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Development Strategy for Polar Equipment in China

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Abstract: Polar regions are currently becoming strategically important. Exploitation of polar resources has become the focus of the international community. Polar equipment guarantees that humans can scientifically understand and sustainably exploit the polar resources. This equipment primarily includes equipment for scientific observation, navigation, and oil and gas exploitation in the polar regions. This study first summarizes the development of polar equipment in various countries and the development status and problems of polar equipment in China. Subsequently, it analyzes the development trend and key technologies of polar equipment. China does not possess sufficient scientific polar equipment, and its under-ice observation capacity is not substantial. China also lacks the capacity for building polar vessels as well as research and design capacities of equipment for polar-resource development. To promote the development of polar equipment by 2035, China should promote Arctic environment observation, communication, and navigation technologies, achieve breakthroughs in key technologies with respect to polar vessels, and develop key equipment for polar-resource exploration to support commercial development of polar summer routes in the second half of the 21st century.

Keywords: polar equipment; scientific observation, communications, and navigation in polar regions; polar vessels; oil- and gas-resource exploitation in the polar regions; key technologies

1 Introduction

In recent years, following the continuous progress in science and technology, global warming, and accelerated melting of sea ice [1], oil, gas, and navigation resources in the polar region have gradually become valuable for exploitation, and economic, military, and political strategic positions have been highlighted, which have become the focus of countries around the world. In particular, the United States, Russia, Europe, and other near-Arctic countries and regions are actively employing polar equipment to enhance polar scientific research, commercial shipping, and resource-development capabilities to effectively safeguard future resource-development activities in the polar regions.

Polar regions are strategically important to China. In 2018, the *White Paper on China's Arctic Policy*, issued by the State Council, stated that China is an important stakeholder in Arctic affairs and is a geopolitical near-Arctic country. The natural conditions in the Arctic and its changes directly affect China's climate system and ecological environment, which subsequently directly affect China's economic interests in the fields of agriculture, forestry, fisheries, and oceans. Polar region is a key area for China to become a maritime power. China's active participation in the development of polar regions and development of polar equipment and technology is crucial to the establishment of an effective and efficient marine power. Thus, establishing an effective global governance model is important.

Polar equipment refers to the equipment used in carrying out scientific research, commercial navigation, oil- and gas-resource development, and tourism in polar regions. Leisure activities using this equipment are an

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important vehicle in the understanding, development, and use of polar regions. Currently, international polar equipment is mainly divided into polar-science, polar-ship, and polar-resource-development equipment. The present study investigates the development of polar equipment in major countries and regions in the world under the three categories. These categories are equipment for polar scientific observation and communication navigation, polar ship, and polar oil and gas-resource development. We need to sort out the development status and problems of polar equipment in China, summarize the future development trend of polar equipment and key technologies, focus on the analysis of the urgency of the demand for polar equipment and technology in China, and provide a demonstration for key development direction of polar equipment for 2035. The key development direction of polar equipment for 2035 must be supported.

2 Development trend of international polar-equipment technology

2.1 Development status of global polar scientific equipment

Polar scientific equipment refers to the equipment required to carry out relevant scientific research in polar regions. This equipment is an important vehicle for understanding the polar regions, which mainly include scientific research vessels, scientific observation, and communication and navigation equipment for polar regions.

In terms of polar research vessels, the United States, Russia, the European Union, and other countries and regions with advantages in polar science all maintain a certain number of polar research vessels. Among them, the United States has four heavy and medium-sized polar icebreakers, and three new heavy icebreakers are proposed to be built to cover the entire polar circle. The European Union currently has nine polar research vessels with icebreaking capability [2]. Russia has two polar research vessels. Japan, Canada, and South Korea have one polar research vessel each.

With regards to polar observation, communication, and navigation equipment, the polar region is a high-latitude ocean covered by sea ice, in contrast to the other oceans in the world. Sea ice blocks the transmission of radio signals; thus, achieving positioning and communication for underwater instruments is difficult, e.g., the submarine collision incident in the Arctic Ocean. In addition, high latitudes provide little communication and navigation satellite coverage, which pose a challenge to communication and navigation in polar regions. Over the years, international research in the field of marine-science observation has achieved great progress, but the development of observation, communication, and navigation in the polar region remains relatively lagging. Many technologies that are commonly used in other seas are not available in the polar region, and overcoming the influence of sea ice and high latitude has become the key to progress in the polar-region development. Therefore, in recent years, networks for polar under-ice observation, navigation, and communication have become the focus of polar-equipment development.

In the polar region under an ice-observation network, the United States, based on years of accumulation, has begun to develop a dual-use Arctic mobile observation system, which will become a key platform for leading Arctic observation and surveillance capabilities in the future. In 2012, the U.S. Department of Defense Advanced Research Projects Agency launched the “Polar Situational Awareness” project, which focuses on the development technologies for under-ice and surface situational awareness. Under-ice awareness uses underwater sensors, which are used in combination with structure, depth, and other measurements, to analyze the acoustic propagation, noise, and non-acoustic characteristics of under-ice environment in the deployment area. The ice-surface sensing uses ice floats in combination with computer networks, big data, and other new technologies to analyze the electromagnetic and optical phenomena in the deployment area [3]. In 2019, the United States began to build the Arctic Mobile Observing System, which focuses on the development of acoustic detection, positioning, and communication technologies, as well as relay technologies for ice-based acoustic and satellite communications to support the activities of under-ice instruments and submarines and to achieve detection capability of enemy underwater ships and equipment. The system is strategically forward-looking and technologically advanced. Once deployed, the system will completely overcome the influence of Arctic ice and achieve systematic observation and real-time monitoring of the Arctic Ocean.

In the polar communication and navigation network, existing communication satellites suffer from the difficulty of covering the area above the 76°N latitude. Deploying a ground-communication system is difficult because of the ocean and sea ice. An iridium communication system can provide polar communication services, but the reliability is not high and the bandwidth is limited [4]. Currently, the United States and European countries and regions are actively developing polar satellite-communication technology. For example, Norway plans to launch two

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high-latitude orbiting communication satellites in 2022 to achieve a 24-h broadband communication in the region above the 65°N latitude [5]. In 2012, the Russian Space Agency started the development of the Integrated Arctic Monitoring System for environmental monitoring and communication in the Arctic region, and in 2017, it launched the first satellite. The system was completed and made operational in 2018 [3]. In terms of satellite positioning and navigation, Russia's GLONASS positioning system has the best coverage in the polar region, but the positioning accuracy in polar regions, especially the vertical motion, is low compared with that in other regions. The multi-satellite dual-frequency technology has good application prospects in reducing interference and improving the polar positioning accuracy [5].

2.2 Current situation of global polar ship equipment development

With the opening up of polar shipping lanes and development of polar resources, the demand for polar ships has been increasing, and polar ships have become an important support for countries to promote polar strategies. Polar ships refer to the ship used for commercial navigation, oil and gas development, tourism, and leisure activities in the polar regions. They mainly include icebreakers, transport ships, sightseeing ships, and fishing ships.

In terms of polar icebreakers, as of 2017, a total of 94 polar icebreakers (including those under construction) [6] existed where Russia (44), Canada (6), and the Nordic countries [Denmark, Finland, and Sweden (21)] have larger icebreakers. Russia has the largest icebreaker fleet in the world when the world's largest nuclear-powered icebreaker, namely, the Arctic, was commissioned in 2019 and will be officially delivered in October 2020. At least nine new icebreakers are expected to be completed by 2024 to maintain Russia's development potential in the polar regions [7]. Currently, almost 60% of the world's icebreakers are more than 20 years old and are in urgent need for renewal. The United States has only one heavy icebreaker built in the 1970s and has recently begun to build a fleet of polar safety icebreakers to protect its polar interests, including at least three heavy polar icebreakers.

In terms of polar transport ships, the Arctic sea ice area is decreasing every year. According to the current global warming trend, 82% of the Arctic sea is estimated to be ice-free in summer and will become suitable for conventional ships in 2045 [8]. The sailing time from East Asia to Europe will be reduced by 40% by then. The polar transport ships as of 2017 owned by various countries are listed in Table 1 [6]. In terms of the development trend in the Arctic shipping lanes, multipurpose ships, tankers, liquefied natural gas (LNG) vessels, and container ships will become the four major transport vessel types in polar waters in the future [9]. Polar multipurpose vessels are convenient, flexible, and efficient and can meet various cargo needs in the Arctic region. Therefore, at this stage, most countries use polar multipurpose ships to test the Arctic waterway [9]. With the development in the Arctic oil and gas resources, the demand for polar LNG vessels will also rapidly grow. Currently, 12 Russian Arc7 icebreaking LNG vessels are put into operation in the Arctic Yamal LNG project. The recent Arctic LNG project, i.e., Arctic LNG 2, is expected to order 15 Arc7 icebreaking LNG vessels, which will be delivered in 2023–2026. The LNG-powered vessel with 45 MW of power will be able to navigate on 2.1-m-thick ice above −52 °C. The vessels will be delivered in 2026.

2.3 Current situation of equipment development for global polar resources exploitation

The oil and gas reserves in the polar regions, especially in the Arctic, are abundant. According to the assessment report published by the United States Geological Survey [10,11], the unproven oil reserves in the Arctic region are 1.84×10^{11} t and 4.7×10^{15} m^3 of natural gas reserves, which account for approximately 13% and 30% of the world's unproven oil and natural gas resources, respectively. These resources are mainly distributed in seven major basins near the Arctic. Currently, many countries and oil companies put the development of Arctic oil and gas resources on their agenda and start research and development (R&D) of related equipment. However, the development of polar oil and gas resources is an extremely difficult project. The harsh wind, wave, current, ice climate, and complex permafrost geological conditions in the Arctic region present a great challenge to polar oil and gas development equipment. The world's major oil and gas development companies are investing more resources to develop new polar oil and gas development equipment that balances ice resistance and economic performance.

Table 1. Polar transport ships owned by various countries (as of 2017).

Vessel type	Owner nationality	Total dead weight tonnage	Average vessel age	Number of vessel
Multipurpose ships	Germany	3 397 955	11	356
	Netherlands	2 512 961	12	242
	Russia	720 079	23	76
	China	250 134	7	13
	Turkey	200 300	22	33
	Norway	177 485	15	27
	Canada	142 701	15	14
Tankers	Greece	7 416 062	12	96
	Russia	3 307 385	14	59
	Norway	1 003 759	13	8
	Germany	989 941	11	24
	Sweden	968 810	10	22
	Italy	923 981	7	25
	Denmark	864 000	10	20
LNG ships	Russia	178 279	1	2
	Greece	123 313	4	14
	Canada	510 000	1	6
	China	255 000	1	3
	Norway	96 740	8	1
	Netherlands	32 931	2	3

In 2012, the Russian Federation published the *Plan for Oil and Gas Development on the Continental Shelf until 2030*, which details the future development of oil and gas resources in the Arctic region [12]. The only polar offshore field in Russia is in the Prirazlomnoye field, located 60 km offshore from the Pechora Sea. This is developed on an ice-resistant reinforced concrete gravity platform that combines oil drilling, extraction, storage, handling, and offloading functions. The mass of the upper block is 2.9×10^4 t, and that of the concrete caisson is 9.7×10^4 t. This field is designed for 32 oil wells. Sixteen wells have already been operating at the end of 2018. The annual crude oil production is approximately 3.2×10^6 t. Russia has two other large onshore LNG fields in the Arctic: Yamal LNG and Arctic LNG 2. The former started operating in 2017 with an annual production capacity of 1.65×10^6 t, and 15 Arc7 icebreaking LNG vessels built by Daewoo Group of South Korea have been put into operation in which 14 are invested and operated by COSCO Shipping Energy Transportation Co. The latter field is expected to enter into production in 2023 and has ordered 15 Arc7 icebreaking LNG vessels from Russia's Red Star Shipyard.

In 2015, Polar Pioneer, an investment by Royal Dutch Shell and built by Swiss Transocean, was put into operation. The rig and manifold are made of low-temperature carbon steel, and the operating area is fully enclosed and actively heated to suit the Arctic drilling environment [13]. In response to the harsh climatic conditions in the Arctic, Technip FMC has developed a new concept of Arctic ice-resistant platform by combining the jack-up platform and concrete technology. The new concept of Arctic ice-resistant platform, which is developed by Technip FMC, combines jack-up platforms and concrete technology to enable year-round polar drilling operations [14]. Netherlands' Huisman has designed a semi-submersible platform for near-Arctic drilling. The platform is moored and can operate in water depths of up to 1500 m. The ice-resistant structure can withstand the impact of 2 m of ice, and it is capable of year-round operation in the near-Arctic region [13]. GustoMSC (Netherlands) has also launched the Nanuq Q5000 drillship, which can operate in the polar region for up to 120 days per year in the polar region under a maximum ice thickness of 4 m and operating depths of up to 1500 m [13]. At present, most of the polar oil and gas platforms are in the design stage, and a certain gap exists between them and the actual

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production and application.

In summary, with the support of their respective polar development strategies, the United States, Russia, Europe and other near-polar countries and regions have formed strong polar equipment strength. They have significant advantages in polar research, polar shipping, and oil and gas resources development. As the strategic status and commercial value of polar regions, especially the Arctic, become increasingly prominent, polar equipment and technology are being developed by all countries. Polar investigation, communication, icebreaking navigation, and resource development are all important to support future strategic and commercial activities in the Arctic.

3 Development status and problems of polar equipment in China

3.1 Current situation of polar equipment development

Polar region is a key area for China to become a strong maritime power. Polar equipment is also an important guarantee in the development, utilization, and protection of the pole. Currently, through continuous investment and layout optimization, we have established a polar work system and strengthened capacity building. Further, the polar research equipment support platform and system has been relatively perfect. After more than 30 years of accumulation, China has made great progress in the field of polar science and technology.

3.1.1 Breakthrough in R&D of polar scientific equipment

China has developed a number of advanced technologies and equipment, such as deep ice core drill for polar ice cap, ice shelf hot-water drill, under-ice geological drill, ice-cap observation robot, space weather monitoring system, atmospheric lidar, sea-ice–air unmanned ice station, and sky survey telescope, which have been successfully applied to the polar field. The BeiDou satellite navigation system has been applied to polar regions. In 2020, the “Xuelong 2” icebreaking research vessel, which was designed and built by China, was successfully put into service. The “Xuelong” and “Xuelong 2” icebreaking vessels have cooperated to complete the first “Double Dragon Exploration” in China, which provide the basic guarantee for China’s future polar scientific research.

3.1.2 Taking off of polar navigation and resource development equipment

In terms of polar navigation, icebreaker “Xuelong” has completed the exploration of the Northeast, Central, and Northwest Passage of the North Pole, and the reporting technology and accuracy have improved. Since the maiden voyage of “Yongsheng,” the summer Arctic voyage has become regular (Fig. 1). The design and construction technology of a polar icebreaker has been initially mastered by designing the “Xuelong 2” icebreaking research vessel.

Fig. 1. Ice class 3.6×10^4 t multipurpose ship “Tian You” sailing in the Arctic passage.

With regard to polar resource development, in 2016, China’s “Ocean Oil 720” exploration vessel completed a three-dimensional seismic exploration work in two areas in the Arctic Circle. After the implementation of the Belt and Road initiative, China has deeply participated in the first major polar energy project—the Yamal LNG project in the Arctic Circle. The Yamal LNG project promotes China’s polar cold-sea drilling rigs, wells, and related supporting technologies in the project and has undertaken construction of most of the project modules. In addition, COSCO Marine Energy Transportation Co., Ltd. has participated in the investment and operation of 14 icebreaking and four conventional LNG vessels. The four conventional LNG vessels are built by Hudong–Zhonghua Shipbuilding (Group) Co. Currently, the Yamal LNG project is continuously delivering clean energy to China through the Polar Silk Road in which 31 voyages of the LNG transport were completed in 2020 alone.

At present, China’s polar equipment development achieves some progress. However, compared with the United States, Russia, and other polar countries, a considerable gap remains. Therefore, China urgently needs to carry out strategic research on the development of polar equipment based on the international development trend, technology foresight, and national top-level design to create a clear strategic direction of development, put forward

relevant industrial development incentives, enhance polar development incentive policy, enhance comprehensive competitiveness of polar development, and protect its polar maritime rights and interests.

3.2 Problems facing the development of polar equipment

As a stakeholder in the Arctic, China's polar equipment can guarantee polar-area development. The development of related equipment is urgent. We should note that the development of polar equipment in China still suffers from a series of problems, e.g., strategic policies have not been developed, innovative research has not been carried out, and design and development is not systematic.

3.2.1 Insufficient polar science equipment and limited under-ice observation capability

At present, China only achieve breakthroughs in a few frontier fields such as the bottom structure of the Antarctic ice cap, Arctic ocean acidification, polar space environment, and a few other frontier fields. Furthermore, the technology reserve remains insufficient in the latest frontier areas such as Antarctic subglacial lake exploration. The development and application of major equipment such as autonomous underwater vehicles (AUVs) under polar ice and network observation in the Arctic ice region as well as the development and application of Arctic technology significantly lag. The lack of a real-time observation network for polar ocean elements restricts China's ability to observe, communicate, and navigate in the polar region. In addition, the research results of China's polar regions are relatively scattered, and supporting role for national demand is much lesser than that of the United States, Europe, and other countries and regions.

3.2.2 Seriously insufficient capacity building of polar ships

China started late in the research, design, and construction of polar ships. At present, only two ice breakers are available for ice breaking in Bohai Bay, namely, two "Xuelong" series polar research vessels, and few polar transport vessels (Fig. 2). In the Yamal LNG project in which China is deeply involved, all 15 icebreaking LNG vessels are built by South Korean shipyards, and Chinese shipyards only participate in the construction of four conventional LNG vessels. In addition, the Asia–Europe container shipping trade is an important part of the world container trade, and the freight volume involving China is more than 70%. Thus, China's future demand for Arctic container shipping is large. However, the capacity building of polar ships in China is seriously insufficient, and an urgent need is present to strengthen the technical reserve and capacity building of the whole chain of basic research, design, analysis, and construction of polar ships.

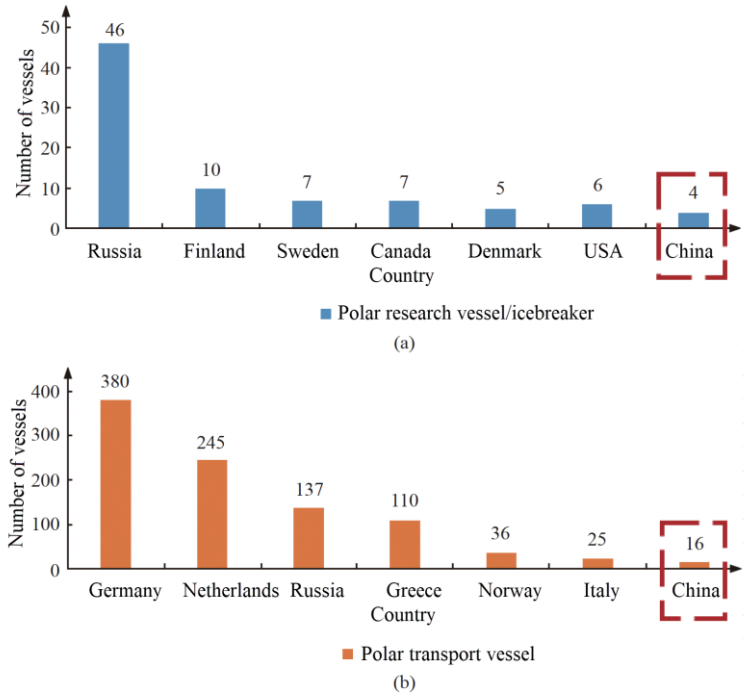

Fig. 2. Number of polar research vessel/ice breaker and polar transport vessel of major countries (as of 2017).

3.2.3 Lack of R&D and design capability for polar resource development equipment

At present, the world's major oil companies are investing more resources in R&D of new polar oil and gas

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development equipment to provide good technical reserves for future polar resource development. In recent years, China has made significant progress in R&D, design, and construction of marine resource development equipment. However, R&D on equipment for polar resource development remains basically in the gap, and construction of equipment is mainly assembled. Thus, establishing an entry point to carry out research and design of new-generation polar drilling equipment and technical research is urgent to establish the technical foundation for future polar resource development.

Looking forward, the demand for polar science, ships, and resource development equipment in China should be increasingly strengthened. National demand should be used as traction to promote polar equipment in R&D, design, construction, and operation of key technologies to achieve breakthroughs to create China's independent three-dimensional observation network, polar fleet, and polar oil and gas equipment and to improve China's polar observation, development, and utilization capabilities.

4 Development trend of polar equipment and key technology analysis

4.1 Development trend of polar equipment and demand

The value of the polar region in terms of resources, transportation, and geo-strategy has become increasingly prominent. Polar equipment is an important support for understanding, developing, and utilizing the polar region. At present, the United States, Russia and other countries are increasing their investment in polar equipment, including scientific, shipping, and resource-development equipment for polar applications. The development of polar equipment has exhibited some new trends.

4.1.1 Polar scientific observation, communication, and navigation equipment

Currently, polar observation, communication, and navigation capabilities are seriously insufficient with weak polar observation capabilities, poor accuracy in terms of communication and navigation, inadequate polar survey and research, and limited observation and research on polar climate change patterns. Countries, especially near-polar countries, have accelerated the technical layout of polar observation, communication, and navigation equipment The main trends include the following: (1) developing a new generation of icebreaking research vessels to improve the carrying capacity of polar research equipment; (2) developing polar satellite remote sensing, communication, and navigation systems to improve the ability to obtain large-scale polar sea-ice conditions and guarantee the accuracy and reliability of polar communication and navigation; and (3) building a polar environment observation system that integrates ice buoys, unmanned under-ice submersibles, under-ice gliders, and ice-based meteorological systems to explore the mechanism of environmental changes in the polar regions and provide data and technical support for polar navigation and polar marine resource development. We expect that by 2050, the United States, Russia, and other countries will have basically built a polar observation and communication system that integrates space satellites, surface research vessels, and polar environmental observation systems in the Arctic region.

4.1.2 Polar ship equipment

The opening of the Arctic shipping lanes can effectively reduce the cost of maritime operation and satisfy the demand for resource development. Currently, polar ships of major countries are generally older, and demand for polar ship renewal has peaked. Near-polar countries and regions such as the United States, Russia, and Europe have incorporated the construction of new-generation polar ships into their future polar development plans. The main trends include the following: (1) carrying out research on technology that guarantees polar navigation and anti-ice technology for polar environment to ensure safety of polar ship navigation; (2) planning and building polar heavy ice breakers to open up the Arctic shipping lanes, maintain, and further improve the polar activity capacity; and (3) developing polar multipurpose ships, carrying out first trial water navigation in the Arctic shipping lanes, and simultaneously developing and building polar LNG ships and oil tankers to provide support for future polar shipping and resource development activities. We expect that by 2035, the initial establishment of the Arctic waterway navigation, ice monitoring, and forecasting systems will be established and used for the construction and operation of polar multipurpose ships and LNG vessels, and by 2050, a commercial Arctic summer transport fleet will emerge.

4.1.3 Polar oil and gas resources development equipment

The Arctic region is rich in oil and gas resource reserves, and polar drilling equipment is the key operating equipment for polar oil and gas resource development. Meanwhile, the harsh climatic conditions and complex

geological conditions of the Arctic expose the development and utilization of polar marine resources to a great challenge. At present, most of the polar oil and gas platforms are still in the R&D stage, and a certain gap exists in terms of production application. Countries around the world are vigorously promoting the development of a new generation of polar drilling equipment, and the main development trends include the following: (1) development of key technologies for development, transportation, and processing of oil and gas resources under polar environmental conditions; (2) development of special equipment with anti-ice and anti-cold functions for polar exploration, drilling, and oil and gas resource extraction as well as technology and equipment for polar ice area oil-spill treatment for the development and utilization of polar oil and gas resources. We expect that by 2035, the equipment for polar oil and gas resource development in each country will be in initial operation in the Arctic region. By 2050, it will usher in large-scale commercial development and utilization of oil and gas resources in the Arctic region.

4.2 Analysis of key technology of China's polar equipment

The development of polar equipment depends on a number of key technology breakthroughs and progress. The urgent development of polar equipment key technologies are as follows: (1) polar satellite remote-sensing observation, communication and positioning, and high-volume data-transmission and processing technology; (2) ice area ocean observation and environmental monitoring technology, which can be subdivided into technologies related to acoustic communication-based under-ice positioning navigation network, real-time under-ice monitoring, polar, meteorology, navigation, and ice clearing; (3) technologies for ice-load forecasting for polar ships, intelligent winterization of ships, low-temperature material and coating, structural integrity management, new icebreaking for polar ships, emergency rescue for Arctic navigation, real-time monitoring system for polar ships, intelligent decision-making system for safe navigation, and comprehensive performance forecasting for polar ships; (4) technology related to laboratory physical-simulation of ice-ship interaction. A large ice-pool laboratory is necessary for polar heavy-equipment testing. The only domestic Tianjin University ice pool (mostly for Bohai Sea ice) still requires strengthening of the test technology research on the Arctic sea ice; and (5) new polar anti-ice exploration and drilling-platform design, polar low-temperature drilling technology, and fully enclosed anti-ice anti-low-temperature platform technology.

The development of polar equipment also depends on the materials, energy, and other common key technology breakthroughs with the following features: (1) suitable for polar development of materials, such as new low-temperature high-toughness materials (new metal and composite materials), low-temperature corrosion-resistant anti-ice coating materials, and low-temperature welding materials and technologies; and (2) green-energy sustainable supply technologies, such as those for high-density clean-energy utilization, automatic energy supply, low-temperature long-duration battery, miniaturized nuclear-energy utilization, and mixed-energy supply.

The breakthrough of the abovementioned technologies will effectively promote the development of China's polar equipment and provide a strong guarantee for protection of China's interests in the Arctic region. Table 2 lists a summary of the core polar equipment and technology in China urgently needed before 2035 and 2050. These can provide support for the follow-up polar equipment development based on the urgency of the demand.

5 Suggestions

Polar regions are strategically important, and China must significantly and actively participate in the development of polar regions. At present, China's polar observation and survey equipment is scarce and insufficient, and its undertaking in polar regions cannot meet the needs of polar development and protection. Therefore, developing polar marine environment observation, navigation, and resource exploration equipment and technology is urgently needed to improve the level of understanding of polar regions and guarantees sustainable development and utilization of polar regions. According to the current situation of China's polar development demand and development capacity, we propose strengthening the R&D of key equipment for polar marine environment observation and resource exploration for polar development in the future. We also propose to simultaneously carry out technology reserve and capacity building for polar navigation vessels to provide technical support for large-scale development of polar summer commercial routes in the second half of the 21st century.

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Table 2. Urgency of demand for polar equipment and technology in China.

Type	Technology/Core equipment	Name	Urgency of demand before 2035	Urgency of demand before 2025
Polar scientific equipment	Technology	Polar ocean observation and environmental monitoring technology	+++	+++
		Polar positioning technology	+++	+++
		Polar communication technology	+++	+++
	Core equipment	Icebreaking research vessels	+++	+++
		Ice buoys, unmanned under-ice submersibles and under-ice gliders	+++	+++
Polar shipping equipment	Technology	Ice-load forecasting technology for polar ships	+++	+++
		Intelligent winterization technology for ships, and low-temperature materials and coating technology	++	+++
		New icebreaking technology for polar ships	++	+++
		Emergency-rescue technology for Arctic navigation	++	+++
		Real-time monitoring system for polar ships and intelligent decision-making system for safe navigation	++	+++
	Core equipment	Polar heavy icebreakers	+	++
		Polar multipurpose ships	++	+++
		Polar LNG ships	+++	+++
		Polar cruise ships	+	+
Polar resource development equipment	Technology	Polar anti-ice exploration and drilling platform design	++	+++
		Polar low-temperature drilling technology	+	+++
		Fully enclosed anti-ice anti-low-temperature platform technology	+	+++
		“Ice model–equipment design and manufacturing–safe operation in ice–ice monitoring–ice warning” lifecycle supporting technologies	+++	+++
	Core equipment	Polar anti-ice exploration ship/platform	+	++
		Polar anti-ice drilling ship/platform	+	++

Note: “+++” represents high urgency; “+”represents medium urgency

5.1 Construction of Arctic environmental observation, communication, and navigation equipment

Because of the harsh climate conditions in the Arctic and the low coverage of communication and navigation networks, long-term observation data on the polar climate-change factors are very scarce, and the lack of observation capacity has restricted the Arctic scientific R&D and utilization. To improve the observation and forecasting capability in the polar environment, by taking advantage of the experience in the development of marine monitoring systems and combining the special characteristics of the complex dynamic environment in the polar region, we develop air-based, ice-based, and sea-based intelligent observation equipment, establish a green and intelligent air–sky–ice–underwater integrated polar monitoring network, and build a polar communication and navigation network for the polar regions. The project will provide support for scientific research, space utilization, resource development, and ecological protection in the polar regions.

5.1.1 Technology and equipment for space-based intelligent observation

This study focuses on the development of polar visible and microwave remote-sensing detection technologies, deep-learning inversion algorithms for hyperspectral signals, breakthroughs in airborne high-resolution ice radar detection technologies, and development of polar short-wave satellite communication equipment and AUV autopilot technologies. We also concentrate on long-term continuous monitoring of changes in the elevation, thickness, surface freezing and thawing as well as the drift trajectories of polar sea ice/sea water, ice cap, ice shelves, glaciers, icebergs, and ice floes. Finally, we establish polar air–sea–ice dynamic analysis models and accurate ice-forecasting methods.

5.1.2 Ice-based unmanned observation technology and observatory

We should focus on developing a polar intelligent meteorological observation technology, broadband seismic wave emission and recovery technology, and ice-cap electromagnetic observation system to analyze the climate change pattern, internal structure of ice caps, and geological structure characteristics of the polar region. We also should focus on breakthroughs in ice-based equipment, automatic energy-supply technology for under-ice equipment, and intelligent information-exchange technology, which centers on the Yellow River Research Station. Furthermore, we should arrange a number of unmanned observation stations in key areas in the Arctic to establish energy supply and communication networks in key areas in the polar region.

5.1.3 Polar communication technology and data sharing platform

The present research focuses on hydroacoustic communication and electromagnetic-wave communication-conversion technology to break the communication barriers of space-based, ice-based, and sea-based observation networks. We should develop a three-dimensional, green, and intelligent polar observation network that is space-based, ice-based and sea-based, creating a data-sharing platform for polar climate, ice cover, geology, and ocean environment conditions as well as a polar climate and ocean environment forecasting model based on observation data that provide data, technology, and equipment support for scientific research, channel opening, and resource exploration in polar regions.

5.2 Tackling the ship technology for polar navigation

By the second half of the 21st century, the Arctic may have ice-free commercial routes in summer because of global warming, and the demand for polar ships from various countries will continue to increase. At present, Russia, the European Union, the United States, and other near-polar countries and regions experience the most urgent demand for polar ships and possess absolute technical advantages over China in terms of polar icebreakers, multipurpose ships, and LNG ships. China suffers from the difficulty in catching up in the short term. Therefore, before the commercialization of the Arctic summer ice-free route, we recommend to rely on the domestic advantages in ship equipment construction technology and capacity, accumulate basic technology related to polar ship equipment, and carry out R&D of the key technologies to ensure Arctic shipping route and for polar large, green, and intelligent freight platform.

5.2.1 Key technologies for the protection of Arctic waterway routes

In the monitoring and forecasting technology for ice area navigation environment, we need to carry out research on the basic physical and engineering properties of polar sea ice, establish a refined numerical model of sea ice that is applicable to the engineering scale, and develop a sea ice element monitoring system based on real ship monitoring in the ice area. We also need to understand the mechanism of rapid changes in the Arctic sea ice and predict, perceive, monitor, and evaluate environmental information such as hydrology, meteorology, waterway, and ice conditions during polar navigation.

In the R&D of navigation safety and environmental rescue technology and equipment in the Arctic, R&D analysis of the danger to ships in distress in the Arctic environment, ship emergency rescue technology, personnel in distress transfer technology, and special equipment for ship emergency rescue need to be carried out to realize unmanned, intelligent, multi-functional, and water–ice amphibious rescue technology.

In the R&D on the technology and equipment for oil-spill emergency disposal and ships in polar ice areas, we need to design ice and oil separation grids, ice crushing devices, heating systems, and modular devices and use biosurfactants to promote the dispersion, emulsification, and dissolution of oil spills that adhere to sea ice and floats on the seawater surface. Further, we need to develop comprehensive biological oil spill removal equipment based on the aforementioned technologies.

5.2.2 Polar large, green, and intelligent cargo-platform technology

In terms of the technologies and equipment for cold-proofing for polar navigating ship equipment and low-temperature materials and coating, research must be conducted on ship anti-freezing and de-icing technology and equipment, risk analysis, and decision-making. In addition, technologies and equipment for winterization of Arctic ship equipment, reliability evaluation and management for operation of Arctic navigation ship, and saving lives in polar ships must be conducted.

In the field of management and new icebreaking technology for the structural integrity of polar ships, we must establish an intrinsic structure relationship to accurately describe the actual mechanical properties of sea ice and

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perform simulations to accurately reproduce a real breakage scenario of sea ice. We also need a numerical technology to effectively simulate the ship–water–ice interaction, develop advanced structural analysis and safety assessment technology based on direct ice-load prediction, and establish a fatigue-strength analysis of the ship hull structure under the action of random dynamic ice load.

In terms of comprehensive performance forecasting and intelligent cargo platform for polar ships, theoretical analysis, numerical calculation methods, physical model tests, virtual simulation, and real-ship tests must be conducted to evaluate the comprehensive hydrodynamic performance of ships, which consider the ice and hydrodynamic characteristics. Forecasting of the main factors that affect the ship performance under ice conditions needs to be established by considering the ice-free and ice-area navigation conditions. Thus, a polar ship optimization design must be established to develop green ship models and improve the energy efficiency of polar ships.

5.3 Development of key equipment for polar resource exploration

Polar regions, especially the Arctic, are rich in potential resources. Following the continuous technological progress and yearly reduction in sea ice, development of the Arctic resources will soon become feasible. The competition on sustainable development and utilization of the Arctic resources is intensifying in the world, and sustainable development of the Arctic resources under the premise of environmental protection has become the core task in the Arctic region. Currently, the degree of exploration of the Arctic resources is low, and equipment is lacking. Improving the capacity of the exploration equipment in the polar region is an important direction for sustainable development of the Arctic resources in the future.

5.3.1 Building an exploration equipment system for polar ice area resource and forming an independent exploration capability for ice area resources

We need to carry out R&D, design, and construction of multi-functional exploration vessels and platforms and their core equipment in the ice area and improve the design and construction capacity of polar exploration equipment. Further, we need to build polar resource exploration fleet consisting of icebreakers, tugs, exploration vessels, platform, and supply vessels. We must basically develop an all-weather-independent exploration capability for resources in the ice area, lay the foundation for sustainable development and utilization of polar resources, and promote the establishment of China’s polar equipment industrial system.

5.3.2 Development of support equipment and technologies for resource exploration that adapt to the harsh polar environment and harsh environmental requirements

We need to understand the solid–liquid characteristics and change mechanism in the resource exploration process under low temperature and large temperature changes to overcome the polar low temperature and permafrost drilling technology. We must also develop key equipment required for polar drilling such as under-ice or under-water acoustic air gun for physical prospecting. In addition, low-temperature drilling rigs and ice-resistant platforms must be developed for fully enclosed operating environment as well as provide guarantee for efficient exploration of polar resources.

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