The Optimization of Parameters for Ships Navigating in Ice

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Collected Works

By

L. G. Tsoy

Translation from Russian: V. Semenov

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Father! where are you! Do you hear me?

N. V. Gogol
"Taras Bulba"

1939

1992

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AUTHOR'S REMARKS

The reason for issuing the present collection of works is the author's intent to consolidate separate miscellaneous publications containing the main results of research studies carried out after World War 2, during the post-Soviet period of the revival of the Russian Arctic fleet. Another purpose of this collection is to share knowledge and experience with those who have just started a career as a naval architect and are dedicated to the design and construction of ships navigating in ice. I hope that the knowledge of practice accumulated during about half a century, and the recommendations based thereon, relating to the search for sound technical decisions, and aiming at the enhancement and improvement of the efficiency and safety of operation of icebreakers and icebreaking transport ships, will be useful to our successors.

As is known, the second half of the previous century was marked by a major modernization of the Russian fleet of icebreakers, which aimed at ensuring sustainable ship traffic along the Northern Sea Route and reliable year-round cargo delivery to the freezing Soviet ports. Accordingly, during the 1950 to 80s, ordered by the Soviet Union, three series of linear diesel-electric icebreakers belonging to the *Moskva*, *Ermak*, and *Kapitan Sorokin* types were built in Finland. In 1959, the world's first nuclear icebreaker, *Lenin*, was commissioned at the Admiralteyskiy Zavod Shipyard in Leningrad. Having gained sufficient experience of its operation, the Baltiyskiy Zavod Shipyard proceeded with the construction of a series of very powerful nuclear icebreakers of the *Arktika* type. The first in its series, the nuclear ship *Arktika*, was commissioned in 1974. In 1989 and 1990, the Wärtsilä Shipyard of Helsinki, acting in co-operation with the Baltiyskiy Zavod Shipyard, constructed two nuclear icebreakers with a restricted draught, *Taymyr* and *Vaygach*, whose purpose was to ensure guaranteed year-round navigation on the Yenissey leg of the Dudinka line, intended for exporting the products of the Norilsk Mining and Smelting Works.

Within the same period, the Arctic icebreaking transport fleet also underwent renovation. During the 1980s, the Finnish Wärtsilä and Valmet shipyards, in accordance with their contract with the "Sudoimport" State Enterprise, constructed two series of multi-purpose dry cargo ships of the *Norilsk* type, having a higher ULA ice class. A series of supply vessels of the *Vitus Bering* and *Ivan Papanin* types, which were intended for helicopter-assisted unloading to an unequipped shore, were constructed by the domestic shipbuilders. A nuclear container and lighter carrier, *Sevmorput*, was also constructed for service in the Arctic.

The dawn of the twenty-first century saw the beginning of construction of a new generation of ships meant to replace the icebreakers and icebreaking transport ships of the Russian Arctic fleet that had reached the end of their service cycle. These were a multi-purpose double-draught nuclear icebreaker with a power output on shafts of 60 MW (with the *Arktika* nuclear icebreaker as a lead ship); a diesel-electric icebreaker with a power output on shafts of 24 MW (with the *Viktor Chernomyrdin* diesel-electric icebreaker as a lead ship); and a series of icebreakers of the *Moskva* type, meant for operation in the Baltic Sea, equipped with azimuthal pods having a total power output of 16 to 17 MW. A series of Arctic container ships of the *Norilskiy Nikel* type capable of double action was built as well.

The author of the materials included in the present collection from 1973 happened to take direct part in the design and research development of icebreakers and icebreaking transport ships during the reinvigoration of the Arctic fleet, in the substantiation of their design characteristics (feasibility studies), in sea-going trials, and in the early phase of their operation. Experimental and theoretical research work served as an important basis for the development of analytical methods for assessing the icebreaking capability of ships, and for the development of a mathematical model of the ship's advancement in ice, which allowed the upgrading of the level of scientific substantiation of prospective types of icebreaking ships and the level of development of technical and operational requirements for their main parameters and performance in ice.

In support of the work related to the substantiation of new types of icebreakers, and to the development of requirements for ice navigation ships, a creative team was convened in 1973 in the Central Science and Research Institute of Maritime Fleet (CNIIMF), which later, in 1980, was transformed into the Laboratory of Icebreaking Engineering and Ship Performance in Ice (LLT), that was headed over a 35-year period by the author of the present collection.

The author would like to express his profound gratitude to the personnel of the laboratory who took direct part in the LLT activities, including the co-authors of a number of papers and reports: Dr. S. B. Karavanov, Dr. A. V. Ierusalimskiy, Dr. A. A. Bogdanov, Dr. N. M. Tkachev, Dr. N. A. Vysotskaya, Mr. A. A. Shtrek, Mr. S. M. Ponomarev, Mr. V. E. Semenov, Dr. F. A. Moreynis, and Mrs. N. G. Goncharova, who rendered remarkable assistance in preparing and editing the present collection. The author would also like to express his gratitude to the experts of the Arctic and Antarctic

Science and Research Institute (AANII), Dr. V. I. Kashtelyan, Mr. O. V. Faddeyev, and Mr. A. A. Dubov, to the specialists of the Central Science and Research Institute of Construction Materials (CNII KM) “Prometey”, Dr. Y. L. Legostayev and Dr. Y. L. Kuzmin, and to the experts in hydrology, Messrs. N. G. Babich and V. M. Losev, for their invaluable assistance in conducting full-scale ice trials. Separate thanks should be addressed to the ice shipmasters Messrs. B. M. Sokolov, V. A. Golokhvastov, Y. S. Kuchiev, A. A. Lamekhov, A. G. Gorshkovskiy, A. N. Olshevskiy, and V. I. Shestopalov for their support and patience during the scientific research, as well as to Dr. B. A. Yunitsyn, then the Deputy Minister for the Maritime Fleet, who was able to convince the then–Ministry of the Shipbuilding Industry that there was a real need to refine the afterbody’s hull lines of the *50 Let Pobedy* nuclear icebreaker.

I consider it is my duty to express my special thanks to my tutors and guides in the profession, Dr. V. S. Dorin, Dr. V. N. Volkov, and Dr. Y. N. Popov, and—beyond any doubt—to Dr. Y. A. Simonov, for having invited me to join CNIIMF to work on Arctic-related issues, and, finally, to the CNIIMF Director-General, Dr. V. I. Peresypkin, for his full understanding and constant support.

L. G. Tsoy
Naval Architect,
D.Sc. in Engineering, Professor

FOREWORD

The present collection of papers and reports by Loliy Georgiyevich Tsoy, D.Sc. in Engineering, contains the results of his scientific activities in the domains of research design, feasibility studies, and the development of main operational requirements, ice trials, and studies of the operational experience of new icebreakers and icebreaking transport ships forming part of the domestic arctic fleet, as carried out within the period from 1973 to 2017.

Starting from the commissioning in 1899 of the world's first polar icebreaker, *Ermak*, which had a power output of 10,000 i.h.p., the operating experience of Russia's Arctic fleet now exceeds 100 years. As is well known, the *Ermak* icebreaker was built upon the initiative of Admiral S. O. Makarov, who believed that the "realization of the dream to find the shortest way through to the Pacific Ocean" was only possible by means of high-powered icebreakers.

Challenges facing the domestic fleet in the Arctic arose in parallel with the exploration of natural resources, and with the development of the production capabilities of the Russian North. With the growth of the industrial exploration of raw mineral deposits, and with the increase of their importance for the state economy, the need to extend the period of navigation in the Arctic up to year-round navigation in the Kara Sea became evident. This required the full renovation of the Arctic fleet of steam ships. This renovation started after WW2 and continued until the early 1990s. As a result of this process, created was the Arctic Sea Transport System, which included the world's most high-powered nuclear icebreakers of the *Taymyr* type, and linear diesel-electric icebreakers of the *Ermak* type.

The last ten years of the existence of the USSR were marked by the expansion of the fleet of icebreaking transport ships. Construction of 19 *ULA*-classed universal multi-purpose ships of the *Norilsk* type, having a deadweight of 15 thousand tons, was completed in Finland, in accordance with a contract concluded with the Ministry of the Maritime Fleet. Following a recommendation by CNIIMF, for the first time ever these ships were equipped with a diesel gear system of the torque transmission to the variable pitch propellers (VPPs). Domestic shipyards have built supply vessels intended for a helicopter-assisted unloading to an unequipped shore, including a series of five *ULA*-classed diesel-electric ships of the *Vitus*

Bering type, and an m/v *Ivan Papanin*, with a direct torque transmission from a slow-speed diesel to a VPP mounted in a nozzle. Also constructed was a nuclear lighter/container carrier, *Sevmorput*, of the highest ice category, which had its VPP enclosed in a nozzle. The tanker fleet acquired a series of 10 Arctic *UL*-classed product carriers of the *Ventspils* type, with a deadweight of 5 thousand tons.

At present, the arctic fleet is ageing, and the majority of icebreakers are now subject to decommissioning. At the same time, prospects of freight traffic development in the Arctic, including the emerging new non-conventional large-scale year-round transportation of hydrocarbons produced in the North, and the expected increase in the international transit through the Northern Sea Route, call for the necessity of a new revival and upgrading of the icebreaker fleet, as well as for the construction of specialized high-tonnage icebreaking transport ships (tankers, gas carriers, container ships).

Taking into account prospects for freight traffic development in the Arctic, and an imminent decommissioning of ships, obsolete in all respects already in the past century, a further complement to the arctic fleet was anticipated of super-powered nuclear icebreaker-leaders of the *LK-110A* type (having a power output of 110 MW), able of ensuring guaranteed year-round navigation through the Northern Sea Route (NSR) in its entirety, together with multi-purpose nuclear double-draught new generation *Arktika*-class icebreakers of the *LK-60A* type, with linear diesel-electric icebreakers of the *LK-25* type, and with auxiliary icebreakers of the *LK-7* type.

The designs of the arctic icebreakers and icebreaking transport ships referred to above, both already constructed and prospective, were substantiated with the direct participation of the author of the present collection, who then served in the capacity of principal developer of engineering and cost-efficiency feasibility studies (ECSs) and the main technical and operational requirements (MTORs) for the nuclear icebreaker of restricted draught (*Taymyr*),[*] the multi-purpose icebreaking transport ship of the *SA-15* type (*Norilsk*), the supply vessels intended for helicopter-assisted unloading to an unequipped shore of the *SAS-5* type (*Vitus Bering*, *Ivan Papanin*), the super-powered nuclear icebreaker-leader, and the nuclear double-draught new generation icebreaker. The very idea and concept of the latter were put forward by the author. As regards the constructed ships, the author took part in their sea trials and in various

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[*] The author was a member of the group of Soviet and Finnish experts in charge of the design and construction of the *Taymyr* icebreaker.

experiments aimed at improving their seakeeping features. The author participated also in the elaboration of MTORs for the prospective diesel-electric icebreaker of the *LK-25* type, and for the linear icebreaker of the *LK-18* type intended for ice operations in the Gulf of Finland.

In the course of these works, the inadequacy of the existing methods of carrying out engineering and cost efficiency feasibility studies for icebreakers and ice navigation transport ships was revealed. A similar insufficiency was identified in respect of the application of practical methods of defining and optimizing their main parameters, including performance in ice. These drawbacks necessitated defining and formulating the scope of the extensive experimental and theoretical studies that should be carried out in the course of the elaboration of the ECSs and MTORs, and the performance of such studies. In particular, upon an initiative by CNIIMF, serial tests of the models of icebreaking transport ships and icebreakers were carried out in the ice testing tank of the Arctic and Antarctic Science and Research Institute (AANII), and in the hydrodynamic testing tanks of the Leningrad Shipbuilding Institute (LKI) and of the Leningrad Institute of Water Transport (LIVT). The author designed a range of models characterized by a systematic variation of their hull shape characteristics and a program of trials. Special field trials and model tests were carried out that allowed the development of a procedure for assessing the effect of the breadth of a channel cleared in ice by the icebreaker on the speed of the ship sailing along that channel behind the icebreaker. These studies and the research into the performance of ships operating in ice, including the studies carried out in the course of scientific and practical expeditions in the Arctic,[**] provided grounds for developing a mathematical economic model for ships navigating in ice, and a methodology of optimization of the ships' main particulars and dimensions in terms of their power output and icebreaking capability, which have no analogs in the world. As a follow-up to these studies, and on the basis of the experience gained from the field trials of icebreaking ships, L. G. Tsoy formulated expressions derived through the regression technique analysis aimed at defining the attainable icebreaking capability and speed in still water in the early stages of the design of icebreakers and icebreaking transport ships, depending on their main dimensions, their displacement, the parameters of their hull lines, the dynamic friction factor for hull–ice interaction, the power available, and the propulsion characteristics of the installed propelling plant.

[**] The author participated in 18 expeditions to the Arctic, and has been awarded the corporate lapel button "Honorable Polar Explorer."

Consequently, a scientific, methodological, and regulatory basis was created to allow the upgrading of the scientific level of the ECSs under development, and to ensure the selection of sound and rational characteristics for prospective icebreakers and transport ships navigating in the Arctic. A threshold value of the power output was established beyond which the use of icebreakers equipped with nuclear power plants would be expedient and rational in the Arctic.

In view of the adverse effect of the snow cover on the ship's performance in ice, and of the snow and ice mass sticking to the hull at low temperatures, which were discovered during the winter navigational periods in the Arctic, individual studies were conducted on the methods and proposals for technological enhancement of the icebreaking capability of ships, and on preventing any decrease in that capability. The efficiency of air-bubble lubricating systems developed by the Wärtsilä Shipyard of Finland was investigated. The main outcome of that work was the development—through co-operation with the experts from the "Aisberg" Central Design Bureau, the Baltiyskiy Shipyard, the Kirovsky Zavod Enterprise, the Special Technical Supervision Group of the Murmansk Shipping Company, and the Central Science and Research Krylov Institute—of a domestic anti-icing system that was successfully implemented on board the *Rossiya* nuclear icebreaker, and on subsequent ships of the series. Another subject of investigation was the state of the outer underwater shell of the ship's hull, its corrosion, and the effect of this corrosion on ice resistance. The efficiency of using stainless steel for the outer shell of icebreakers was assessed and the expedience for nuclear icebreakers of using clad steel in combination with a system of electrochemical protection was substantiated.

In order to assess the prospects of applying to domestic icebreakers conceptually new non-conventional hull shapes proposed abroad, full-scale ice trials were carried out on the *Mudyug* and *Kapitan Sorokin* icebreakers. These icebreakers underwent conversion at the German Thyssen Nordseewerke Shipyard, where they were equipped with a fore hull extremity of the "Thyssen-Waas" forebody system; the *Kapitan Nikolaev* icebreaker was retrofitted at the Kvaerner Masa Yards, where a so-called "conic" forebody was fitted to its hull. The results of these trials—the operational verification of year-round navigation in the Arctic—as well as the outcome of modeling in the testing tanks, rendered questionable the expedience of using non-traditional hull lines for general purpose icebreakers. At the same time, the research carried out demonstrated the feasibility of refining the conventional lines of the icebreaker's forebody. Taking into account the results obtained, L. G. Tsoy developed and substantiated proposals on optimizing the hull shape of icebreakers and icebreaking transport ships, that allow the enhancement of their icebreaking capability and ensure substantial energy savings (up to 50%), without any degradation in their maneuvering and seakeeping features. Following his initiative, the shape of the fore extremity was improved on the most recently constructed *50 Let Pobedy* icebreaker.

A number of joint research works on the ice performance of newly built and prospective icebreakers and icebreaking ships were carried out in co-operation with the foreign shipbuilding companies Wärtsilä, Valmet, Rauma-Repola, Thyssen Nordseewerke, and Canada Maritime Transport Group.

In particular, the author organized model testing in the ice testing tank of the Wärtsilä's Arctic Research Centre of the multi-purpose double-draught new generation icebreaker proposed by him. This testing allowed the formulation of a set of substantiated requirements for the main parameters and the hull shape of the new nuclear arctic icebreaker of the *LK-60A* type, which is now under construction. Development of consistent recommendations on the ships' ice strength was a meaningful outcome of the joint research into the full-scale long-term effect of the action of ice loads on the ship's hull, and on the hull damage rate, performed in co-operation with the Finnish experts. The research carried out and the studies of the experience of ships operating in the Arctic and of the prospects of their evolution demonstrated a need for a further refining of the rules published by the Russian Maritime Register of Shipping relating to the classification of ice navigation ships, the requirements for ice strengthening of ships, and the hull lines of icebreakers and of other ships operating in the Arctic. Furthermore, the author, upon his own initiative, and anticipating the opening of the Northern Sea Route to international shipping, forwarded a proposal addressed to the leading foreign classification societies to identify ice classes for Arctic navigation ships. L. G. Tsoy participated in the development of the IACS' Unified Requirements for ships operating in polar waters, and of the IMO International Code for Ships Operating in Polar Waters, and expressed, in a number of cases, his criticism of proposals put forward by other parties when it was justified by the extensive domestic experience of the exploration of the Northern Sea Route.

L. G. Tsoy also took active part in international research into the prospects for the development of shipping in the aquatic area of the Northern Sea Route, and of the industrial exploration of the Arctic shelf; he served as a head and coordinator of the scientific works while representing Russia in the INSROP Project initiated by Norway and Japan, and in the ARCDEV, ARCOP, and AMSA Projects led by the European Commission.

The complex scientific and research works carried out led to the development of an essential basis for the research design of and a set of techniques used for assessing a ship's performance in ice, and for appraising the design and operational characteristics of ice navigation ships. A mathematical model was proposed for the ship's movement in ice (both for icebreaker-assisted and autonomous modes of operation), whose application provided a possibility of carrying out engineering and cost-efficiency feasibility studies, which take the ships' individual features into consideration at a new qualitative level.

The scientific and research works and analyses of operational conditions for ships operating in the Arctic performed by L. G. Tsoy allowed the formulation of proposals on a range of types and dimensions of prospective Arctic icebreakers, and the development of recommendations for the selection of sound parameters and the harmonization of the ship's main particulars and the power characteristics of icebreakers and icebreaking transport ships.

While highly appreciating the practical importance of the author's scientific activities, another remarkable feature of Dr. L. G. Tsoy deserves separate mention: namely, his inherent flawless engineering intuition. He did not make a single mistake in the discussions with naval architects on icebreaker design issues. Dr. L. G. Tsoy knows quite well how to build icebreakers.

President of CNIIMF,
D. Sc. in Engineering,
Academician of the
Russian Academy of
Transport

V. I.
Peresypkin

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Hereby I would like to express my sincerest gratitude to my kind-hearted responsive daughters, Natalya Goncharova and Karina Tsoy, as well as to my grandson, Fedya, for their great and invaluable contribution to the preparation, design, and correction of the present monograph in its English version, especially taking into account the conditions of isolation due to the Covid-19 pandemic, and the associated limited possibilities for direct communication and the exchange of views. I would also like to extend my thanks to my colleague Vladimir Semenov, who took upon himself the heavy work of the translation of the Russian text and accompanied it with valuable comments.

Loliy Tsoy
October 2021

PREFACE

This collection of scientific works presents a brief history of the construction and evolution of icebreakers and ice-going merchant ships in Russia and abroad, and contains comparative analyses of their technical and operational characteristics and of their ice-going performance. Various structure options are compared, including non-conventional solutions related to the reduction of ice resistance and saving energy. This book considers the design of Arctic icebreakers of the future. The type and size parameters of prospective domestic icebreakers are substantiated in light of recent Arctic exploration, which requires the construction of large-capacity icebreaking transport ships for year-round cargo transit along the Northern Sea Route and the export of crude hydrocarbons. The results of the analytic and experimental systemic research related to the studies of ships' ice performance are provided. A mathematical model is developed of the advancement of ships in ice for autonomous and icebreaker-assisted modes of navigation, and a methodology of optimization of the main parameters of ships is proposed. Recommendations are formulated for the further enhancement of Arctic navigation ships, the selection of optimized ship hull lines, and the derivation of their required icebreaking capability, depending on the ship's purpose and its ice class. Proposals are put forward relating to the improvement of the classification of sea-going icebreakers, of the rules of navigation in the water area of the Northern Sea Route, and of the IMO's International Code for Ships Operating in Polar Waters.

The present book is intended for students, postgraduates, and professors at shipbuilding and navigation educational institutions; it may also be useful for scientists and designers involved in the substantiation of performance data (feasibility studies) and the construction of new icebreakers and icebreaking merchant ships; it is dedicated to all those who are interested in the history and prospects of the evolution of the icebreaking fleet.

All questions, feedback and comments to be sent by e-mail to nata.goncharova.68@mail.ru and karina_tsoy@mail.ru.

ICEBREAKERS

1976

Photo by L.G. Tsoy, 1983

THE WORLD'S CONSTRUCTION OF ICEBREAKERS IN THE NINETEENTH AND TWENTIETH CENTURIES: MAIN TRENDS OF THE ICEBREAKERS' EVOLUTION

The geographical location of Russia, which is characterized by the considerable length of its northern and eastern maritime borders, made necessary the building of a powerful icebreaker fleet. Continuous exploration of the high north and the far east, together with the vicinity of major industrial hubs in freezing non-Arctic seas, pre-determined the quantitative as well as qualitative dominance of the Russian icebreaking fleet.

The tug and rescue ship *Pilot*, having a length of 26 m and equipped with a steam engine with a power output of 85 h.p., which belonged to the tradesman M. O. Britnev from Kronstadt, is considered to be a prototype of the first Russian icebreaker. In order to extend the period of navigation in the Gulf of Finland, he decided to modify the ship's hull structure. In 1864, the fore extremity of the *Pilot* was cut off and its stem was inclined to an angle of 20°, which enabled the ship to climb onto ice using the thrust of its propeller, thus breaking it (Fig. 1).

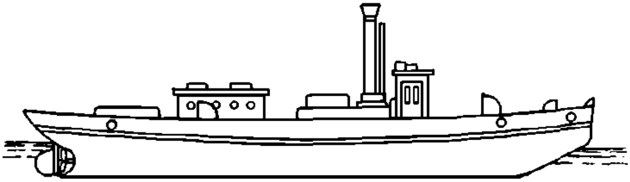

Fig. 1. The *Pilot* steamer, a great-grandfather of the Russian icebreaking fleet.

Afterwards, in 1890, the Russian engineer R. I. Runeberg developed a theoretical dependence interlinking the propeller's thrust, the forebody's hull lines, and the vertical force acting on the stem. This is viewed as an origin for the theory of the construction of icebreakers.[1]

The successful experience of the *Pilot*'s retrofitting served as a basis for the implementation of the Russian idea not only domestically but also abroad.[2]

In 1890, a specialized icebreaker, *Murtaja*, at that time the most powerful in the Russian Empire (1,200 i.h.p.), was built in Sweden for the Head Office of the Finnish Pilotage and Lighthouse Departments. Its length was around 48 m, and its breadth equaled 11 m.

Construction of icebreakers abroad started for the first time in Germany with the aim of ensuring the reliable operation of the port of Hamburg. The leading ship in the series, *Eisbrecher-1* constructed in 1871, had a specific spoon-shaped bow, which proved to be effective in the relatively thin land-fast ice of the Elbe River (Fig. 2). This type of icebreaker was afterward called the *Hamburg* type.

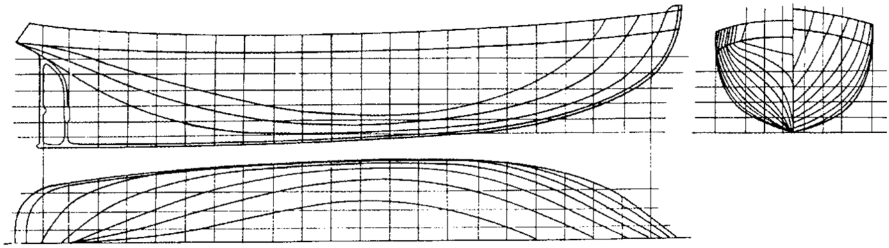

Fig. 2. The hull lines of the *Hamburg*-type icebreaker.

Construction of icebreakers in America started in the late nineteenth century for operation in the Great Lakes. A distinct feature of the *American* type of icebreakers was a propeller installed in the fore ship's extremity, which was used for enhancing its icebreaking capability by sucking off water from below the solid ice and eroding the snow-covered hummocked ice. The first icebreaker equipped with a fore propeller, *St. Mary*, was built in 1893. In total, around 40 medium-sized steam icebreakers had been built by the beginning of the twentieth century.

A special place among the icebreakers built in the late nineteenth century belongs to the first Russian polar icebreaker *Ermak*, constructed upon an initiative, and with the direct participation, of Admiral S. O. Makarov, who believed that such ships would contribute to Russia's exploration of a sea route towards the Ob and Yenissey Rivers, as well as to the year round operation of the port of St. Petersburg. Its construction was ordered at the

British Armstrong Shipyard in December 1897. In January 1899, *Ermak* proceeded to the sea for trials conducted by the shipyard, and in February the ship flew the Russian commercial flag.[3] The *Ermak* icebreaker substantially differed from its predecessors in its larger dimensions and power output. According to the initial design, its maximum length equaled 93 m, its breadth was 21.6 m, its draught 7.6 m, and its displacement was about 9,000 tons. The ship had four steam engines with a total power output of about 10,000 i.h.p., driving three propellers at the stern and one at the fore. Its features also included a heel system, a special structure, and hull lines. These lines, characterized by a wedge-shaped bow, advantageously combined the functions of icebreaking and pushing ice apart and came to be known as the "Russian shape". The final exteriority of the *Russian*-type icebreaker was formed after the *Ermak*'s experimental voyages to the Arctic during the summer of 1899. Following the results of these voyages, in 1901 the fore propeller was dismounted, and the hull structure and shape of the hull lines were modified accordingly (Fig. 3). The *Ermak* icebreaker continued its service for nearly 66 years.

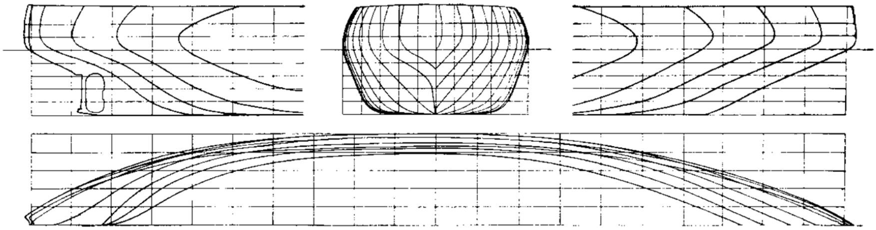

Fig. 3. The hull lines of the *Ermak* icebreaker after its modification

Subsequently, the *Angara* icebreaker, which was intended to service a railroad ferry line crossing Lake Baikal, was built at the same Armstrong Shipyard. It is the oldest surviving icebreaker, preserved since the 1900s to the present day. Currently, it is moored at a special berth on the Irkutsk Reservoir, and serves as a museum (Fig. 4).

Fig. 4. Irkutsk. The *Angara* icebreaker serving as a museum (photo by L. G. Tsoy).

The evolution of the *Russian* type of icebreakers continued during the First World War, when the port of Archangel needed support for its year-round operation gave an impetus to Russia for the urgent construction of new icebreakers abroad. Within this period, the *Tsar Mikhail Fyodorovich* (afterwards, *Volynets*) icebreaker, with a power output of 5,200 i.h.p., the two-propeller *Ilya Muromets* and *Dobrynia Nikitich* icebreakers, each with an output of 4,300 i.h.p., the three-propeller (two propellers aft and one fore) *Kozma Minin* and *Knyaz Pozharskiy* (afterwards, *Stepan Makarov*), with a power output of 6,600 i.h.p., the *St. Aleksandr Nevskiy* (afterwards, *Vladimir Ilyich*), and the two-propeller *Mikula Selyaninovich*, with an output of 8,000 i.h.p., as well as the *Svyatogor* icebreaker of the *Ermak* type, renamed *Krasin* in 1925 (Fig. 5), were built in Germany, Great Britain, and Canada. The *Krasin* icebreaker became known to the whole world in 1928 after having rescued the members of Umberto Nobile's expedition after the crash of the *Italia* blimp on its way to the North Pole. At present, the *Krasin* is berthed on the Neva River in St. Petersburg, and serves in the capacity of a floating museum.

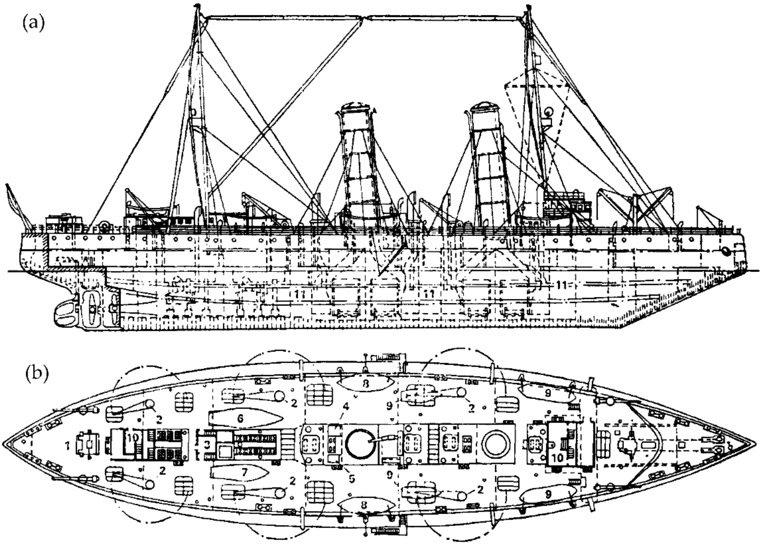

Fig. 5. The *Svyatogor* icebreaker: (a) lateral view; (b) upper deck plan: 1. towing winch; 2. steam cranes; 3. radio room; 4. locker for explosives; 5. snow melting unit; 6. steam tender; 7. boat for handling anchors; 8. lifeboat; 9. ice boat; 10. egresses to middle deck; 11. coal store.

Electric propulsion played a significant role in the evolution of icebreakers' construction. The replacement of steam engines with coal-fired boilers used as main propulsion plants and diesel-electric power installations allowed the specific power rate to increase, thereby improving the maneuverability of icebreakers and the efficiency of their operation. The first diesel-electric *Ymer* icebreaker, with a power output of 10,000 h.p., was built in 1932 in Sweden (Fig. 6). This type was used in 1939 to build the *Sisu* icebreaker in Finland and, some time later, from 1943 to 1946, for constructing in the United States a series of diesel-electric icebreakers of the *Wind* type, which had an output of 12,000 h.p. It is worth mentioning that these latter ships had their hulls welded. Welding was used for the first time for assembling the hull's outer shell in 1939 for the US-built *Raritan* icebreaker.

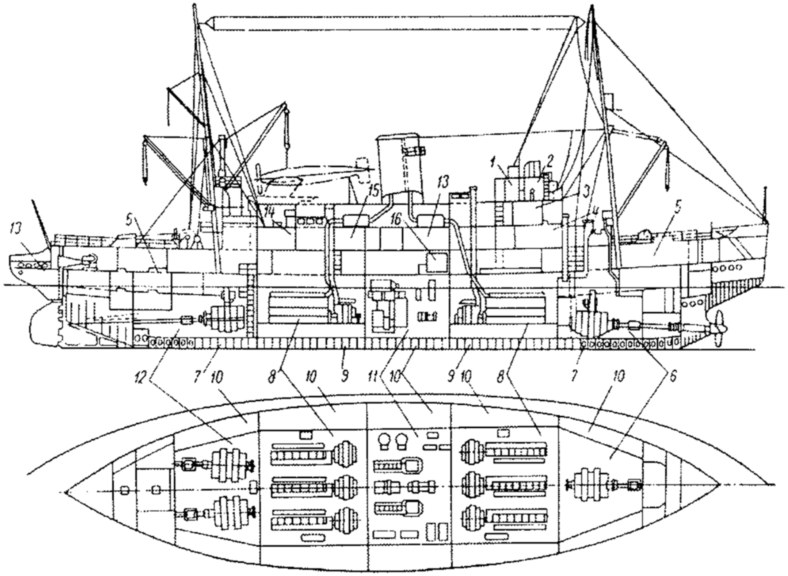

Fig. 6. General arrangement of the first diesel-electric icebreaker *Ymer*: 1. plotting room; 2. wheelhouse; 3. master’s cabin; 4. messroom; 5. cargo spaces; 6. fore compartment for the electric propulsion unit; 7. ballast tanks; 8. compartment for the main diesel alternators; 9. lubricating oil tanks; 10. fuel oil tanks; 11. auxiliary mechanisms compartment; 12. aft compartment for the electric propulsion unit; 13. store spaces; 14. crew canteen; 15. galley; 16. service fuel oil tank.

Shipyards in the Soviet Union proceeded with the construction of heavy-duty, high-powered sea-going icebreakers in 1935. In order to supplement the Soviet fleet of icebreakers, and to widen the scope of operations in the aquatic area of the Northern Sea Route, as well as to enhance the safety of navigation along it, the government took the decision to design and build a series of four steam icebreakers with a power output of 10,000 i.h.p. The *Ermak* and *Krasin* icebreakers were used as prototypes for their design.

In 1935, two icebreaker keels were laid simultaneously in Leningrad, and two in Nikolayev. In 1938, the Baltiyskiy Zavod Shipyard commissioned the lead icebreaker *J. Stalin* (afterwards, *Sibir*). In 1938, the Nikolayev Shipyard commissioned the *Lazar Kaganovich* (afterwards, *Admiral Lazarev*) icebreaker. In 1941, two of the remaining icebreakers of that series were put into operation: *V. Molotov* (afterwards, *Admiral Makarov*) and *Otto Shmidt* (renamed *A. Mikoyan* in the course of its construction). These icebreakers had practically identical main particulars − a maximum length of about 107 m, breadth of 23 m, draught of 9.2 m, displacement of 11,200 tons, and speed of 15.3 knots − and were capable of surmounting solid level ice up to 0.9 m thick while maintaining their continuous pace.

Thus, the Soviet Union had the largest number of icebreakers during the pre-war period. All these ships had steam propulsion plants. The six most high-powered polar icebreakers, each with a power output of 10,000 i.h.p. were owned by the USSR. The main particulars of icebreakers constructed within the stated period are summarized in Table 1.

Of the icebreakers constructed and operated of icebreakers in the first half of the twentieth century, the majority were built and used by the states surrounding the Baltic Sea. Between 1923 and 1938, three high-powered icebreakers were built in Finland, and two icebreakers were constructed in Denmark, two in Sweden, and one in Latvia. These icebreakers were intended for operating in the freezing Baltic ports and in approaches thereto, and for that reason they were equipped with fore propellers. Construction of the Finnish *Voima* icebreaker in 1954, with a total power output of 10,000 h.p., which had two fore and two aft propellers, led to the emergence of a *Baltic* icebreaker type, for which the presence of two fore propellers was a specific distinctive feature (Fig. 7).

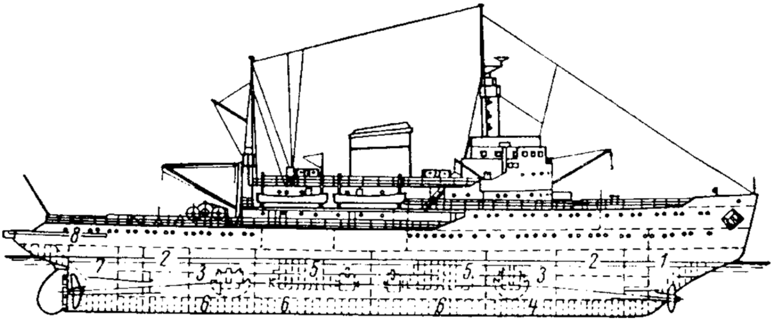

Fig. 7. Lateral view of the *Baltic* icebreaker of the *Voima* type: 1. forepeak; 2. hold; 3. electric propulsion motors; 4. water ballast; 5. main engines; 6. fuel oil; 7. after peak; 8. steering compartment.

The second half of the twentieth century was marked by a complete renovation of the icebreaker fleet. Experience gained from their use demonstrated that a more efficient operation in the ice of the Arctic basin, and of other freezing seas, required the construction of mightier ships and the improvement of their ice performance. That is why the building of