crossing the northeast transit route

2.2.2. Temperature. The temperature reached the lowest in January ~ March in the northeast route, and the lowest temperature appeared in East Siberia. The average temperature in January near New Island was -15℃, and the temperature component in East Siberia decreased. The minimum temperature can reach -40℃~-50℃. The average winter temperature of the Balen branch sea and the east-west Liaxia in the northeast route is shown in Table 1.

Table 1. Summer and winter average temperatures in the main sea areas of the Northeast route

Sea Area	Barents Sea,℃	East Siberia ,℃
Winter (January)	-25(North); -5(South)	-32
Summer (July)	0(North); 10(South)	0(North); 6(South)

2.2.3. Water depth. The average water depth of the main sea area of the northeast route is shown in Table 2.

Table 2. The average water depth of the main sea areas of the Northeast route

Sea Area	Average water depth, m	Sea Area	Average water depth, m
Bering Strait	40	West Portia	45
Chukchi Sea	88	Barents Sea	229
Dron Strait	36		

3. Nuclear propulsion systems and key technical requirements

The ship takes LK-60Ya as the reference mother type, LK-60Ya continuous ice breaking capacity at 2 kn speed is 2.8 m, its axle power requirement is

60MW, main turbine generator set power is 36 MW ×2, reactor thermal power is 175 MW ×2.

The maximum ice breaking thickness of a nuclear-powered icebreaker is 3 m, and the tentative shaft power requirement is about 70 MW, Referring to the proportional relationship between the LK-60Ya shaft power and the reactor thermal power 17.14%, the reactor thermal power requirement of the ship is about 204 MW×2.

3.1. Selection of Nuclear Power Plant and Main Technical Requirements

The civil marine nuclear energy industry in China is still in its infancy. At present, the main reactor type is China Shipbuilding heavy Industry HHP25, China Nuclear ACP100S, China-Guangzhou Nuclear ACPR50S [8] as shown in Table 3.

ACPR50S thermal power is close to the requirement of 204 MW ×2 for the thermal power of nuclear-powered ice-breaking reactors, taking into account the impact and vibration environment unique to ice-breaking ships while sailing in the ice zone, the compact reactor greatly reduces the length of the main pipe, reduces the possibility of the main pipe rupture accident, and ACPR50S uses non-dynamic technology to further improve the inherent safety of the reactor.

Table 3. Comparison of parameters of domestic small-scale offshore reactors under research

Reactor reactor type	HHP25	ACP100S	ACPR50S
Reactor	Decentralized	Compact	Compact
Reactor thermal power/ MW	100×2	310×2	200×2
Steam flow/ t $\cdot h^{-1}$× units	80.4×2	470×2	297×2
A system pressure/ MPa	14.0	15.0	15.5
Case size range/ m	17.4×10.0×14.0	φ15×18 per cent	13 m×10.0×15
Electricity/ MW	25×2	125×2	60×2

ACPR50S meet the power demand of nuclear power ice-breaking ship and meet the needs of the integrated application and development of marine nuclear power plant in China, ACPR50S is chosen as the research and development reactor of nuclear power ice-breaking support ship.

Combined with the operation experience of the Russian nuclear-powered ice-breaker power plant, the following requirements are put forward for the nuclear power plant:

1. Reducing the weight and size of nuclear power plants;
2. Reducing the power density and energy consumption in the reactor active zone and increasing the energy reserve in the active zone;
3. Improve device reliability, life, radiation safety and efficiency;
4. It has stronger mobility to adapt to the rapid and drastic change of ice breaking load during ice breaking ship operation;
5. Minimum reactor plant maintenance shutdown frequency and minimum shutdown duration;
6. By improving the initial parameters of steam, reducing the condensing pressure, using electric frequency conversion drive and other means to improve the thermal efficiency of steam turbine;
7. Improve the generality of power plant and reduce the development cost and cycle.

3.2. Type Selection of Propeller

Icebreaker can be divided into direct propulsion and electric propulsion according to the mode of propulsion, in which electric propulsion can be divided into motor-shaft propeller propulsion, full rotary propulsion and pod propulsion according to the different storage position of motor.

Russian pilot and waterway ice-breaking ships are driven by "speed regulating motor + pitch paddle ", in which Sevmorput nuclear-powered ice-breaking container ships use direct propulsion [9] However, according to the statistics of various types of icebreaker propulsion devices, the thrusters of icebreakers, especially scientific icebreakers, are more inclined to use electric pod propulsion [10].

For various propulsion devices, comparative analysis is carried out from the aspects of feasibility, propulsion efficiency, power application range, layout space requirements, operability, economy and so on, as shown in Table 4.

By contrast, the following conclusions are drawn:

1. "Motor-axis propeller propulsion" in the propulsion efficiency, operational, layout space requirements are better than "direct propulsion ";

2. The function definition of nuclear-powered ice-breaker is "waterway opening, resource development and utilization, bipolar tourism and comprehensive supply guarantee ", which is different from polar scientific research ship and does not need special high maneuverability and maneuverability. Therefore, from the economic point of view ," motor-axle propulsion" is more suitable for nuclear-powered ice-breaker;

3. 90% nuclear-powered ice-breaking ships adopt the form of "motor-shaft propeller propulsion ", all of which are arranged with three oars.

Therefore, the nuclear-powered ice-breaker adopts the form of motor-axle propeller propulsion and three-paddle propulsion.

Table 4. Comparison of icebreaker propulsion devices

	Direct promotion	Electric propulsion	
		Motor - propeller propulsion	Pod propulsion
Feasibility	Mature applications in nuclear-powered ships	90% of nuclear-powered ice-breaking ship using this form of propulsion	Widely used in ice-breaking ships, mainly used in polar science, oil slick cleaning, ice recharge, port security
Typical application cases	Nuclear submarines, Northern Route	LK-60, Temer	Snow Dragon 2
Power scope	Uniaxial output power ≤67 MW	Uniaxial output power ≤40 MW	Uniaxial output power ≤25 MW
Advance System Efficiency	—	Higher than nuclear direct propulsion	Higher than motor and propeller propulsion
Space requirements	High requirements for steam turbine and shafting installation, large space occupied	Flexible motor arrangement can shorten shafting and save space	Save drive shaft, gear box, rudder, save a lot of space, improve engine room layout
Operational	not suitable for complex working conditions of ships	good speed regulation performance	good speed regulation performance, reversing, steering, braking and other aspects of more flexible maneuver
Economy	Simple configuration, good economy	Increase in generator, propulsion motor, elimination of gearbox, cost input	The cost of podded thrusters is high and the cost of operation and maintenance is about twice as high as that of motor-shaft propeller propulsion
Additional features	No additional functions	No additional functions	It is helpful to realize the function of ship dynamic positioning and bidirectional ice breaking

The technical requirements are put forward for the electric propulsion device of nuclear icebreaker:

1. To meet the requirements of the following requirements of ice load on ice-breaking ships;

2. Improve the reliability of propulsion device, adjust performance and load tracking capability in harsh environment;

3. Reduce the weight, size, noise and vibration of the propulsion unit;

4. Optimize the maintenance and operation process of the propulsion device, reduce the operation hazard and the frequency of human intervention;

5. Optimize propeller and improve propulsion efficiency.

4. Overall Scheme and Technical Requirements for Hull

4.1. General layout and scale

Because the nuclear-powered ice-breaker uses a power propulsion system, there is no need for the power plant to be adjacent to the propeller shafting. Therefore, there are two types of horizontal arrangement and two longitudinal arrangement (at the same time, the two main steam turbines are at the front and rear end of the reactor). The stack layout is shown in Fig 3.

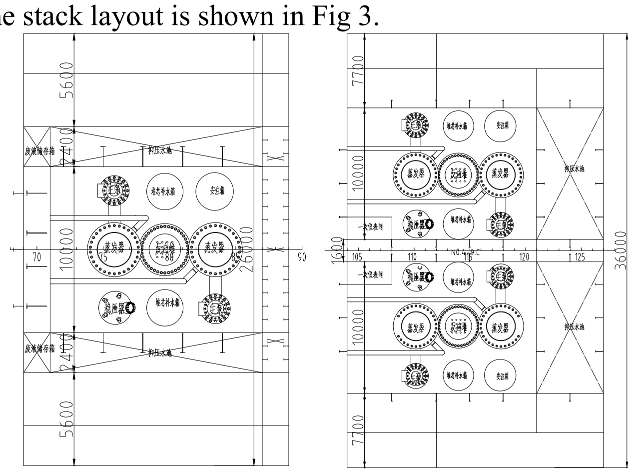


Figure 3. Schematic diagram of the layout of the two piles of longitudinal and transverse containment areas

Requirements for nuclear ship codes [11] the two schemes are required to meet the protection of the B/5 area on the side of the containment vessel. Based on the size of the ACPR50S reactor, the width direction of the containment vessel is 11 m.

The width of the ship is 26 considering the pressure suppression pool and side cabin protection on both sides m, but the longitudinal arrangement of the reactor and steam turbine in this scheme leads to a length of about 182 m. between the water lines

Two piles of transverse arrangement, and considering the isolation of the middle area of the two containment 1.6 m, the width of the two containment is 23.6 m, the width of the ship is 36 m to meet the protection requirements of the containment side compartment. Combined with the overall layout requirements, the water line length of the scheme is about 165 m. The two piles are shown in Fig.4.

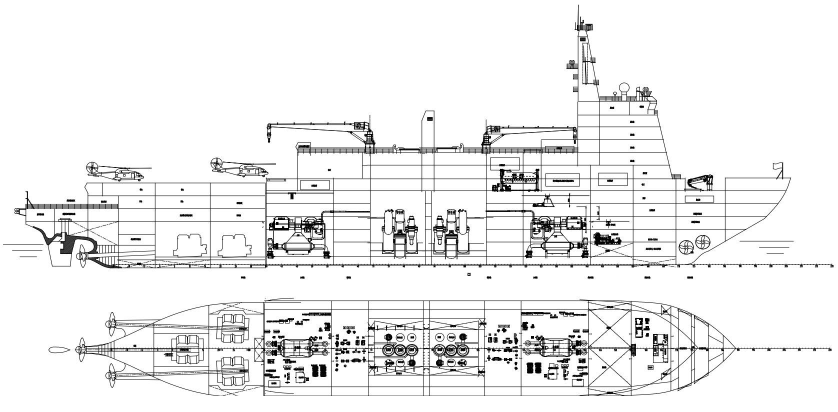


Figure 4. Sketch of the longitudinal layout of the two piles

The width ratio of pilot ice breakers is about 4.53~4.85, the square coefficient is about 0.52~0.56, the specific power (maximum power / displacement of propulsion system) is 1.82~2.04, while the vast majority of ice breakers range from 4.5 to 5.5.

At present, the aspect ratio of the two piles longitudinal arrangement scheme is 7, and the aspect ratio of the transverse arrangement scheme is 4.58. It is also considered that :(1) as a pilot icebreaker, a wider ship width is needed to open up the channel ;(2) the horizontal arrangement of the two piles is more favorable to the arrangement of the same equipment and the utilization of public resources.Therefore, the horizontal arrangement of the two piles is beneficial to the overall scheme and performance.

On the basis of the square coefficient and the average specific power (0.54 square coefficient and 1.93 kW /t specific power) of the Russian pilot nuclear-powered ice-breaker, the displacement △ is about 36269 t, the draft T is about 11.03 m.

Therefore, the nuclear power integrated support ship adopts two piles of transverse arrangement, the width of the ship is about 36 m, the length of the water line is about 165 m, the draught is 11.03 m, and the displacement is about 36269 t.

4.2. Power estimation of ice breaking axis

The Lewis formula, the Edwards formula and the Lewis&Edwards formula are selected to estimate the resistance of the icebreaker scheme. Through comparison, the estimated value of ice breaking resistance of Edwards formula is the largest. Considering the conservatism of the design scheme, the Edwards formula is adopted to estimate the resistance of ice breaking ship.

1976, Edwards, etc [12] By analyzing the real scale data of the Louis S.St.Laurent, the following formulas for estimating the resistance of ice-breaker are obtained:

$$R = \rho_w * g * B * h^2 * (4.24 + 0.05 * \frac{\sigma}{\rho_w \cdot g \cdot h} + 8.9\,\mathrm{Fn}) \tag{1}$$

Formula: R is ice resistance; h is ice thickness; ρ_w is the density of sea water ; g gravity acceleration; B the width of the ship; Fn is the frost - thick Fourier number; $Fn = v / (\mathrm{gh})^{0.5}$; σ is the bending strength of ice; ρ_w =1025 kg / m^3 , σ =1100 kPa, Fn= 0.2325, v =3 kn.

The ice breaking power of the ship when breaking 3.0 m ice thickness at 2 kn speed is 26 MW. respectively

After a series of power transfer, the axle power of ice-breaking ship is finally used for ice-breaking ship. There is a certain efficiency coefficient between the axle power of ice-breaking ship and the resistance power of ice-breaking ship.Compared with the typical ice breaking axle power and ice breaking resistance power at home and abroad, the efficiency coefficient is obtained as the basis for estimating the axle power $\eta = 22/60 = 0.37$ Using the above estimation method, The ice breaking power LK-60YA breaking 2.8 m ice thickness at 2 MW, speed is 22 60 MW, shaft power So the propulsion efficiency is about, Based on the efficiency of LK-60YA, Estimated total propulsion shaft power about 70.27 MW, At the same time, considering the sea condition margin of 5%, the total ice breaking propulsion shaft power of the ship is about 73.78 MW.

4.3. Main technical requirements for hull

According to the study of the design data of Xuelong 2 and nuclear-powered ice-breaker, the hull design of nuclear-powered ice-breaker should follow the following requirements:

1. In order to obtain better navigation capacity and efficient ice removal efficiency, the external inclination angle, the waterline angle and the first column angle and the longitudinal profile angle should be increased;

2. The tail shape should be beneficial to improve the ice breaking ability, propulsion efficiency and protect the propulsion device;

3. In order to meet the requirements of rapidity and stability of open water navigation, to meet the requirements of ice breaking performance and ice zone maneuverability;

4. Minimize radioactive areas and facilitate operation and maintenance management;

5. Ensure watertight and fire separation between spare equipment for vital nuclear power plant systems;

6. To evaluate the impact of collision, reef contact and helicopter crash on hull structure;

7. To strengthen the protection of radioactive areas and reduce the damage to nuclear power plants caused by collision, grounding and flying objects;

8. The cab shall have a clear view of all directions and a connection passage with the nuclear plant control room.

5. Conclusion

1. China urgently needs to design and build a nuclear-powered ice-breaking ship with strong ice-breaking capacity, comprehensive, large-scale, long-term continuation, energy conservation and environmental protection, and safety and reliability;

2. Based on ACPR50S and motor-shaft propeller, the nuclear power propulsion device is designed;

3. Overall technical specifications: Lwater =165 m, B = 36 m, T= 11.03 m, Δ= 36269t, P= 73.78 MW, reactor power 215 MW×2.

Nuclear icebreaker is an organic combination of ship engineering and nuclear energy engineering. It is a multi-functional polar integrated support ship with ice-breaker as carrier, carrying nuclear power plant and polar research support equipment, taking into account the functions of escort, rescue, supply, tourism, power supply and water supply technology.

Although China has broken through the relevant key technologies and accumulated a certain technical basis in the design and construction of Xuelong 2 icebreaker and nuclear-powered ship, there are still some key technologies to be studied and broken, especially the overall design of ship and power plant, the integration of nuclear power plant and ice breaking safety, the study of high efficiency of steam conversion system, the study of ice breaking adaptability and reliability of nuclear power propulsion system, and the fast large load tracking ability of nuclear power plant under ice breaking condition; Under the condition of polar fragile environment, nuclear safety and emergency response mechanism need to be deeply studied to lay a technical foundation for the design and construction of nuclear power ice-breaking ships in China.

Acknowledgments

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