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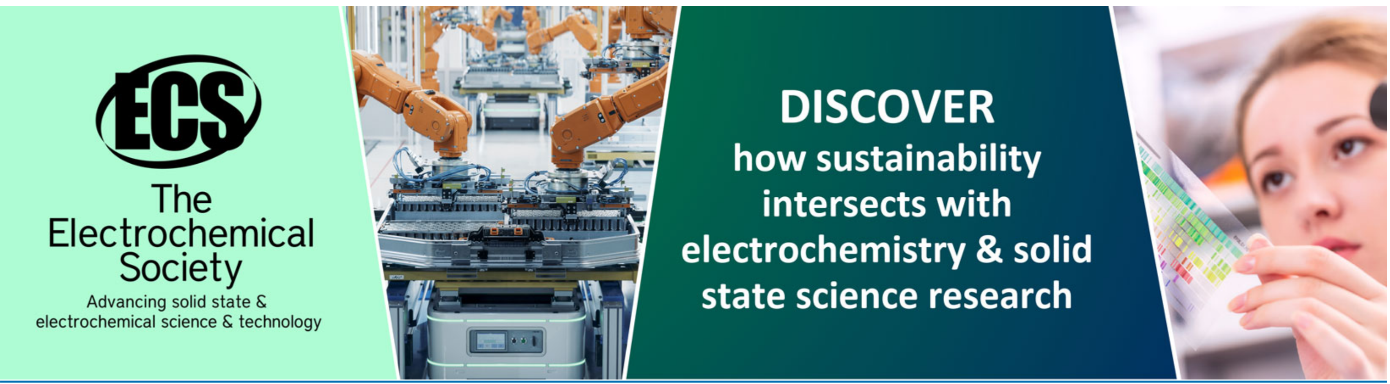

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History and prospects for the development of the icebreaking fleet: significance for Russia and the world

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Abstract. As world experience shows, from a geographical point of view there are many settlements, the access to which is mainly possible by sea transport ensuring the delivery of large volumes of goods. Quite often it is possible to get to the areas blocked by a thickness of ice only using icebreaking equipment. The development of the Arctic and the Northern Sea Route, ensuring the security of the state, and the growth of Arctic transportation are priority areas in the maritime policy of states with access to ice-covered waters. Therefore, the issues related to the development of the icebreaking fleet are quite relevant and significant. The purpose of the study is to show the development stages of the icebreaking fleet and determine its significance for Russia and other countries. The authors set the task of analyzing, systematizing and summarizing the world's most significant studies for science and the shipping industry on the development of the icebreaking fleet, key trends in the construction of icebreakers, as well as the prospects for the development and renewal of icebreaking in general. The study utilized theoretical research methods (system method, construction from the general to the specific, etc.). The discussion of the study results is widely tested through scientific and practical discussion not only at all-Russian, but also at international conferences, symposia, round tables on the development of the icebreaking fleet. The study examined the history of the construction of the largest icebreakers known to the world, the modern state of the icebreaking fleet on the example of the Russian Federation and revealed certain features of the construction of nuclear icebreakers. Conclusions were made on the need to increase the environmental friendliness of icebreakers, on the role of the icebreaking fleet for state economies. The study provides characteristics of a number of icebreakers that allow assessing the development dynamics and the current state of the icebreaking fleet (including in Russia). The issues related to improving the maneuvering characteristics of icebreakers were considered, as well as the connection between the use of the icebreaking fleet and research and rescue operations in the Arctic zone was revealed.

1. Introduction

The development of the Arctic and the Northern Sea Route (Fig. 1), ensuring state security, and the growth of Arctic transportation are priority areas of Russia's maritime policy. This work is devoted to research in the field of the icebreaking fleet, modern areas in the field of icebreaker construction, as well as prospects for the development and renewal of icebreaking in general.

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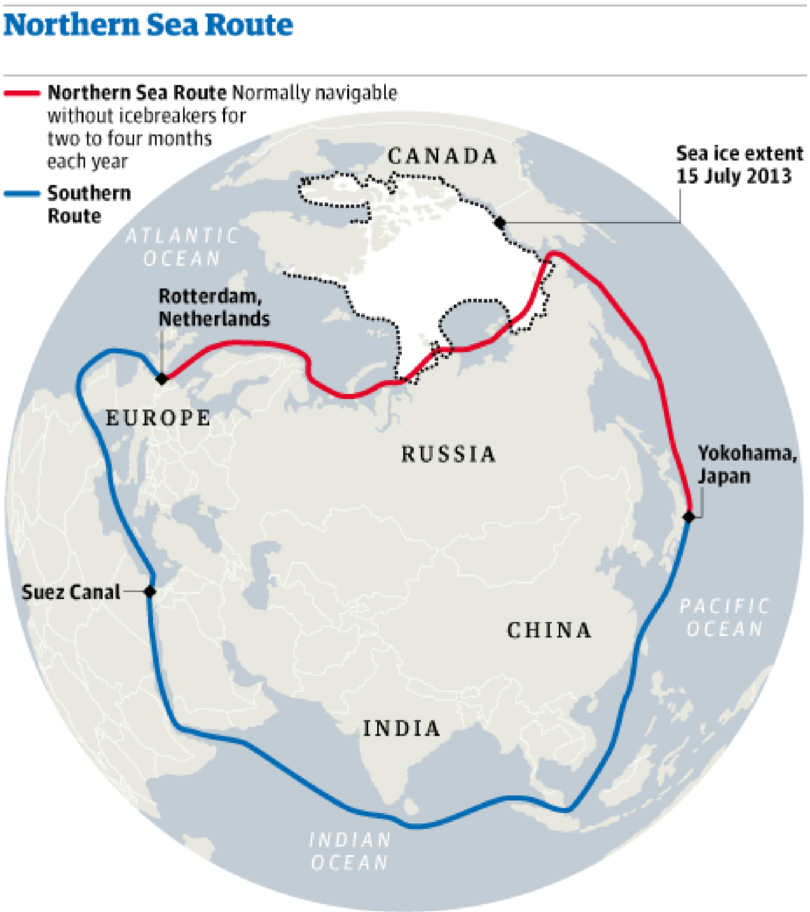

Figure 1. Northern Sea Route (downloaded from https://achangingarctic.wordpress.com/group/international_perspective/)

The history of world icebreaking dates back to 1834 with the construction of the *Assistance* icebreaking-type steam ship in the USA. This icebreaker was originally built to escort ships to the port of Helen Delich Bentley (Baltimore). For rational passage through frozen estuaries of rivers, the shape of the hull of the vessel was “spoon-shaped”, which made it possible to break through ice 0.3 meters thick.

The Russian shipbuilder Mikhail Britnev played a huge role in icebreaking industry. His contribution made it possible to improve the *Pilot* screw steamer. The purpose of creating such an icebreaker was to provide postal and passenger service in cold times. The bow of the *Pilot* was cut at an angle of 20°, which significantly improved the passing ability of the ship on the ice.

The *Eisbrecher* icebreaker (Germany) was erected in 1871 using the drawings of Mikhail Britnev and the practical significance of the Russian icebreaker.

In the future, the successful operation of new types of icebreakers led to the effective development of the construction of port icebreakers around the world. It is known historically that only in the period from 1871 to 1892 Europe had about forty icebreakers of a new type. The rapid development of icebreaker construction began in such countries as Finland, Denmark and Sweden.

It is impossible to overestimate the contribution made by the Finnish engineer R.I. Runeborg to the industry of world shipbuilding. Having conducted numerous studies R.I. Runeborg determined that the Hamburg type of construction of icebreaking vessels is not the most reliable and effective for ships passing on the ice.

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His theory was based on the practice of operating the *Murtaya* ship (Hamburg type). V.I. Runeborg established that the shape of the fore part, which has a full shape, greatly complicates the seagoing performance in broken and hard-to-pass ice.

Thus, the Finnish engineer proposed to improve the head of the ship, namely, to make the bow end of the ship sharper instead of “spoon-shaped”.

In Denmark, the first *Slapper* icebreaker was built in 1896. All the recommendations of the Finnish engineer were taken into account to build this ship. Ballast tanks were installed in the bow of the *Slapper* so that the ship could successfully sail in the ice without a possible jam of the icebreaker head.

The successful construction of icebreakers took place in the United States at the end of the 19th century. The active development of the construction of the new “American” type icebreakers was due to the presence of additional equipment – the bow screw and the specific shape of the fore part. The first time the bow screw was to be installed on the *St. Ignace* sea icebreaking transport.

Icebreaking ferries with bow propellers installed on them accompanied icebreaking crossings on the Great Lakes. The bow propeller placed on icebreakers improved the maneuverability and effective operation of ships.

An important stage in the construction of icebreaking transport was the *Imer* ship (Sweden, 1932). This vessel was equipped with a diesel-electric power unit. The installation and use of a diesel-electric power unit significantly increased the level of transport capacity, contributed to the improvement of maneuvering and tactical techniques of the icebreaking transport.

Marine icebreakers with a diesel-electric power unit began to be built in various countries: in 1939 the *Sisu* icebreaker was launched in Finland, in 1943-1945 a new series of the *Wind* icebreakers was launched in the United States of America.

The construction of a unique Finnish icebreaker with an interesting name *Voima* began in 1953. This icebreaker was equipped with two stern and two bow screws. Subsequently, the *Voima* icebreaker served as a prototype for a number of icebreakers of the Baltic States designed in subsequent years. These icebreakers were privately called the “European series”.

The work studies the activities in the field of the icebreaking fleet, modern directions in the field of icebreaker construction, as well as prospects for the development and renewal of the icebreaking industry.

This work has both scientific and practical significance, which is associated with the development of the Arctic and the Northern Sea Route, ensuring state security, and the growth of Arctic transportation, which are current priority areas in maritime policy.

The results of this study on certain issues have already been tested through a scientific and practical discussion in the framework of Russian events (regional, all-Russian and international conferences at Russian higher educational institutions and research centers) devoted to the development of the icebreaking fleet, as well as in the framework of international scientific and practical conferences [1, 2].

2. Materials and Methods

To define the concept of an “icebreaker”, the authors analyzed the most significant studies in the problem area, including using the concept laid down in Article 1.2. of the International Code for Ships Operating in Polar Waters, according to which “an icebreaker is any vessel which operational functions may include escorting functions or ice-work functions, the power and size of which enable it to operate actively in ice-covered waters” [3].

To solve the problems formulated in the study, the authors used the speculative method (methods of construction from the general to the specific, the method of system analysis, etc.).

The study conducted by the authors is complex in nature, since the icebreaking fleet is considered not only from a historical point of view, but also provides specific technical characteristics of individual icebreakers. The study reveals modern directions in the field of icebreaking industry, prospects for the development and renewal of the icebreaking fleet, and also details the main purpose of icebreakers within the Project 22220.

The study details the main views on the problems outlined in foreign sources on the development of the icebreaking fleet, as well as the design and construction of new icebreakers. The present study is based on the works of W. Zhang [4–6], A. Topaj [7], J. Sawamura [8], G. Aiello [9] and others.

3. Results

The history of the development of the Arctic icebreaking fleet in Russia dates back to March 4, 1899. Despite the meter layer of ice, the world's first Arctic icebreaker the *Ermak* approached the Kronstadt port.

This day has become one of the most significant in the history of Russian shipbuilding. Finance Minister S.Yu. Witte, great chemist D.I. Mendeleev, radio inventor A.S. Popov, Vice Admiral S.O. Makarov – all these great people made their contribution to the icebreaker construction project.

The personality of S.O. Makarov plays a huge role in the construction of the icebreaker as one of the first initiators of a heavy vessel. In a memo to the manager of the Ministry of the Sea, Makarov proposed creating an icebreaker for the purpose of sailing in Arctic waters. The application for the construction of the icebreaker was rejected. Makarov, being a confident and purposeful person, did not come to terms with this and prepared a series of lectures "Straight to the North Pole" and soon the entire St. Petersburg learned about his idea.

An important figure that contributed to the success of the icebreaker construction was the Minister of Finance S.Yu. Witte. S.O Makarov and D.I. Mendeleev assured him that the construction of the icebreaker will bring significant results to the Russian Empire in the field of the Arctic ice development and the ship will subsequently be able to become an effective military vessel for the Russian Imperial Navy.

In November 1897 S.Yu. Witte introduced Emperor Nicholas II to the work of S.O. Makarov and received his approval. S.Yu. Witte wrote: "...the immediate goal of building this huge icebreaker was that I had the idea, on the one hand, to make navigation in St. Petersburg and other important ports of the Baltic Sea throughout the winter, but mainly to try whether it is impossible to go to the Far East through the northern seas along the northern coast of Siberia".

Admiral Makarov dreamed of conquering the North Pole on the *Ermak*. However, fortune did not always favor the icebreaker and no matter how Makarov tried, his ship was not ready to overcome the ice of the Arctic. Only in 1901, making the third Arctic voyage "to the west coast of Novaya Zemlya and to Franz Joseph Land", the improved icebreaker *Ermak* managed to pass heavy Arctic tests.

Technical characteristics of the ship:

1. Three bow four-blade propellers were used to ensure the efficiency of a propulsion system.
2. The construction of the ship was based on the experience of European engineers, a bow propeller was used, which improved ice-reinforced performance in thick ice.
3. The power of the steam propulsion unit was designed up to 9,000 hp.
4. The forms of the ship hull bypass took into account the earlier experience of icebreaking operation based on the conditions of the best characteristics of seaworthiness on clean and ice water in flat and broken ice.
5. Ballast tanks were installed on the icebreaker to escape ice jamming.
6. The inclination angle of the forward bow was taken as 20°.
7. The hull was divided into 9 main compartments by waterproof bulkheads.
8. According to the project, the strength of the hull was supposed to withstand an impact on the ice even at the maximum speed.
9. The parapet above the waterline fell inward, which reduced the weight of the entire hull.

The *Ermak* icebreaker in its declared capacity and size significantly exceeded all icebreakers operating at that time around the world.

The *Ermak*, which cost 1.5 million rubles, paid for itself. In 1899, during a snowstorm, the *Admiral General Apraksin* battleship ran aground. The crew of the *Ermak* icebreaker saved the battleship worth 4.5 million rubles.

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Subsequently, the icebreaker was operated and provided maritime transportation in the Baltic, Arctic and White Seas. The *Ermak* icebreaker participated as a warship in the Japanese War (1904-1905), World War I (1914-1918) and World War II (1939-1945) and served in the Far North for more than 60 years. The construction of the *Ermak* is a historically important event.

1916 is marked by the construction of the legendary *Krasin* icebreaker (*Svyatogor*) – a symbol of Arctic research and the marine heritage of Russia. The *Krasin* is the peak of ship construction at the beginning of the 20th century, the heir to the best traditions of the Russia's icebreaking fleet.

In 1927, the *Svyatogor* was renamed the *Krasin* and it was the beginning of the history of the Arctic known to all school textbooks.

In the period from 1928 to 1930, the icebreaker continuously carried out research and long expeditionary work.

In 1936, the *Krasin* ensured the passage of warships by the Northern Sea Route. During the Great Patriotic War, it established the passage of ships to the port of Arkhangelsk.

In 1956, the icebreaker was sent for repairs. In 1960, it was modernized and eased in again.

Tactical and technical characteristics of the ship:

1. The *Krasin* icebreaker is a five-deck three-screw steamer driven by steam engines using the superheat steam energy.

2. The *Krasin* is a crank-case icebreaker. All its moving parts are covered with a close-connected body – a crankcase.

3. The type of icebreaker – the Stephenson triple expansion piston steam engine.

4. The icebreaker has a compound machine – the axes of cylinders are located parallel to each other.

The design of historical advanced icebreakers *Ermak* and *Krasin* determined the entire development of Arctic icebreaking and a new modern type of Arctic icebreakers.

The new era of icebreaking in Russia is associated with the "birth" of the *Lenin* nuclear ship in 1953. The icebreaker played a significant role in the development of a peaceful atom in Russia.

The goal of creating an icebreaker was to escort ships on the ice, to help those who were stuck in ice in the Northern Sea Route.

The scientific management for the creation of the *Lenin* nuclear icebreaker was carried out under the guidance of academicians I.V. Kurchatov and A.P. Alexandrov. Young scientists N.S. Khlopkin, B.G. Pologikh, Yu.V. Sivintsev and others performed theoretical calculations of the nuclear reactor.

Technical characteristics of the *Lenin* icebreaker:

1. The nuclear unit located in the central part generated steam for 4 main turbine generators. The turbogenerators provided direct current to three propeller motors, which activated propellers of strong construction.

2. Extremely low fuel consumption: nuclear fuel on the *Lenin* icebreaker was used instead of dozens of tons of oil.

3. The total capacity of the power unit was 32.4 megawatts.

4. All necessary measures were taken to prevent the threat of environmental pollution and harm to the crew of the ship in the presence of a nuclear facility.

5. Special lines for the bow gave greater maneuverability to the icebreaker and allowed easier passage through the ice fields.

6. The power unit was automated (all auxiliary mechanisms on the ship were also automated).

7. The presence of special systems of ballast tanks provided the *Lenin* icebreaker with a quick passage from jamming on the ice.

The world's first nuclear icebreaker *Lenin* went from the shipyard of the Admiralteisky Plant to sea trials. On the ice tracks, it was used for three decades. The icebreaker participated in 26 Arctic navigations, went more than six hundred thousand nautical miles. Today, the *Lenin* icebreaker stands on an eternal pier in Murmansk.

In 1974, the final sea trials of the second Arctic nuclear icebreaker were carried out, which became the main in the eponymous series of the largest icebreakers in the world.

The *Arctic* project was created for the development of the Arctic Seas – the first icebreaker in the world to reach the North Pole overcoming ice in free sailing.

The historical significance of the *Arctic* icebreaker was that a few years after its commissioning, the ship was able to fully conquer the North Pole for the first time. Its record was that in 1999-2000 the ship worked in the Arctic for a whole year without entering the home port.

The first combat icebreaker was *Dobrynya Nikitich*, which was built at the Admiralteisky Plant (Project No. 97). In 1960, the icebreaker became part of the auxiliary fleet of the USSR Navy.

Subsequently, the plant produced another 30 combat icebreakers. The technology for the construction of icebreaking transport has been modernized with each new order.

In the late 60s, the construction of new combat versions of icebreakers began, which received the design number 97P.

The descent of the *Ivan Susanin* icebreaker was carried out in 1973. It was distinguished from the usual 97 version by the absence of a bow screw, increased length, a runway for a Ka-25PS helicopter designed for search and rescue operations at sea. There were art installations AK-726 and AK-630 on board the ship.

4. Discussion

Traditionally, the construction of icebreakers is one of the most difficult industries in shipbuilding [10–12]. Russia occupies a leading position in the field of icebreaking. In particular, Russia has a large qualified specialization in the construction of nuclear icebreakers.

It seems advisable to consider the main trends in the construction of icebreakers today.

The main positive effects of icebreaker construction are summarized in Table 1.

Table 1. Modern directions in the field of icebreaking

n/n	Directions in the field of icebreaking	Positive effect
1	Environmental friendliness	improved environmental sustainability of the ship; new ship systems
2	Multifunctionality	efficiency of fleet operation
3	Maneuverability	improved maneuverability and stability of icebreaker
4	Low speed	improved research in the Arctic
5	Helipad	improved supply of scientific expeditions and rescue operations

Prospects for development and renewal of the icebreaking fleet

This present stage is marked by the commissioning of the nuclear *Arctic* (2020), *Siberia* and *Ural* icebreakers (operation is designed for 2021 and 2022) within the Project 22220. Universal nuclear icebreakers of the Project 22220 will become the largest and most powerful in the world (Table 2).

The new technically advanced icebreakers will provide caravans of ships in Arctic conditions, will supply vessels with hydrocarbon raw materials, will be able to conduct year-round continuous navigation along the Northern Sea Route and solve all the corresponding complex tasks.

What are the benefits of the next-generation icebreakers?

1. The autonomy of navigation lies in the duration on the routes in the Northern Sea Route.
2. The operation of new icebreakers significantly reduces costs.
3. A powerful nuclear power plant for ships passing in the Arctic.

Currently, the Arc7 ice-class ships within the Project 23550, which will be able to simultaneously carry out both the functions of a tugboat and an icebreaker, are being constructed. In addition to these functions, the ships may be used as patrol ships with the ability to overcome heavy ice.

The project implies the design of the *Ivan Papanin* icebreaker and the first serial icebreaker *Nikolai Zubov*. The terms of transferring the ships for operation to the fleet are 2023 and 2024, respectively.

Ivan Papanin and *Nikolai Zubov* icebreakers will be able to perform uninterrupted work (up to 70 days) for expeditionary and research purposes without the need to replenish food supplies, medical and additional services.

The objective of the project is to secure and protect Arctic resources, escort and tow detained vessels to port, escort and support ships.

On board the ship is a modern artillery installation AK-162MA with digitalized control systems capable of successfully defending air attacks, and an anti-submarine helicopter of the new type Ka-27.

An important military strategic element is that on board the ship it is possible to install containers with *Caliber* or *Uranus* cruise strike missiles.

Table 2. Icebreakers of the Project 22220

New-generation icebreakers	Purpose
Arctic	year-round operation in the Arctic; independent piloting of ships and caravans in the Arctic; icebreaking piloting of ships in shallow areas of the Yenisei and Ob Bay; towing of vessels and other floating structures in ice and clean water; assistance to ships and rescue operations in ice and clean water;
Siberia	overcoming flat ice 2.8-2.9 m thick with steady speed; high penetration through a thick layer of ocean and river ice; independent piloting at sea and at the mouths of major rivers;
Ural	piloting vessels in the Arctic, in the Yenisei and Ob Bay areas; towing of vessels and other floating structures in ice and clean water; assistance to ships and rescue operations in ice and clean water; year-round navigation along the Northern Sea Route.

The *Leader* icebreaker is a modern nuclear icebreaker of the Project 10510. The commissioning of this icebreaker according to the plan should take place in 2027. A modern icebreaker with a capacity of 120 MW will be able to lay a path up to 50 meters wide through the ice with a thickness of more than four meters. The icebreaker will be used for the continuous conduct of caravans along the Northern Sea Route.

The construction of the ship will be carried out by the Zvezda shipyard. It is designed to put into operation at least 3 *Leader* icebreakers.

The life of one ice ship is 40 years, it will be able to transport up to 127 people on board and maintain full autonomy and life support for up to eight months.

5. Conclusion

Today, we can confidently talk about the exceptional importance in the development of the Northern Sea Route. The construction of one of the most complex types of ships – icebreakers has a huge and great history around the world [13–16]. Icebreakers provide a secure and safe piloting of ships in continuous shipping, serve a huge platform for research, provide conditions for reliable operation of the Northern Sea Route.

It is worth distinguishing several the most important and generalizing elements of the icebreaking industry development:

1. Today, the issue of the state of the environment in the country is an acute problem, therefore, first of all, it should be noted that icebreakers are becoming more environmentally friendly. The use of liquefied natural gas (LNG) as a fuel in the design of ships allows improving the environmental friendliness of icebreakers, as well as ensuring the prospects of developing new ship systems in the market. Thus, for example, LNG-based icebreakers for the Atomflot with a capacity of 40 MW are currently being developed.

2. Modern icebreakers are designed depending on their purpose and operation. Multi-purpose ships are being created for research, for the defense of the state, for the transportation of goods and cargo. Thus, we can say that icebreakers become multifunctional. In this regard, the efficiency of the operation of the icebreaking fleet is improving.

3. Modern icebreakers are equipped with azimuth propulsion plants. The introduction of such equipment eliminates the need to install a steering wheel. This significantly improves the maneuverable characteristics of the vessel and the stability of the icebreaker in cases of operation in open water. One example of such icebreakers is the icebreakers of the Project ARC130A *Alexander Sannikov* and *Andrei Vilkitsky*.

4. Modern technology to reduce the level of noise of icebreakers uses damping materials, and also develops the strategic location of engines. This characteristic is especially important for improving research in the Arctic.

5. The presence of a helipad on icebreakers of the latest models showed its viability. Due to it, the supply of scientific expeditions and rescue operations is improved. It is advisable to continue to use such technologies in the construction of icebreakers in the future.

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