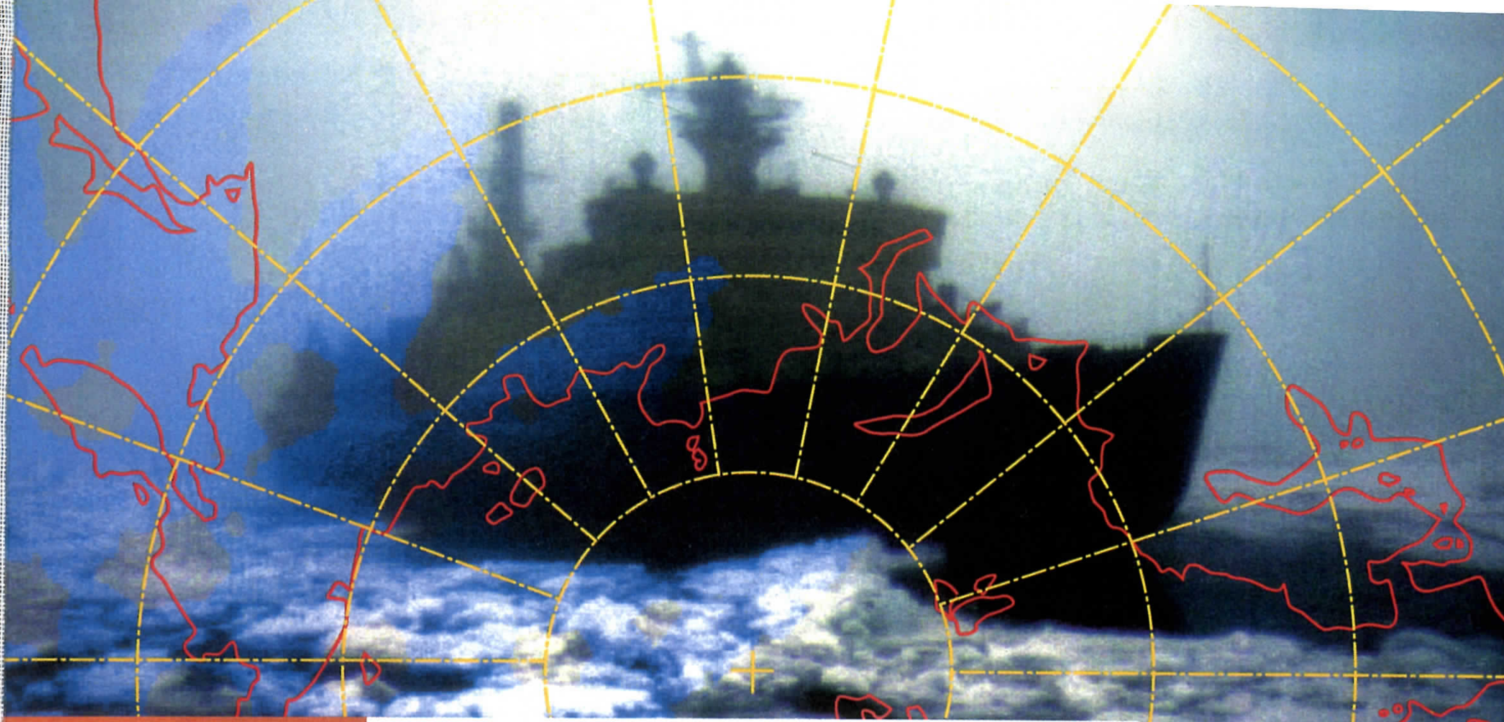

INSROP WORKING PAPER
NO. 160 - 1999, I.1.4

Design Requirements for Future NSR Ships

By L.G. Tsoy, S.B. Karavanov, Yu.V. Glebko,
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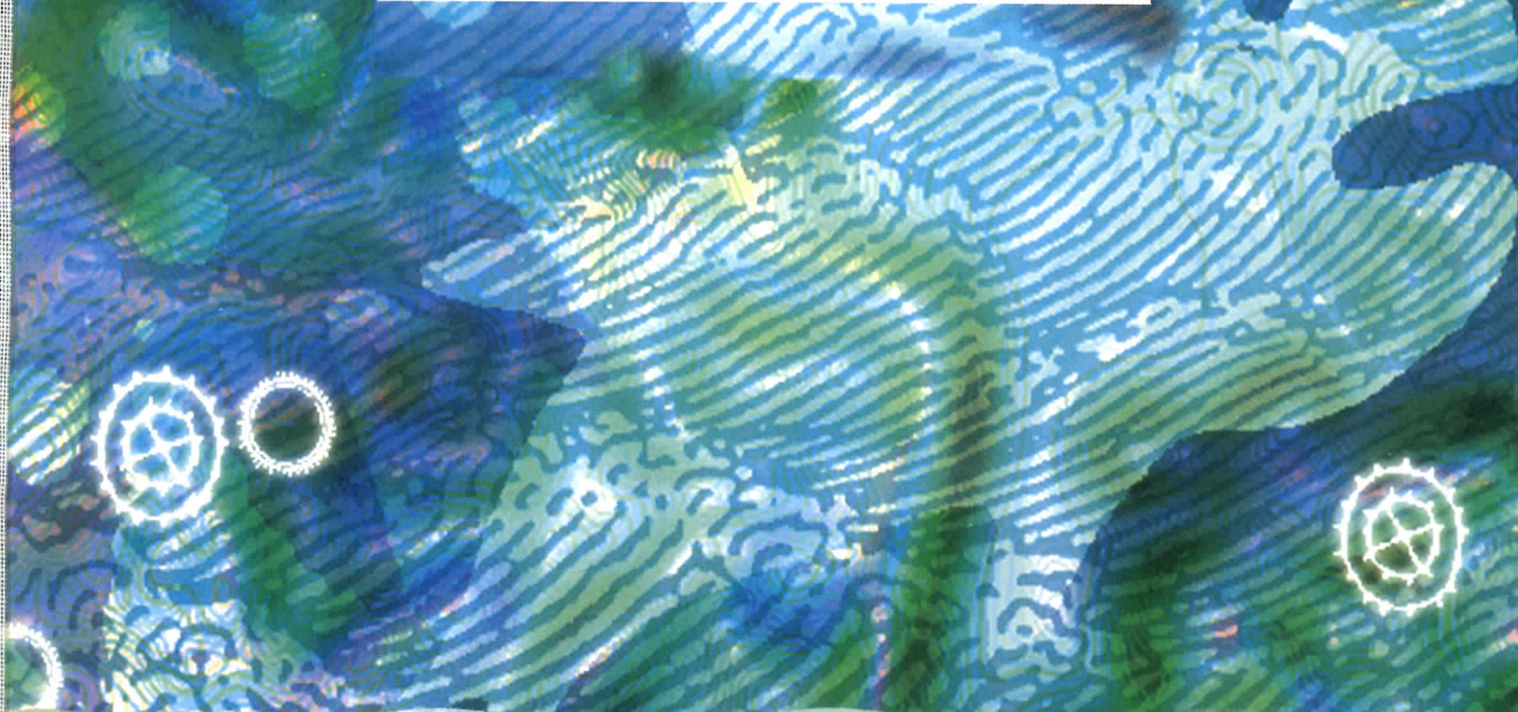

INSROP International Northern Sea Route Programme

Central Marine
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International Northern Sea Route Programme (INSROP)

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Ship & Ocean Foundation, Japan

INSROP WORKING PAPER NO. 160-1999

Box C LR
Sub-Programme I: Natural Conditions and Ice Navigation

Project I.1.4: Design Requirements for Future NSR Ships

Supervisor: Loly G. Tsoy, CNIIMF

Title: **Design Requirements for Future NSR Ships**

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Date: 23 March 1999

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FOREWORD - INSROP WORKING PAPER

INSROP is a five-year multidisciplinary and multilateral research programme, the main phase of which commenced in June 1993. The three principal cooperating partners are **Central Marine Research & Design Institute (CNIIMF)**, St. Petersburg, Russia; **Ship and Ocean Foundation (SOF)**, Tokyo, Japan; and **Fridtjof Nansen Institute (FNI)**, Lysaker, Norway. The INSROP Secretariat is shared between CNIIMF and FNI and is located at FNI.

INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

The complete series of publications may be obtained from the Fridtjof Nansen Institute.

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GENERAL

The objective of this Project was to elaborate design requirements to future ships for the Northern Sea Route (NSR) based on the research and investigation of the experience of design, construction and operation of domestic arctic ships. Safety of the ice navigation in the Arctic, operational and economic efficiency of new types of ships provided for by different scenarios of the prospective cargo traffic on the NSR will to a considerable degree depend on the right choice of their dimensions, power, icebreaking capability as well as on the relation between sizes and ice performance both of cargo ships and icebreakers carrying out the escorting of ships through ice.

In the process of realization of the project, problems concerning the design of modern icebreaking cargo ships and icebreakers were considered and summarized, the experience of their operation studied, statistical data on the ice damageability of hull structures depending on the conditions of navigation and tactics of work collected and analysed. With the help of the systematic simulation and full-scale tests the investigations were made of the influence of dimensions and hull shape of icebreaking cargo ships on the ice performance and seaworthiness. Effect of the shallow water on the ice performance of prospective ice superships was estimated. The required icebreaking capability of these ships taking into account the area and period of their use in the Arctic was determined.

For the subsequent simulation of the transportation by ships of raw materials from the Arctic and the transit navigation along the NSR, dimensional series of large arctic tankers, gas carriers, bulkers and container ships were developed. Accordingly design studies of new types of icebreakers for the escorting of these ships were carried out.

On the basis of the investigations made, technical and operational requirements to main characteristics, construction and ice performance of future ships for the NSR have been prepared and recommendations on the choice of an ice class and a rational hull lines shape of arctic ships given.

Authors of the report on Project I.1.4 are grateful to Dr Keinonen (AKAC, Calgary, Canada) for his attentive familiarization with the present report, for useful comments and high appraisal of the work as a whole. Remarks and proposals expressed by the reviewer have permitted to improve final wording of the report. The reviewer has also touched on discussion issues, especially those concerning untraditional technology, which require further study and clarification. These investigations have to be a subject of separate special research.

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INTRODUCTION

Regions of the North, Siberia and the Fat East of Russia long since have attracted attention by the presence of rich and various natural resources: hydrocarbons, rare and noble metals, valuable minerals. They are concentrated in the unique, as to the scale, deposits not yet sufficiently explored from the geographical, demographic and consequently technical viewpoints. The exploitation of major natural resources of these regions and their commercial usage necessitates the development of productive forces of the North, appropriate infrastructure and the establishment of stable interrelated transport communication

Solution of this problem is associated with need of the extended and more fundamental study of the continental and shelf coast of northern seas, involving development of the extractive and processing industry, different modes of transportation and first of all of the sea and river transport. Only using the sea transport the following principal problems of the development of the arctic region and adjoining areas may be tackled:

- exploration of natural resources of new oil- and gas-bearing provinces in severe, often extreme climatic conditions;
- provision of the vital activity, social and economic development of arctic regions,
- improvement of their productive forces;
- organization of stable transport relations between eastern and western regions;
- use of the Northern Sea Route within the international shipping system.

Efficient solution of the above problems involves the construction of specialized sea ships in the best way adapted for work under severe ice conditions.

Sea transport as the only acceptable mode of transportation providing for large-scale cargo flows in the Arctic plays a key role in the exploration of shelf deposits.

Taking up one fourth of the world ocean shelf area the continental shelf of Russian arctic seas is estimated by specialists as containing more than 75 billion tonnes of hydrocarbons (oil equivalent). Deposits of the Barents, Pechora and Kara Seas with the potential reserves of hydrocarbons as of 1995 amounting to 54 billion tonnes have received the most study. Ten deposits (2 of oil and 8 of gas and gas condensate) have been brought to light here. One should note among them such fields as Prirazlomnoye oil deposit (shallow water area of the Pechora Sea) and Shtockmanovskoye gas-condensate deposit (deep water portion of the Barents Sea).

Shallow water areas of the Kara Sea are promising from the point of view of the future industrial exploitation of oil and gas deposits. Most significant here are Kharasaveyskoye, Kruzensternovskoye and Bovanenkovskoye fields.

Among all the deposits of the Yamal Peninsula shelf one should distinguish those of gas of the Ob and Tazovskaya Gulfs (Tambeyskoye, Novoportovskoye, Kamennomysskoye et al.). Consequently the production of oil and gas in the Arctic was supposed to be carried out by 4 principal regions:

- Pechora Sea (Prirazlomnoye field);
- Barents Sea (Shtockmanovskoye field);
- south-western part of the Kara Sea (Kharasaveyskoye, Kruzensternovskoye and Bovanenkovskoye fields);
- Obsko-Tazovskiy region.

Near the Barents and Pechora Seas one third of all resources of the shelf is concentrated. Objects of the investigation and extraction of mineral resources are situated in comparatively favourable physical and geographical conditions at an acceptable distance from principal consumers. Conception of the exploitation of hydrocarbons of these seas is based on principle of the free drawing in, equally with state consumers, of private investors including foreign ones.

Potential reserves of hydrocarbons on the shelf, coast and in deep land areas are estimated as being 5 billion in the oil equivalent. Programs of the exploration of the region have been developed for last 20 years.

Exploration of the Prirazlomnoye field on the shelf of the Pechora Sea to the east of the Kolguev Island is at present at the stage of preliminary consideration. Joint investigations on the exploitation of the field are carried out by AO *Gazprom*, AO *Rosshelf* and *BHP Petroleum* Company. Main oil reserves are concentrated on shelf at a distance of 65 km from the shore of the Pechora Sea at depths of about 20 m. The transportation of oil is supposed to be made by ice tankers, supported by icebreakers during the winter-spring period of navigation.

The Shtockmanovskoye gas-condensate field discovered in 1988 is situated 650 km to the north of Murmansk and 290 km to the west of the Novaya Zemlya at depths of 320 - 350 m. According to the preliminary estimation, potential reserves of hydro-carbons are: 3 billion cub. m of gas and 22.5 million tonnes of condensate. It is anticipated that the industrial exploitation will begin in 2003. The transportation of gas is supposed to be carried out by the gas pipeline up to Murmansk and further on to the centre of Russia and abroad as well by sea.

Potential resources of the south-western part of the Kara Sea and the Yamal Peninsula are as a whole estimated as 16.6 billion cub. m. As of January, 1, 1990, the explored reserves of gas, condensate and oil are accordingly 5.2 billion cub.m, 337.3 and 417.7 million tonnes. Volume of the largest deposits of the Yamal Peninsula shelf – Kharasaveyskiy, Kruzensternskiy and Bovanenkovskiy – is, according to the predicted estimates, about 6.5 billion cub.m of natural gas.

For more distant future, of practical interest are oil and gas reserves on the shelf of the south-western part of the Kara Sea. On evidence derived from the search geological organization *Sevmorgeologiya*, the predicted oil resources here amount to 14.5 billion tonnes, gas reserves are 19.34 billion cub. m. Of primary attention are two largest local structures – Rusanovskaya and Leningradskaya – located at accessible depths near the mouth of the Kharasavey river. Alternatives of the production of oil and gas on shelf of the Kara Sea and the transportation by sea of hydrocarbons are now at the stage of research and the industrial exploitation will apparently begin after 2015.

In the Obsko-Tazovskiy region, along with such huge continental deposits as Urengoiskoye, Medvezhye, Yamburgskoye et al. the development is under way of the use of resources of the Yamal Peninsula shelf. In the future the transportation by sea out of these regions both of liquefied gas and of gas condensate may be envisaged. Industrial exploitation of this region is possible in case of substantial investments into the development of the infrastructure. It will be necessary to construct a transshipment terminal, port side accumulation capacities for gas condensate and factory for the processing and liquefaction of gas.

One should specially mention the Vankorskoye oil deposit situated in the Turukhanskiy District of the Krasnoyarsk Territory 125 km to the west of Igarka. Production of oil here started in 1995. In the future it is planned to transfer oil to Dudinka or Dickson by a pipeline loading it then onto ships.

Transportation of hydrocarbons by sea from the regions of the Ob and Tazovskaya Gulfs and the Yamal Peninsula is conducted at present only during individual commercial voyages. In the future during the industrial exploitation of the above deposits it is possible to organize a complex system of the transportation of hydrocarbons with the basic point of transshipment onto superships in the port of Murmansk.

Such regions as the Taimyr Peninsula and the Khatangskiy Gulf are also rich in deposits suitable for the industrial exploitation. Here there are considerable reserves of hydrocarbons and of other mineral resources and in some distant future a large-scale industry may come into being with the possible use of sea ways of transportation. Among numerous natural resources of the Khatangskiy Region of special interest are the reserves of apatites in the vicinity of Maimecha-Kotuy. The exploitation and taking out of this raw material by sea may be an alternative to depleting resources of the Kola Peninsula.

Of significant importance is the use of the Northern Sea Route for transit carriage of national-economic cargoes from the Far-East to western areas of the country and of cargoes of foreign freighters from countries of the South-Eastern Asia, China and Japan to the Western Europe. At the beginning of the 90-ies the volume of transit transportation exceeded 200 000 tonnes. It gives rise to prerequisites for further study of the development of through transportation along the Northern Sea Route between the West and the East. In accordance with the preliminary data, some 750 000 tonnes of chemical and mineral cargoes can be drawn for the transportation along the NSR. These cargoes include first of all apatites to be carried to China and chemicals to be transported to Japan and the South-East Asia. Besides, it is intended to transport transit cargoes in containers.

The above outlooks for the development of untraditional large-scale transportation of cargoes in the Arctic will require the construction of principally new types of arctic ships. These are mainly large icebreaking oil tankers, gas carriers for the transportation of the liquefied natural gas, large bulk carriers and container carriers.

The present work based on the study of the experience of operation of the domestic fleet in the Arctic and on the investigations of design characteristics and ice performance of icebreaking cargo ships to be built in the future formulates principal technical and operational requirements for their design. In compliance with the specific character of work of these ships in ice, main attention was paid to the requirements for the ice class, structure, ice impact strength, ice propulsion, means improving the icebreaking capability and hull shape of future ships for the Arctic depending on their purpose and navigational conditions.

1. GENERALIZATION AND ANALYSIS OF OPERATIONAL CONDITIONS AND ICE DAMAGES OF ARCTIC SHIPS

1.1. General characteristic of the ice damageability of cargo ships working on the Northern Sea Route

In the middle of seventies, with the advent of new nuclear icebreakers as a part of the arctic fleet the period of operation in ice of cargo ships was considerably extended. This led to the increase of ice loads on ships and consequently to the growth of the ice damageability of hulls having no structural strengthenings of the underwater portion of ship which would conform to more rigid ice conditions. The subsequent increase of the number of new powerful icebreakers on the NSR associated with the extension of periods and areas of navigation of ships under heavy ice conditions called forth ever sharper increase of the damageability level of arctic ships. Average level of the relative susceptibility to failure in ice at the beginning of eighties was 2 - 2.5 times as high as that of the beginning of seventies.

It should be noted that more severe operational conditions of ships over the entire NSR resulted in the increase of the damageability of hulls not only of old worn out ships, but also in greater number of heavy hull ice damages of modern ships built in accordance with the Rules of the Marine Register of Shipping at leading foreign yards for the highest ice categories UL and ULA [1, 2, 3].

Distribution of hull ice damages by classes (ice categories) of ships largely reflects the composition of the fleet used in arctic navigations. Of the highest frequency lately became damages within the most numerous group of ships involved in the arctic traffic - those of category UL the strengthenings of which are inadequate for the intensive operation in the Arctic, especially in its Eastern area. Heavily worn out ships (older than 15 years) suffer ice damages practically on every passage through ice (mainly ships of category L1). In the Arctic however also ships with particular strong hulls (of category ULA and icebreakers) are often damaged accounting for 25 - 30 % of the total number of damages. This is associated with their use under extreme severe ice conditions. In the mid- and at the end of eighties the share of ULA class ships in the group of the most frequently damaged ships drastically increased.

Ice damageability of arctic ships and the distribution of damages over the hull areas depend on a number of factors including the complexity of ice conditions during the navigation period, tactics of sailing through ice, structural features, extent of the ship's hull wear, ice class of ship.

While analysing the damageability of cargo ships in the arctic ice it is necessary to take into account the fact that in the Russian transport fleet only ULA class ships are directly adapted for the work in the Arctic all the year round. UL class ships (analogous with the highest Baltic class 1A Super of the Finnish-Swedish Rules) are intended for use on the NSR only during the summer-autumn period of navigation under the assistance of icebreakers. L1 class ships may be admitted for the navigation in the Arctic under the easiest ice conditions in summer (in open floating ice decayed by melting). These recommendations are formulated in the "Rules of navigation along the NSR" [4] and proved by more than half a century experience of navigation in the Arctic of the domestic fleet – L1 class ships account for up to 50 - 75 % of all ice damages of ships during the arctic navigation. Ships of the L1 category represent mostly reclassified old ships of the former UL class considerably worn out with time. Their use in the arctic navigation was bound up with the necessity to provide for the heavy cargo traffic characteristic of the Arctic in the seventies and eighties. Only recently due to the obsolescence of these ships and their replacement with those more adapted for sailing in the Arctic and built in accordance with the improved Register Rules their share in the total extent of the ice damageability began to diminish. Dynamics of this change is shown in Table 1.1.

Table 1.1

Dynamics of the damageability of hulls of ships of principal classes, %

Class	Years							
	1960-ies	1974-76	1978	1981	1983	1987	1988	1989
ULA	3	2	2	1.3	9	8	13	16
UL	28	5.5	6.5	19	19	41	34	42
L1	40	73	74	68	54	37	33	16

The greatest number of ice damages (up to 70 % – 1983) and their largest sizes are observed in the east of the Northern Sea Route, mainly in the East Siberian and Chuckchee Seas characterized by the heaviest ice conditions on the NSR. During heavy (as to ice conditions) navigation periods up to 50 - 60 % of all ice damages of the arctic fleet occurred just on the ships which were operating on this section of the route.

Absolute sizes of ice damages of the shell plating and framing considerably differ. So, the major part of bulges and corrugations of plating have deflections of 15 - 50 mm, only individual bulges reaching 70 - 80 mm. Dents (hull framing damages) are mainly from 30 - 40 mm up to 100 - 200 mm deep. Below there are graphs of the probability **F** that possible deflection of a framing element may exceed the value of deflection **f** plotted on the abscissa (Figures 1.1 and 1.2, where **r** – probability of the occurrence of the given permanent deflections). Figure 1.1 shows graphs for particular ships, Figure 1.2 – generalized graphs for ships of classes UL and ULA.

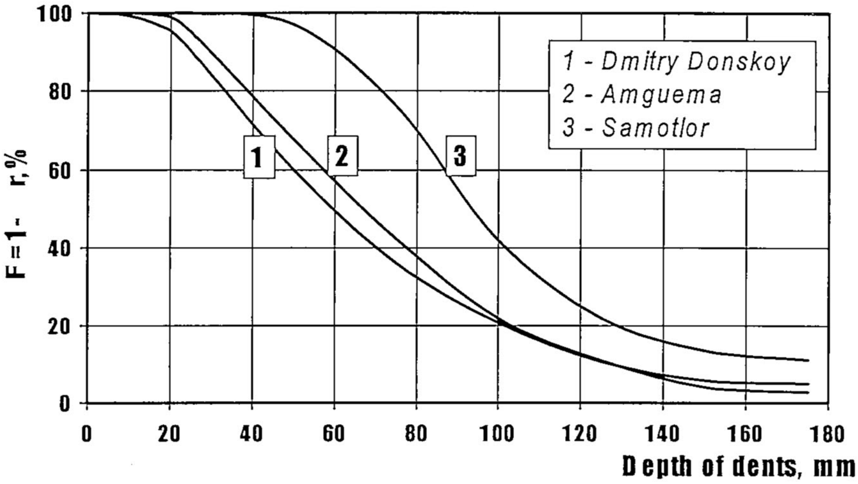

Fig.1.1. Graph of function **F** = **1** - **r** for bottom strakes of the middle and intermediate parts of the hull

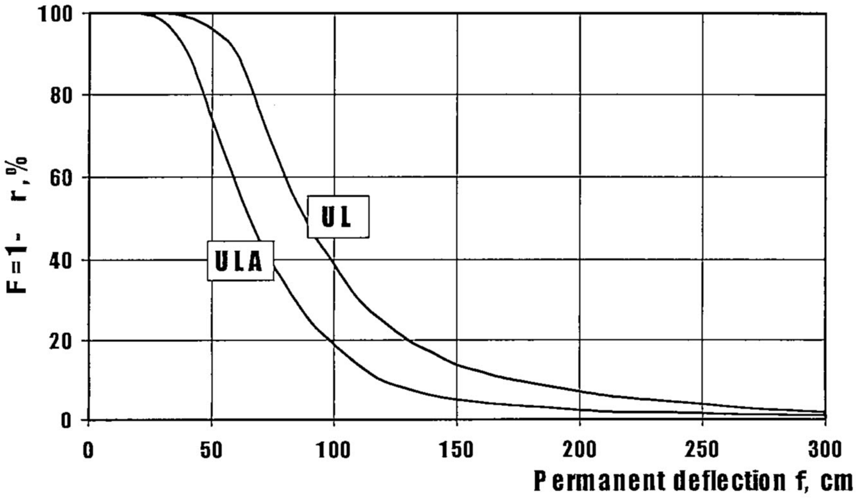

Fig.1.2. Generalized graph of function **F** = **1** - **r** for the forebody of ships of classes UL and ULA

The largest sizes of damages for ships of different classes also differ. So, with ships of class L1 (*Baskunchak, Pioner*) the hull of which is not sufficiently strengthened for the navigation through arctic ice, maximum depth of dents reaches 400 - 500 mm, with ships of the UL class (*Samotlor, Dmitriy Donskoy*) – 250 - 300 mm, with ships of the ULA category of strengthening (*Amguema, Norilsk*) specially constructed for operation in the Arctic the depth of dents does not exceed 200 - 250 mm. Characteristics of ships representing these classes are given in Tables 1.2 and 1.3.

Table 1.2

Principal characteristics of cargo ships of category ULA

Characteristics	*Sevmorputj*	*Norilsk*	*Amguema*
Length between perpendiculars, m	228.8	159.6	118.4
Breadth, m	32.2	24.5	18.5
Depth, m	18.3	15.2	11.6
Draft, m	10.7	9.0	8.9
Deadweight, t	25480	14700	9050
Load carrying capacity, t	22200	10350	7000
Displacement, t	54380	25900	14160
Type of engine	Nuclear	Medium speed	Diesel-electric
Shaft power, kW	29420	13960	4400
Speed, kn	19.8	18.1	15
Icebreaking capability, m	1.4	1.0	0.6

Ships of category L1 have numerous framing damages including holes over the entire side and bilge the extent of damages to the structural elements (such as maximum bending deflection) being 1.5 - 2.0 times and more as large as those for ships of the highest ice classes.

Proportion of damages (bulges, corrugations and dents) followed by the leakage varies within 25 - 40 % of the total number of hull ice damages.

Dents in this respect are the most hazardous hull ice damages because, as the experience shows, even large deflections of plating between the framing (bulges, corrugations), as a rule, do not cause the water leakage.

Table 1.3

Principal characteristics of cargo ships of categories UL and L1

Characteristics	*Dmitriy Donskoy*	*Samotlor*	*Volgoles*	*Pioner*	*Baskunchak*
Ice category	UL	UL	L1	L1	L1
Length between perpendiculars, m	154.9	148.0	115.0	96	74
Breadth, m	22.9	23.0	16.7	15.6	12.2
Depth, m	13.5	12.9	8.45	8	5.3
Draft, m	9.9	9.2	6.8	6.8	4.6
Deadweight, t	19890	17200	5895	4670	1660
Load carrying capacity, t	18740	15100	5170	4090	1540
Displacement, t	27340	24570	9220	7200	2920
Type of engine	Low speed	Low speed	Low speed	Low speed	Low speed
Shaft power, kW	8240	8360	2980	2300	1470
Speed, kn	15.2	15.7	14.8	13.8	13.2
Icebreaking capability, m	0.6	0.5	0.3	0.3	0.3

Deep bulges may be accompanied by cracks only on the extremely worn out ships (with the wear of plating exceeding admissible standards) this usually pointing to the slipshod operation of ship. Probability of the occurrence of a water leaking bulge with the undamaged framing is very low.

It should be noted that when dents are deeper than 80 - 100 mm in joints of the framing with plating, in the latter water leakage cracks arise; with deflections ≤ 200 mm their disclosure, as a rule, does not exceed 30 mm and the extent may reach 1 - 1.5 m. With large sizes of dents these parameters are increased more than twice (L1).

On ships of the highest ice categories UL and ULA holes occur comparatively seldom and, as a rule, are associated with operator errors (for instance, forecastle, hawse areas and stem damages at ships' close towing) or with the movement under especially complex ice conditions (characteristic of the Eastern Region of the NSR).

The distinguishing feature of ice holes is their relatively small area. The majority of such holes arise within dents and represent slit cracks formed in weld seams or in the near-seam zone. Such cracks – holes extend usually along the ship, more seldom – across, having a length of 50 - 1000 mm and edge disclosure from 2 up to 50 - 60 mm. In rare cases of heavy damages the extent of ice cracks may reach 2 - 3 m and width of their disclosure – 100 - 200 mm. As a whole, for a navigation the number of water leakage damages varies from 20 - 30 % to 45 - 50 % (L1 class ships) of their total number.

Operating experience of the transport fleet in the Arctic shows that the majority of hull ice damages of cargo ships occur while moving through channel behind the icebreaker (including close towing).

Not more than 10 - 12 % of ice damages occur during the independent sailing and contraction. This relationship is also in agreement with the distribution of the number of ice damages between separate hull portions over the length of ship: from 60 to 80 % of ice damages are concentrated in the forebody and not more than 20 % of damages fall within the midship, Figure 1.3.

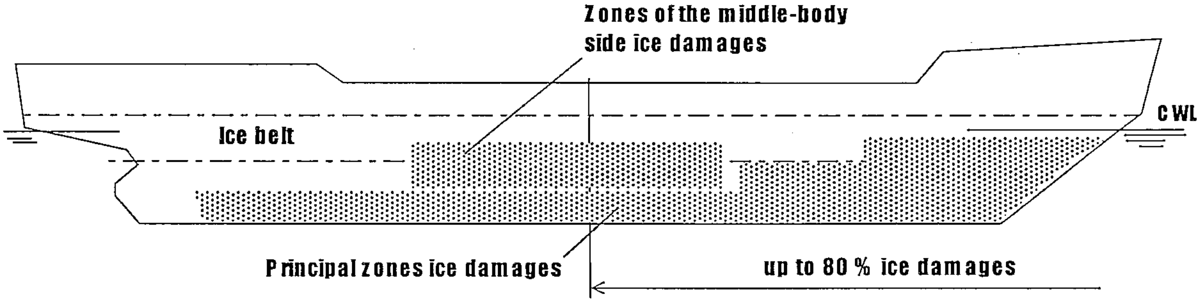

Fig.1.3. Distribution of permanent ice deflections over the underwater hull portion of ships of arctic navigation

Only on ships of category ULA which closely approach, as to working conditions, icebreakers the most damaged area is somewhat shifted abaft and embraces the midship. Bottom grillages of the ships which follow the icebreaker at a close tow are exposed to higher ice loads caused by the impact of ice blocks thrown off from under the icebreaker propellers. Location of the most frequently damaged hull areas is shown in Table 1.4 where letters F, A, B, C designate forepeak, fore- , middle- and afterbody.

Table 1.4

Damageability of hull areas as shares of the total number of damages, %

Area	ULA	UL	L1
Side	30 (B - 21, A - 8)	63 (A - 33, F - 28)	50 (A - 25, F - 13)
Bilge	19 (A - 14, B - 6)	19 (A - 11, B - 6)	23 (A - 18, B - 4)
Bottom	51 (A - 35, A - 10, C - 6)	14 (A - 4, B - 6, C - 4)	26 (A - 18, B - 7, C-1)

Distribution of ice damages in sides, bilge and bottom shown in the table is rather approximate because during the inspections for defects at the ship repair facility the bilge sometimes is not separately distinguished, but falls into either bottom connections or the side grillage. At the same time, it follows from the table that bilge and bottom account for 30 - 70 % of all damages. This is associated mainly with the shallow water of the NSR. Apparently for superships with a high draft the influence of the shallow water on the damageability will be even more substantial.

The predominant proportion of ice damages of grillages (up to 90 %) is of local nature that is consists of local dents – damages of framing elements restricted in length (individual stiffeners, brackets, web plates). The analysis shows that framing damages of the kind are mainly linked with the inadequate stability of plate structures (framing webs, brackets, diaphragms) when exposed to local ice loads – Figure 1.4. As a rule, the indicated plate structures are 10 - 12 mm thick and either are not supported by stiffeners at all or the latters are too widely spaced. Due to this factor, at impacts against large ice floes (in the wall plane) the areas of such plates adjoining the shell plating easily lose their stability and are bulged. To prevent these damages, it is necessary producing walls out of plates not less than 14 - 16 mm thick simultaneously installing sufficient number of additional stiffeners.

On ships of the highest ice categories UL and ULA there is practically no loss of the bearing capacity of the (entire) grillage.

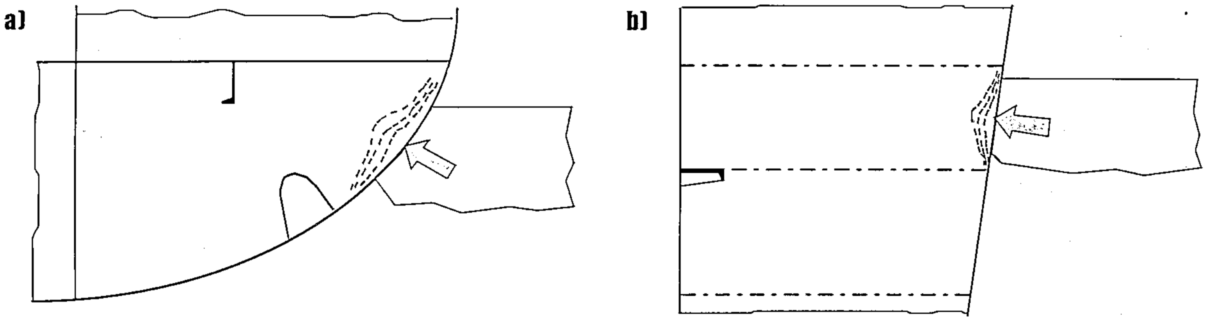

Fig.1.4. Typical ice damages of framing webs (a) and diaphragms (b)

As it was already noted, more rigid operating conditions on all routes of the Arctic Basin resulted in the considerable increase of the number of heavy hull ice damages of modern ships built according to the USSR Register Rules for ice categories UL and ULA.

So, numerous damages of the shell plating and framing were recorded on tankers of the *Samotlor* type built for category UL of the USSR Register. These are mainly damages in the forebody as well as those of bilge and abutting bottom strakes right to the midship. The maximum deflections of framing on these ships reached 200 mm, several dents were up to 300 mm and bulges up to 70 - 80 mm deep. To ensure resistance in the Arctic to ice loads typical for ships of this category, extra ice strengthenings had to be fitted in the process of the repair of ships.

Similar character of ice damages is observed on large ice ships of active navigation (ULA) of the new generation – of the *SA-15* type, though these ships (for instance[1], *Norilsk*) are specially designed for all the year round operation in the western area of the Arctic with regard to the requirements of the Register Rules published in 1981 adequately taking into consideration present-day conditions of the ice operation of ships in the Arctic.

The most damageable hull portions on the domestic arctic ships are forepeak, bilge strakes and abutting bottom areas in the forebody and amidships. High susceptibility to damages of bottom strakes is attributed both to the escorting of ships by close towing and to the shallow water of the NSR. It should be noted that for sister ships operating in western and eastern regions, along with common features there are certain differences in the location of zones of the mass ice hull damages especially different being their sizes. So, heavy ice damages of hulls of the *Norilsk* type ships in the forepeak sometimes accompanied by the water leakage (Figure 1.5) were recorded only after voyages in ice of the eastern region of the Arctic. After sailing in this area during very early periods of the navigation characterized by the heaviest ice conditions, hulls of this type of ships suffered extensive side ice damages also amidship embracing partially ice belt structures – Figure 1.6. It should be noted that on modern ships of the highest ice classes UL and ULA operating in the western part of the NSR, ice damages of side grillages in the midbody are not detected.

Practically all ships of the *SA-15* type which regularly made voyages in the eastern region of the NSR (especially in autumn and winter) – *Arkhangelsk, Bratsk, Igarka, Monchegorsk, Okha, Nikel, Nizhneyansk, Anadyr, Kola* et al. suffered from numerous heavy damages. Sizes and number of ice damages received in the east of the NSR are much larger than in the west. For instance, for ships of the *Norilsk* type the area of damages is on the average 100 - 300 m^2 per ship (in the west it is 50 - 60 m^2). After navigations in the eastern part of the NSR, in the process of repair hundreds of square meters of the underwater plating and framing are replaced mainly in almost inaccessible areas of the bilge and the second bottom.

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[1] List of ships of the series with the indication of shipowners is given in the Annex, Table A.1

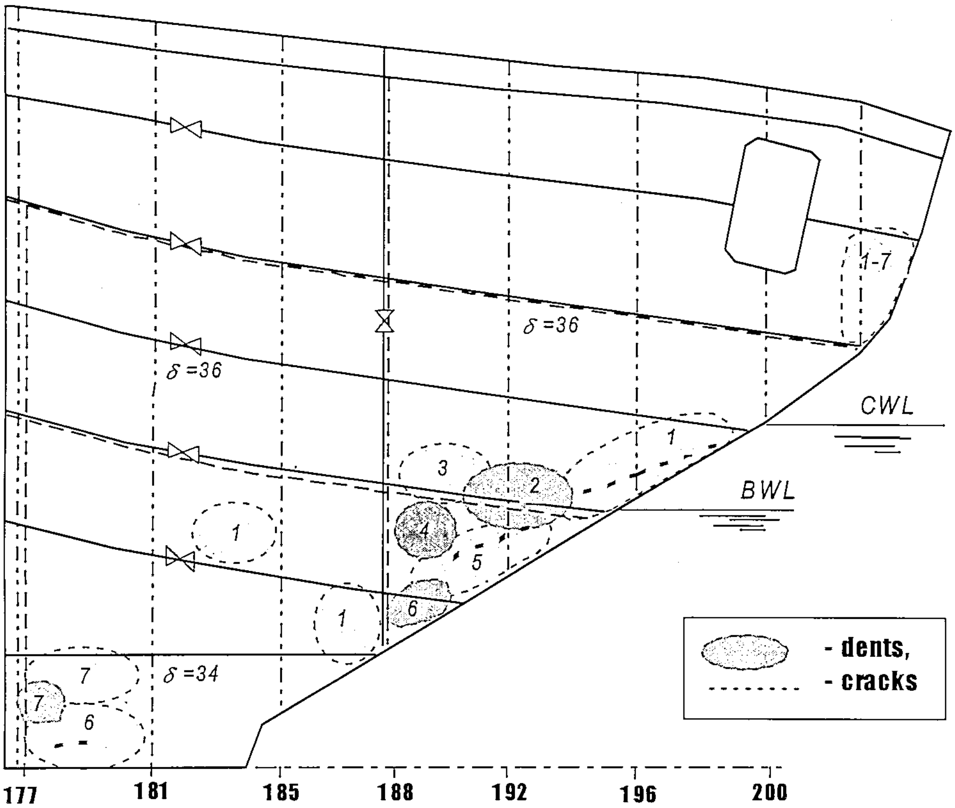

Fig.1.5. Ice damages (dents and cracks) in the forepeak plating of ships: *Arkhangelsk* (1), *Monchegorsk* (2), *Anatoly Kolesnichenko* (3), *Igarka* (4), *Bratsk* (5), *Anadyr* (6), *Nikel* (7)

Modern arctic ships fairly well sustain the loads arising as a result of ice pressure. The portion of structural damages caused by the ice pressure does not exceed 5 - 6 % of the total number of damages. The ice pressure accompanied often by the shearing of floes along the pressure front is of serious danger principally for old ships with considerable age wear of members (such as category L1 ships of the *Pioner* and *Volgoles* types). Hull damages of ships of these types caused by the ice pressure are excessively large and even resulted in the loss of timber carrier *Vitimles* (*Volgoles* type) in 1964 and of motorship *Nina Sagaidak* (*Pioner* type) in 1983 in the East Siberian Sea. The experience has shown that ice strengthenings of category L1 do not provide safety of ship during its operation in the eastern part of the NSR.

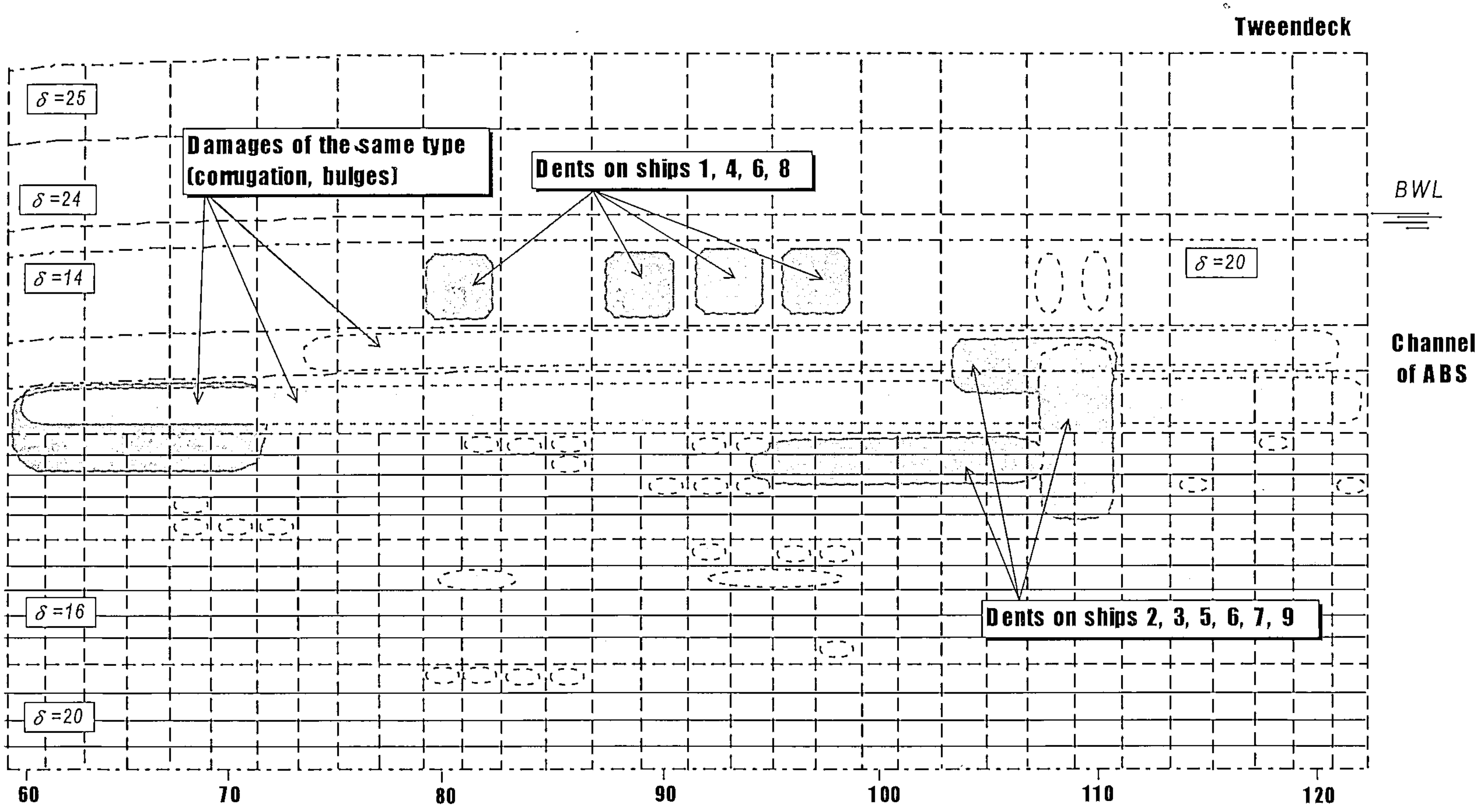

Fig.1.6. Ice damages in the midbody: *Arkhangelsk* (1), *Bratsk* (2), *Kandalaksha* (3), *Kola* (4), *Kemerovo* (5), *Monchegorsk* (6), *Nizhneyansk* (7), *Nikel* (8), *Tiksi* (9)

While analysing ice damages, of considerable difficulty is to determine ice conditions under which the damages occurred. These conditions are adequately identified only if the damage is caused during the action of ice pressure. Medium and moderate damages arising in the course of the ship's movement through ice practically are not accompanied by any specific effects and therefore are not identified during the voyage. Such damages are detected only by the hull inspection in dock after the navigation when it is already impossible to accurately identify conditions of their occurrence.

1.2. Reasons of hull ice damages of arctic ships

Along with complicated navigational conditions (ice situation characterized in the Russian Arctic by high variability) there are the following technical and operational reasons of the high level of ships' damageability on the Northern Sea Route:

- special features of construction and of the hull lines shape of cargo ships;
- errors and deviations from the Rules requirements admitted in the design of structures;
- use of ships with insufficient hull ice strengthenings in the areas of heavy ice conditions (for instance, use of the UL class ships during early periods of navigation in the east of the NSR);
- considerable wear (including corrosion) of hull structures in the zone affected by ice loads;
- poorly selected tactics of the icebreaker escorting, errors of operators in the choice of the speed of movement of ships through ice;
- contact of the ship's bottom with the ground under conditions of the shallow of arctic routes (ships carrying out the supply operations often operate under such conditions).

It is worth noting that from the analysis of ice damages it was not possible to establish any direct relationship between these damages and mass and power of ships, the fact of interest for the design of future superships for the Arctic. Apparently the existing Rules of the classification and construction of ice ships within certain limits fairly well account for the effect of these factors while assigning ice loads and determining the extent of ice strengthenings of cargo ships. At the same time there are grounds to think that in the process of the operation of future arctic ships the influence of the mass increase may show up as some increase of sizes (extent) of the zones of hull ice damages of new large icebreaking cargo ships the displacement of which may several (3 - 4) times exceed that of modern large arctic ships of the *Norilsk* or *Dmitriy Donskoy* types.

It is apparent that powerful cargo ships with a displacement of 70 000 - 100 000 tonnes and over would be able to independently surmount considerable distances through ice including medium and thick one. As these ships due to their great mass have considerable inertia it is quite probable that they can collide at a high speed with large ice floes or fast ice the thickness of which exceeds the ice thickness broken by bending (equal to or over 3 m) that is with the heavy ice practically not shifted at the impact.

As applied to this scenario, proceeding from known theoretical prerequisites, one may in a numerical way approximately assess the effect of the variation of the ship's mass $\mathbf{M}_i$ on sizes of the contact zone and values of force parameters of the collision – of the total force **P** and intensity of ice loads **p** with the use of relations obtained on the basis of the hydrodynamic model of the ship's impact against ice [5].

According to this model and on the basis of [5, 6], corresponding values of the total contact force **P**, height of the zone of hull/ice contact $\mathbf{b}_k$ and ice pressure intensity **p** are determined by formulas:

$$\mathbf{P} = 0.88\ \mathbf{V}_0^{17/12}\ \mathbf{M}^{2/3}\ (2\mathbf{R})^{1/6}\ \mathbf{a}_p^{2/5}\ \mathbf{F}_P\ , \qquad (1.1)$$

$$\mathbf{b}_k = 1.25\ \mathbf{V}_0^{7/12}\ \mathbf{M}^{1/3}\ (2\mathbf{R})^{1/4}\ \mathbf{a}_p^{-2/5}\ \mathbf{F}_b\ , \qquad (1.2)$$

$$\mathbf{p} = 0.61\ \mathbf{V}_0^{13/24}\ \mathbf{M}^{1/6}\ (2\mathbf{R})^{-1/12}\ \mathbf{a}_p\ \mathbf{F}_p\ , \qquad (1.3)$$

where

$\mathbf{V}_0$ - ship's speed at the moment of impact;
M, R - ship's mass and curvature radius of the ice floe edge;
$\mathbf{a}_p$ - ice crushing strength factor;
$\mathbf{F}_P$, $\mathbf{F}_b$, $\mathbf{F}_p$ - shape functions depending on angles between tangents to frames and waterlines and the central plane.

Taking the hull shape (factors $\mathbf{F}_P$, $\mathbf{F}_b$, $\mathbf{F}_p$), ice strength $\mathbf{a}_p$, ice floe curvature radius **R** and ship's speed at the moment of impact $\mathbf{V}_0$ to be constant one can estimate the anticipated effect of the variation of the ship's mass $\mathbf{M}_i = \mathbf{k}_i\ \mathbf{M}$ upon the value of ice loads **p** and contact zone sizes.

Let us consider two versions of the increase of the ship's mass $\mathbf{M}_i$ at $\mathbf{k}_i = 2$ and $\mathbf{k}_i = 4$.

It follows from formulas (1.1, 1.2 and 1.3) that change of values **P**, $\mathbf{b}_k$ and **p** will be accordingly proportional to $\mathbf{M}_i^{2/3}$, $\mathbf{M}_i^{1/3}$ and $\mathbf{M}_i^{1/6}$ that is the increase of **P**, $\mathbf{b}_k$ and **p** will be equal to corresponding power of factor $\mathbf{k}_i$ (Table 1.5).

Table 1.5

$\mathbf{k}_i$	$\mathbf{P}_i / \mathbf{P}$	$\mathbf{b}_{ki} / \mathbf{b}_k$	$\mathbf{p}_i / \mathbf{p}$

2	1.59	1.26	1.12
4	2.53	1.59	1.26

In that way the increase of the intensity of ice loads at the double increase of mass possible with the unaltered traditional lines shape will be 12% ($\mathbf{b}_k$ – 26 %) , at four-fold increase - 26% ($\mathbf{b}_k$ – 59 %).

As the investigations (Chapter 2) have shown, however, such increase may be compensated by the improvement of the hull lines shape of ships to be built in the future. It seems real, because the increase of the icebreaking capability of prospective icebreaking cargo ships through the improvement of the bow lines shape is in turn accompanied by the reduction of ice loads on the forebody.

2. INVESTIGATION OF THE EFFECT OF THE HULL LINES SHAPE OF ICE SHIPS ON ICE LOAD VALUES

The form of forebody lines of ships substantially affects ice load values in the ship / ice impact contact zone. The effect of the hull shape on ice loads is taken into account both by the Rules of leading foreign classification societies (American Bureau of Shipping, CASPPR) and by the Rules of the Russian Marine Register of Shipping (MRS). The regulation of design ice loads in the MRS Rules is based on the solution of hydrodynamic problems of the ship's hull collision with a floating ice floe obtained in the 70-ies at AARI by Yu.Popov, D.Kheisin, V.Kurdyumov [5, 6]. Proceeding from this solution the authors have produced a formula for the calculation of the intensity of ice loads (1.3) permitting with a reasonable completeness to take into account the effect of the shape of bow lines on ice load values. This relationship formed later the basis of the calculation of ice loads in the MRS Rules for ships of all ice classes. In a general way this relationship is presented in the Rules as formula:

$$\mathbf{p} = \mathbf{a}\ \mathbf{A}\ \mathbf{D}^{n}\,\mathbf{F}_{p}(\alpha, \beta)\ , \qquad (2.1)$$

where

a - factor taking into account the ice class of ship,

A - function of the ship's dimensions (displacement),

D - ship's displacement,

$\mathbf{F}_p(\alpha, \beta)$ - hull's shape parameter,

α, β - angles between tangents to the waterline and frame and the central plane in the considered section, degrees.

As one can see from the formula, the hull shape factor (shape parameter) $\mathbf{F}_p$ directly affects the value of ice loads. Character and magnitude of this effect may be determined by the comparative analysis of the dynamics of the variation of numeral values of this factor for ships representing different ice classes as well as of fluctuations of its values within one class at various inclination angles α and β. Such analysis may allow developing specific recommendations on the design of hull lines of the prospective arctic superships aimed at the reduction of ice loads on the forebody.

In the MRS Rules it is customary to divide the forebody into two sections - the first one extends to 0.25 **L** from the fore perpendicular and the second is located abaft of the first section. Let us consider the variation of the hull's shape parameter $\mathbf{F}_p$ for a large area of the forebody defined in the Rules by relationship:

$$F_P = (0.278 + 0.18\bar{x})\,(\alpha^2 / \beta)^{1/4}, \qquad (2.2)$$

where

$\bar{x} = x / L$ – relative distance of the section from the fore perpendicular,

L – length of ship.

Results of the calculations of shape parameters are given in Figure 2.1, where F_P parameter is plotted against the distance of the section from the fore perpendicular $\bar{x}$ for ships of ice classes ULA and UL used for the arctic traffic.

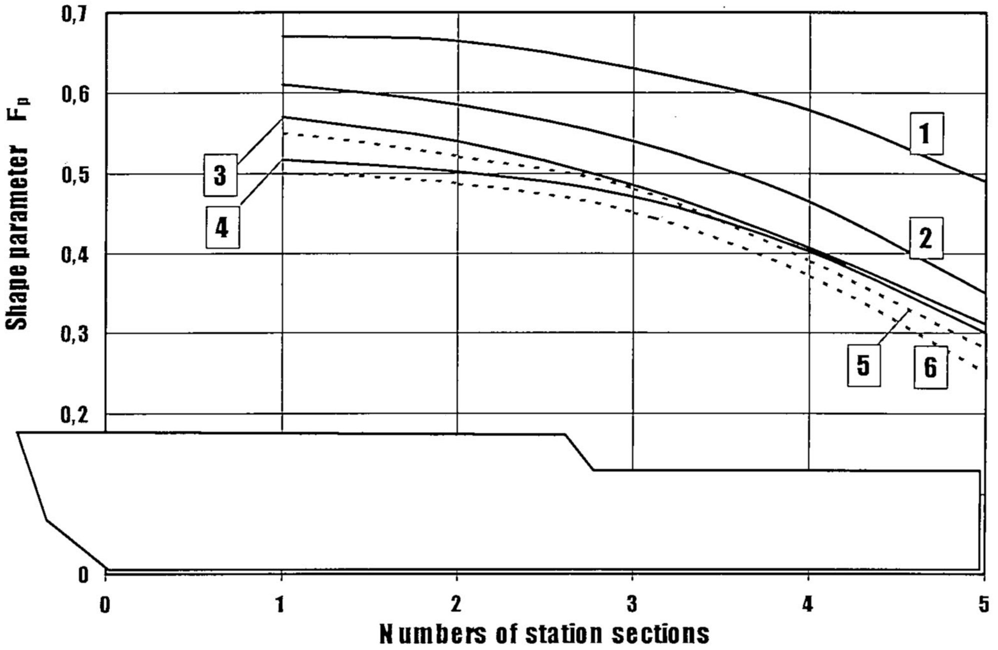

Fig.2.1. Values of parameter Fp: upper limit for ships of the UL (1) and ULA (2) categories; ships *Norilsk* (3) and *Sevmorputj* (4); recommended values for ships of the UL (5) and ULA (6) categories

As one can see from the plots, the smallest (best) values of the hull shape parameter are characteristic of fairly new ships of the *Sevmorputj* and *Norilsk* (both ULA) type. Exception is the area adjacent to the stem 0 - 0.1 **L**, F_P = 0.56 - 0.6 where quite a number of heavy ice damages on ships of the *Norilsk* type is detected. First domestic ships of the ULA class, *Amguema* type, successful in this respect have the hull shape parameter F_P = 0.54 - 0.55.

Taking into account the fairly compact position of F_P curves for different ships it seems possible in the real range of values of the block coefficient (0.66 - 0.76 for classes ULA and UL), while designing the hull, to provide for minimum values of Fp shown in Figure 2.1 by dotted lines.

It should be noted that on ships of class L1 as well as on some ships of class UL with a low level of the ice damageability (*Pioner, Baskunchak, Samotlor*) the shape parameter in the forebody part of the hull reaches the highest values – about 0.65 - 0.67.

Extent of the effect of hull shape characteristics (α and β) upon the value of design ice loads on the forebody may be illustrated by the comparison of ice loads determined by the above formula (1.3) for two versions of lines of ship of the *Norilsk* type).

The comparison was made for a production type ship with traditional bow lines – SA-15 and ship of the same design, but with substantially increased (according to the proposal of the Canadian company *Canarctic*) flare of fore frames (with a forebody of the *Melville Bow* type). Results of the calculations are presented in Figure 2.2 as curves describing the distribution of design ice loads lengthwise the forebody.

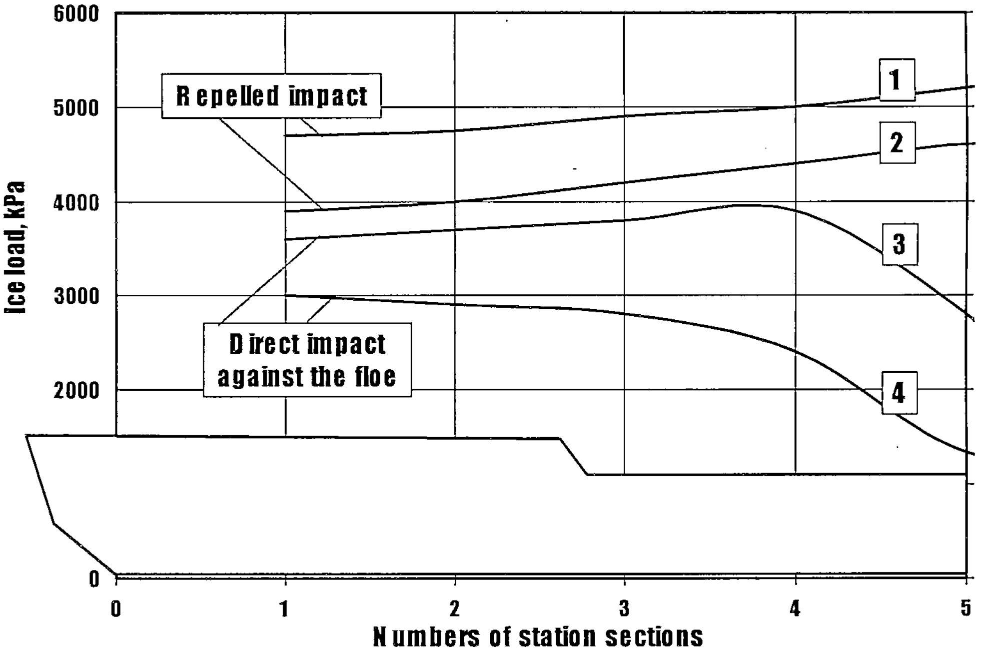

Fig.2.2. Influence of the flare of frames upon the intensity of ice loads in the forebody of icebreaker of the *Kapitan Nikolaev* type prior to the refitting (1) and after it (2) as well as ships of the *Norilsk* type with traditional (3) and *Melville Bow* lines (4)

While performing calculations the reference ice conditions – thickness, strength and mass of the floe as well as speed of the ship/ice collision were taken the same. Ship's displacement was 24 500 tonnes the main difference in the hull shape being in values of α and β angles in way of 0.25 **L** of the fore perpendicular, Table 2.1.

Table 2.1

Values of angles α and β of the compared versions of ships of the *SA-15* type

Number of frame	Conventional forebody		*Melville Bow*	
	α	β	α	β
0	30	45	30	62
1	27	39	30	59
2	20	31	20	54
3	11	21	10	42
4	6	13	4	30

Design ice loads on icebreakers of the *Kapitan Sorokin* type[1] prior to and after refitting were also compared.

On the refitted icebreaker *Kapitan Nikolaev*[1], following the proposal of Finnish specialists, the so called conical forebody shape was used with the considerably increased flare of frames. So, at station section 2, angle β was brought to 53° in comparison with 44° in the original version realized during the construction of the icebreaker.

As one can see from Figure 2.2, the reduction of ice loads on the forebody at the expense of the increase of flares of fore frames may be within 15 - 45 % in the zone of the highest ice loads (in way of 0 - 0.2 **L** from the fore perpendicular). When deciding to implement such shape however it is necessary to take into account the deterioration of the seaworthiness of ship in the seaways caused by strong impacts of the forebody against waves (slamming). It especially concerns ships making long transits through open water towards the ice covered areas [7].

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[1] Principal characteristics of the icebreaker are shown in the Annex, Table A.2

On the basis of the generalization of data on the domestic fleet (Figure 2.1) at the initial stages of design the following approximated relationships for the assessment of values of the shape parameter $\mathbf{F_P} = f(\mathbf{x/L})$ of prospective ships may be recommended:

$\mathbf{x/L} < 0.05$ – $\mathbf{F_P} \leq 0.5$ - ULA, $\mathbf{F_P} \leq 0.55$ - UL

$\mathbf{x/L} \geq 0.05$ – $\mathbf{F_P} \leq \mathbf{A} - 6\,(\mathbf{x/L} - 0.05)^2$,

where $\mathbf{A} = 0.5$ for class ULA and 0.55 for class UL.

As the analysis made by CNIIMF, Leningrad Shipbuilding Institute and AARI [8] has shown, for the ULA class cargo ships it is possible to have vertical midbody sides, but in this case design ice loads should be increased by 20 and by 15 % in way of the station sections 3 - 6 and 6 - 13 accordingly.

3. CRITERIA OF THE COMPARATIVE ASSESSMENT OF ICE PROPULSION AND MANEUVERABILITY OF ICEBREAKING SHIPS

3.1. Criteria of the assessment of ice propulsion and maneuverability of ships in level compact ice

In the Russian practice, the main criterion characterizing the ship propulsion in ice is the maximum thickness of level compact ice $\mathbf{h}_i$ broken through in continuous motion, ice bending strength and steady speed being specified. As a rule, the latter is taken equal to 1.5 - 2.0 kn[1] and the ice bending strength – not less than 500 kPa. Ice has natural snow cower about 20 cm deep.

Criterion defining the capability of an icebreaking ship to move through the level ice at a minimum steady speed while being a principal measure for the comparison of icebreaking qualities does not characterize the ice propulsion of ship within the whole range of ice thicknesses: from zero (in open water) to a maximum value when icebreaker has to force its way through ice by ramming. In principle, it is possible to construct two ships with the same icebreaking capability, but developing different speeds in ice of a lower thickness (Figure 3.1).

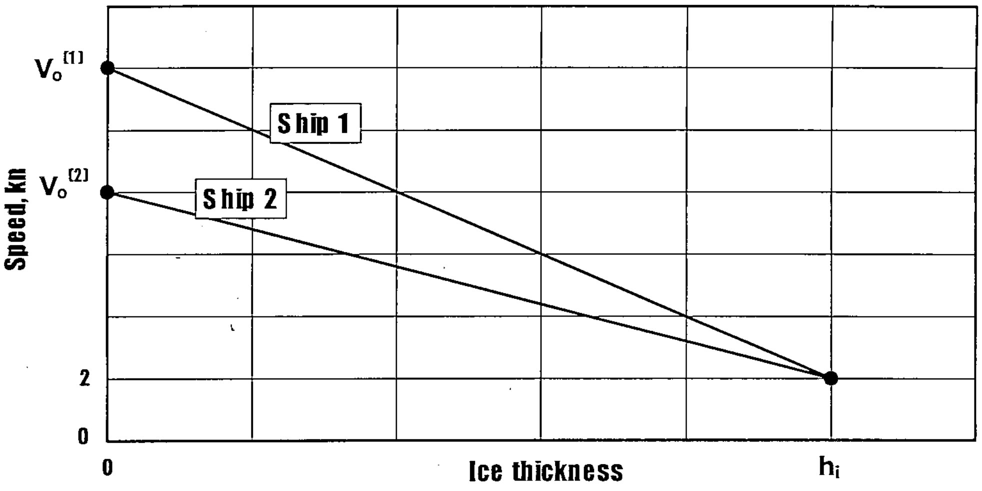

Fig.3.1. Icebreaking ship speed / ice thickness relation (diagrams of ice propulsion)

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[1] In some countries (for example, in USA, Canada and Sweden) the speed of 3 knots is adopted as a minimum speed at which maximum level ice thickness is evaluated (in Norway such speed is 4 knots).

Ship 2, within the whole range of ice thickness, with the exception of a maximum value, as to the propulsion ranks below *Ship 1*. Assuming the relationship $\mathbf{V}=f(\mathbf{h})$ to be linear, the ice propulsion of ship can be judged from two values: icebreaking capability $\mathbf{h}_i$ and speed in open water $\mathbf{V}_0$.

At early stages of design of ships with conventional lines their icebreaking capability and maximum speed in open (calm) water can be determined by experimental-empirical formulas proposed by L.G. Tsoy [9]:

$$h_i = \frac{0,07 \cos^{\frac{3}{2}}\varphi \ \sin^{\frac{1}{2}}\left(\frac{\alpha_0+\beta_0+\beta_2}{3}\right)}{\sqrt[2,6]{f_d}\ \sqrt[5]{L/\ B}\sin^{\frac{3}{2}}\left(90^\circ-\beta_{10}\right)}\sqrt{P_e\ /\ B}\,\sqrt[6]{D}\ , \ \text{m} \qquad (3.1)$$

$$V_0 \ = \ 2,55 \ \sqrt[7,3]{N_p}\ \sqrt[5]{\frac{L}{T\ \delta}}, \quad \text{kn.} \qquad (3.2)$$

where

φ - stem angle, deg
α_0 - entrance angle of design water line, deg
β_0 - flare angle of frame line No.0[1], deg
β_2 - flare angle of frame line No.2, deg
β_{10} - flare angle amidships, deg
L - vessel's length on DWL, m
B - vessel's breadth on DWL, m
T - draft, m
δ - block coefficient
D - vessel's designed displacement, t
$\mathbf{P}_e$ - total propeller bollard thrust , t
$\mathbf{f}_d$ - coefficient of the dynamic ice/ship's hull friction.

The total propeller thrust $\mathbf{P}_e$ under conditions close to the bollard pull mode of operation needed for the calculation of the icebreaking capability is the function of propeller diameter **d** [m], shaft power $\mathbf{N}_p$ [kW] and factor $\mathbf{k}_p$ accounting for geometric characteristics of propellers, their number and interaction with the ship's hull.

$$\mathbf{P}_e = \mathbf{k}_p\ (\mathbf{d}\ \mathbf{N}_p)^{2/3}, \ \text{kN.} \qquad (3.3)$$

---

[1] In the Russian practice the frame line No.0 is assumed to be at the fore perpendicular and not at the after one as it is the case abroad.

Number of propellers at a given power of the propulsion plant is determined on the basis of requirements to the maneuverability and the survivability of ship as well as of the efficient condition of power handling. Existing empirical relationships permit to determine critical values of power which may be handled by one propeller without cavitation and aeration (section 4.3).

In addition to the above factors exerting effect on the icebreaking capability a dependence (Figure 3.2) was obtained to take into account the influence of height of the ice knife t_k at the stem base (Figure 3.3). Recommended relative values of the knife height should not exceed 30 % of the ship's draft.

As an example proving the reliability of the suggested formulas (3.1) and (3.2), Table 3.1 shows results of the comparison of calculated values with actual ones as applied to cargo ships of the ice category ULA.

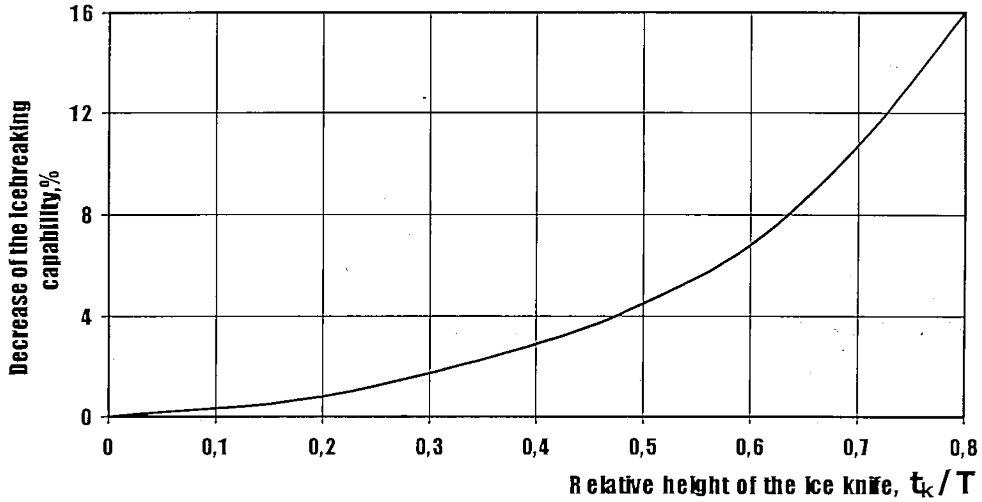

Fig.3.2. Influence of the bow ice knife height upon the icebreaking capability

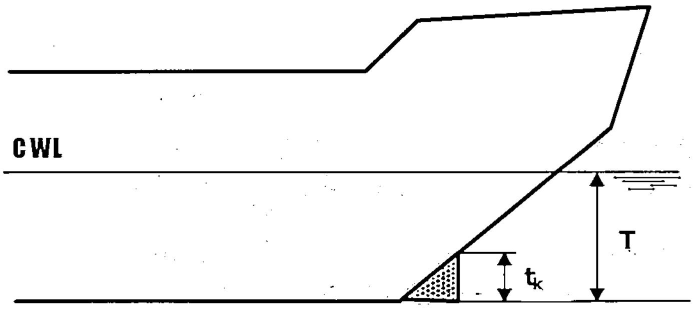

Fig.3.3. Ice knife at then stem base of an icebreaking ship

Table 3.1

Comparison of actual and calculated values of the icebreaking capability and speed of icebreaking cargo ships

Characteristics	*Amguema*	*Norilsk*	*Sevmorputj*	*Ivan Papanin*
Length, m	127.0	164.0	229.1	132.5
Breadth, m	18.8	24.0	31.3	21.7
Draft, m	8.5	8.5	10	6.5
Displacement, t	14000	23500	49000	12600
Shaft power, kW	4700	13300	27900	11900
Angles, deg.				
φ	29	30	30	25
α_0	24	30	21	30
β_{10}	7	8	11	8
Icebreaking capability $\mathbf{h}_i$, m				
actual	0.6-0.7	1.05	1.4-1.5	1.1
by formula (3.1)	0.66	1.08	1.49	1.09
Speed $\mathbf{V}_0$, kn				
actual	15.0	18.1	20.8	18.1
by formula (3.2)	15.1	18.0	21.0	18.3

One of the main characteristics of maneuverability and turning ability of ship is the radius (or diameter) of gyration. Under ice conditions, especially in the fast ice, when the turning area is limited by the narrowness of the fairway, in the practice of operation of icebreakers and icebreaking cargo ships the "herring bone" method of turning is used. In this case the turning is made by 180° changing the rotation (reversing) of propellers with simultaneous shifting of the helm to hard over in the headway. During the movement astern the rudder is set directly in the middle line plane. In this way the turning of ship is performed practically with its position unchanged. While carrying out ordinary turning only on account of the helm shifting, diameter of the ship's gyration in ice is considerably longer than that in open water. Bearing in mind the above, it is advisable to assess turning capability not only by the diameter of gyration, but also by the comparison of time consumption for the "herring bone" turn by 180°. Besides, the efficiency of this maneuver is evaluated by the number of reverses or notches made by the icebreaker bow and stern.

As follows from the above stated, the maneuvering qualities of icebreaking ships depend upon the icebreaking capability not only when they move headway, but also during the movement astern. As a rule, icebreakers with a traditional hull shape have better possibility in compact ice while moving astern than making headway. This is explained by the positive influence of stern propellers exerting a drawing in and washing out effect in the stern/ice interaction. However the use on ships of principally new forms of the forebody substantially changed the headway/astern icebreaking capability relationship in favour of the headway movement. In a number of cases, the search for a better headway icebreaking capability adversely affected the astern movement. So, the application of the *Thyssen-Waas* forebody or of another bow shape with side reamers results, because of its "plough" effect, in the considerable deterioration of the astern movement right up to its complete exclusion as it was the case, for instance, with the converted icebreaker *Mudyug*[1]. The above proves the necessity to pay serious attention to the astern icebreaking capability and to consider the stern ahead movement of ship as one of the important elements of the maneuverability under ice conditions.

In this case the question is of ice ships with a propeller-rudder system of the traditional type. At the same time, in the construction of icebreakers the attempts are being undertaken lately to introduce principally new untraditional solutions: on tankers *Uikku* and *Lunni* and on icebreaker *Röthelstein* the propulsion-rudder systems Azipod are mounted, on icebreakers *Fennica* and *Nordica* there are swinging propellers of the *Aquamaster* type. The first experience of operation of the above mentioned ships has shown that turning propulsion systems permit to substantially improve the maneuvering qualities of ships in ice. If in the future the operational reliability and structural strength of new swinging propellers during the operation in ice conditions are proved, such systems should find wide application on icebreaking ships.

3.2. Propulsion and maneuverability criteria in drifting ice and ice channels

Besides propulsion and turning capability in the level compact ice the maneuverability and safety of navigation in drifting ice substantially depend upon the capability of ship to break through hummocks, get free from sticking and keep motion under conditions of compression.

While being assisted by the icebreaker or moving through the channel a ship should have good propulsion both in the ice cake of the newly made channel and in old channels filled up with jammed brash barrier, small ice cake and dry ice. It is important for icebreakers to possess the capability of good penetration into the channel's edge for the quick getting out of the channel.

Propulsion of ship following an icebreaker substantially depends on its width and on the degree of its clearing from the broken ice. Therefore in the assessment of the efficiency of

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[1] Principal characteristics of the icebreaker are shown in the Annex, Table A.2

work of icebreakers it is necessary to compare them by the capability of making a wide and clear channel.

Taking into account the above stated the following criteria should be added to those earlier mentioned to assess the efficiency of operation in ice of icebreaking cargo ships and icebreakers:

- headway and astern movement through hummocks;
- headway and astern movement under conditions of compression;
- headway and astern movement through natural ice cake and old channels;
- penetration into the channel's edge and getting out of the channel;
- width and clearing of the channel made by icebreaker.

For the ships designed to operate under ice conditions at restricted depths of importance is the capability of operation in shallow water.

Ice ships should have acceptable seaworthiness because for the most part of operational time they sail in open water. It is especially important for cargo ships.

3.3. Comprehensive expert evaluation of the efficiency of the operation of ships in ice

Diversity of navigational conditions and operational aspects of the work of ships in ice does not allow to put forward a universal criterion of the assessment of their icebreaking qualities. The comparison of ships with special technical features may be made by separate operational indices. One of the principal such indices is at present propulsion in the compact level ice (section 3.1 and Figure 3.1).

Complexity of the comprehensive evaluation of the efficiency of ships in ice is due to the high degree of uncertainty of the basic information, when the number of parameters (factors) analysed is considerable and their systematization is impossible or difficult. In the lack of the sufficient body of model or full-scale investigations the values of indices and their significance for the operation of ship may be evaluated only with the use of the expert (factor) analysis. From expert estimates based on specialists' opinions a qualitative and / or quantitative index is formed reflecting properties or capabilities of the ship in question.

Comparative analysis (taking into account the effect of each factor) of operational qualities of icebreakers *Mudyug*, *Kapitan Sorokin* and *Kapitan Nikolaev* by results of the refitting of their forebodies serves as an example of such evaluation. Methods of this analysis and the criteria system were developed by the Finnish company *Wärtsilä* in co-operation with CNIIMF [10,11]. Its essence is the assessment of operational capabilities of icebreakers by 16 factors. Experts assess each factor by marks $\mathbf{A}_i$ (using the five-point scale) characterizing its significance for icebreaker in dependence on the operational conditions (sea, river). Then values $\mathbf{q}_i$ (according to the five-point scale) are assigned which correspond, in the opinion of experts, to the level of realization of each of the factors on icebreakers. The comparison of integral indices (3.4) by each version of ship permits to judge about the degree of its operational capabilities and advantages.

$$\mathbf{Q} = \sum_{i=1}^{16} \mathbf{Q}_i \, \mathbf{q}_i \, . \qquad (3.4)$$

Using this method, specialists of CNIIMF and captains of icebreakers of MSCO were assessing ice qualities, maneuverability and seaworthiness of sea, river and universal icebreakers with different forebody shapes. Four lines alternatives were compared: that of *Thyssen-Waas* system, conical one suggested by *Wärtsilä*, traditional and traditional improved (developed by CNIIMF) ones. Conditions of navigation of icebreakers were defined by their purpose. The sea icebreaker is designed for the operation in drifting ice, river icebreaker – mainly in the level fast ice, universal icebreaker – 2/3 of time in drifting ice and 1/3 – in the fast ice. From results of the expert assessment (Table 3.2) a conclusion was drawn that for a universal icebreaker the most preferable were improved traditional hull lines using icebreaking advantages of the conical bow shape, but not resulting in an appreciable deterioration of the seaworthiness and maneuverability.

This comparison of ice performance of ships with different shapes of hull lines testifies to the advisability of the application on arctic ships of traditional icebreaking lines the potentiality of the further improvement of which are not yet exhausted.

The method in question of the comprehensive comparison of ice performance may be used for a preliminary analysis of the efficiency of icebreaking cargo ships being designed in the choice of their hull shape and assignment of operational conditions.

Table 3.2

Assessment of the efficiency of sea and river icebreakers with different types of the forebody: *Thyssen-Waas* (1), conical (2), traditional (3) and traditional improved (4) ones

Factors	Assessment Q_i		Assessment q_i			
	Sea	River	Version 1	Version 2	Version 3	Version 4
Level ice						
• movement ahead	4	5	5	4.5	3	4
• backward movement	4	3	3.5	4	4	4
Hummocks						
• movement ahead	4	1	3	4.5	3	4.5
• backward movement	3	1	3	4	4	4
Compression						
• movement ahead	4	1	2	4.5	4	4
• backward movement	4	1	1.5	3.5	4	4
Old channel						
• movement ahead	3	5	2.5	4.5	3	4.5
• backward movement	3	5	3.5	4	4	4
Channel clearing	2	4	4.5	2	2	2
Breadth of channel	4	4	3	2.5	2	2.5
Leaving the channel, penetration	3	5	3.5	4	2	3.5
Release from sticking	5	3	3	4.5	4	4.5
Circulation in ice	3	2	2.5	4	4	4
Turning by herring-bone	4	5	3	3.5	4	4
Operability in shallow water	1	5	3	2	2	2
Seaworthiness	4	1	3.5	1.5	4	3.5
Integral index **Q** for						
• sea icebreaker	–	–	170	204	189	211
• river icebreaker	–	–	170	182	157	182
• universal icebreaker	–	–	170	197	178	201

4. RESULTS OF THE INVESTIGATION OF THE INFLUENCE OF HULL LINES AND PRINCIPAL DIMENSIONS OF ICE SHIPS ON THE ICEBREAKING CAPABILITY AND SEAWORTHINESS

Insufficient development of reliable analytical methods of taking account of the influence of hull lines and ratios of principal dimensions upon ice propulsion of ships served as a basis for the fulfilment of special experimental investigations with the use of serial model tests in the ice tank [12, 13].

The task of construction of efficient ice ships possessing both good ice quality and satisfactory seaworthiness is complicated also by the lack of necessary methods for the assessment of the propulsion of ships with icebreaking hull lines under conditions of open calm water and waves. Taking this into account, serial tests of icebreaking ship models were performed simultaneously in the hydrodynamic tank [14].

For the study of the influence of hull shape parameters of arctic cargo ships upon the icebreaking capability and propulsion in open water CNIIMF has developed a series of models with systematically changing stem angle φ, design waterline entrance angle α_0, flare angle at the middle frame β_{10}, ship's length **L** / breadth **B** and **B** / draft **T** ratios. Principally, these parameters define ice qualities of ship. Considered limits of the change of varied parameters, main characteristics and number of models of the series are shown in Table 4.1. The hull shape of a modern large icebreaking cargo ship of *SA-15* type (m/s *Norilsk*) of ULA category with an icebreaking capability of 1 m at a propeller thrust of 140 t was taken as an original version (reference model 1). Model scale is 1:50.

Peculiarity of the series in question was one and the same length equal to 3.2 m adopted for models, chosen as a limiting admissible value in compliance with the conditions of tests in the old ice tank of AARI. Proceeding from this, **L/B** ratio (except models 17 and 18) varied due to the change of breadth and draft of models.

Table 4.1

Varied parameters and principal model elements of the icebreaking transport series

Version	Ratios		Angles, deg.			Coefficient	Dimensions, m		
	L/B	**B/T**	φ	α_0	β_{10}	δ	**L**	**B**	**T**
1	6.5	3.0	30	30	7	0.664	3.2	0.492	0.164
2	5.5	3.0	30	30	7	0.609	3.2	0.582	0.194
3	7.5	3.0	30	30	7	0.700	3.2	0.427	0.142
4	6.5	2.5	30	30	7	0.657	3.2	0.492	0.197
5	6.5	3.5	30	30	7	0.674	3.2	0.492	0.141
6	6.5	3.0	20	30	7	0.652	3.2	0.492	0.164
7	6.5	3.0	40	30	7	0.666	3.2	0.492	0.164
8	6.5	3.0	30	20	7	0.648	3.2	0.492	0.164
9	6.5	3.0	30	40	7	0.667	3.2	0.492	0.164
10	6.5	3.0	20	20	7	0.616	3.2	0.492	0.164
11	6.5	3.0	20	40	7	0.657	3.2	0.492	0.164
12	6.5	3.0	40	20	7	0.660	3.2	0.492	0.164
13	6.5	3.0	40	40	7	0.669	3.2	0.492	0.164
14	6.5	3.0	30	30	0	0.678	3.2	0.492	0.164
15	5.5	3.0	30	30	0	0.625	3.2	0.582	0.194
16	7.5	3.0	30	30	0	0.719	3.2	0.427	0.142
17	6.5	3.0	30	30	7	0.648	1.92	0.295	0.098
18	6.5	4.0	30	30	7	0.655	2.56	0.394	0.098
19	6.5	5.0	30	30	7	0.666	3.2	0.492	0.098

Programme of tests in the ice tank provided for the towing of models through the level compact ice of different thickness **h** at a constant towing force. On the basis of tests the relationships of the towing speed of models as a function of the ice thickness **V**=f(**h**) were obtained.

As a whole, the results of serial tests proved the ideas existed earlier of the influence of principal dimensions and ship's hull shape upon the ice propulsion. At the same time, functional dependences of the ship's icebreaking capability on principal parameters of the hull shape were obtained and factors most strongly affecting the ship's ice propulsion were brought to light.

Programme of the model tests in the hydrodynamic tank made provision for the tests in calm water and head regular seas and also tests for the determination of rolling characteristics at the ship's position beam to the sea.

4.1. Influence of the shape of hull lines

The obtained dependences of icebreaking capability **h**$_i$ (thickness of the level compact ice broken by the ship moving at a speed of 2 kn) on entrance angles φ and α_0 are presented in Figures 4.1 and 4.2. Substantial effect of the stem angle upon icebreaking capability can be seen from the first graph. This effect here is enhanced by the additional influence of the simultaneous flare of bow frames with the decrease of stem angle. Design water line entrance angle also substantially affects the icebreaking capability. As to the ice propulsion the increase of α_0 is advisable.

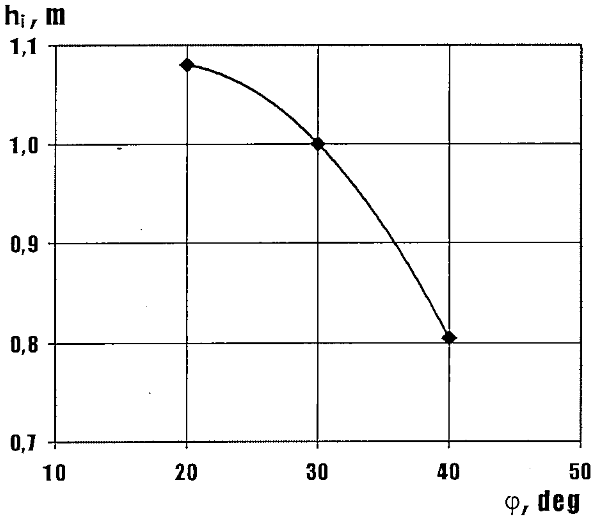

Fig.4.1. Relationship between the ship's icebreaking capability and the stem angle at $\alpha_0 = 30°$

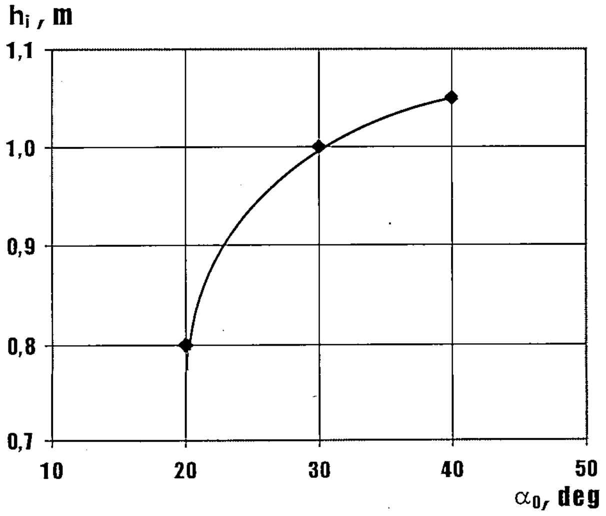

Fig.4.2. Relationship between the ship's icebreaking capability and the DWL entrance angle at $\varphi = 30°$

Analysis of the results of tests of models with vertical and inclined boards in the midbody has shown that the transfer to the vertical board causes slight reduction of the icebreaking capability. Difference in the icebreaking capability of models with the inclined ($\beta_{10} = 7°$) and vertical ($\beta_{10} = 0°$) boards did not exceed several percent. It should be noted that channel behind the vertical board model is less clogged with the loose pack ice some portion thereof being drawn under the edge of the channel. Accordingly, the propulsion unit is better protected against the impact of ice.

The results of model tests in the hydrodynamic tank permitted to come to a number of practical conclusions as to the influence of hull lines shape, characteristic of ice ships, upon the water resistance to the ship movement in calm water and the loss of speed in the head seas as well as upon pitching and rolling parameters. It was found out in particular that the decrease of the stem angle positively influencing the increase of the icebreaking capability of ship within 20 - 40° does not noticeably affect service properties of icebreaking cargo ships in calm water (Figure 4.3).

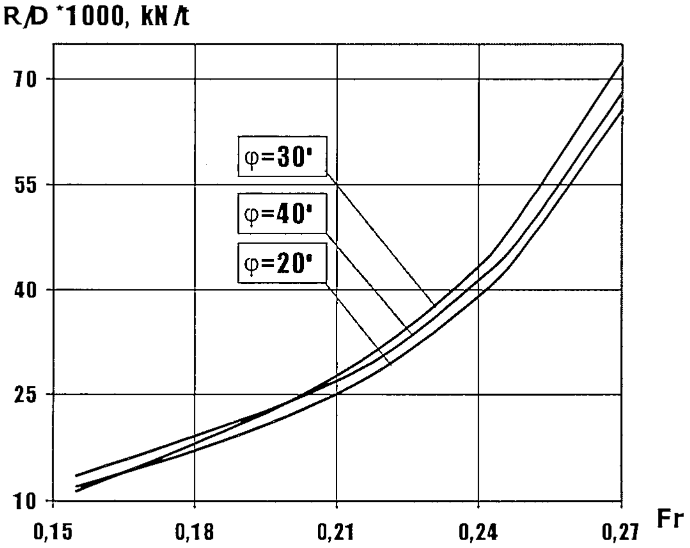

Fig.4.3. Relationship between the specific towing resistance, Froude number and the stem angle for a full-scale ship with $\alpha_0 = 30°$

The obtained experimental values of the damping coefficients of rolling have shown that the linear damping coefficient of rolling $2\nu_\theta$ for models of the version with vertical board at the list up to an angle of deck flooding is 1.5 - 1.7 times as much as that of the version with inclined board. Therefore taking into account the absence of bilge keels on icebreaking cargo ships and accordingly the deteriorated characteristics of rolling in waves for those ships the operation of which implies frequent and long passages through open water, the use of a vertical board may be preferable. Vertical board permits to increase the block coefficient and accordingly at the same dimensions to increase the displacement and useful cargo-carrying capability of the ship.

The analysis of the influence of forebody shape upon the loss of speed in the regular head seas enabled to determine rational combination of DWL entrance angles and stem angle resulting in a lower loss of speed. This corresponds to the traditional forebody lines of ULA class ships of the Russian Marine Register of Shipping.

4.2. Effect of the length/width ratio

The dependence of the model speed with different values of **L/B** on the thickness of level compact ice obtained in the ice tank is shown in Figure 4.4. Data on models with the vertical midsection board is presented.

As it was already mentioned, models of the series were manufactured with the same length, therefore variations of the **L/B** ratio were reached by the change of width and draft of models at the constant **B/T** ratio. Hull line parameters α_0 andφ were kept the same and equal to 30°. The tests have shown that change of the icebreaking capability turned out to be approximately proportional to the square root of width in compliance with the existing ideas about the influence of width on the ship's icebreaking capability.

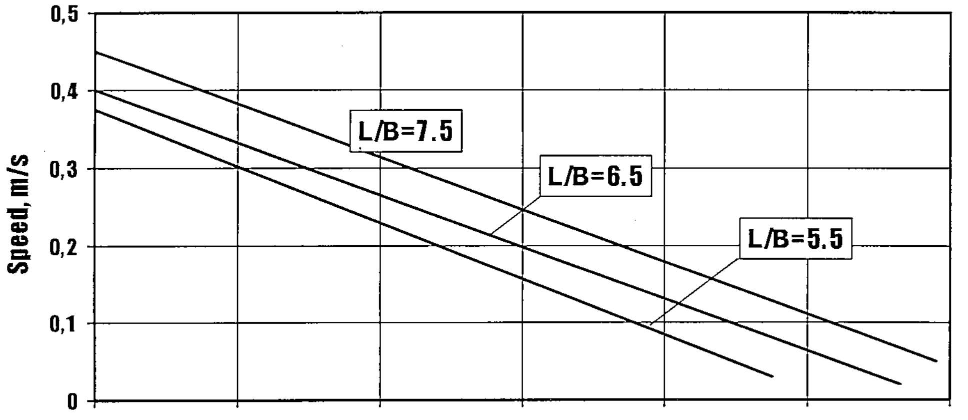

Fig.4.4. Dependence of the speed of towing of models with different **L/B** ratios upon the ice thickness

Towing tests in the level compact ice of models with different length of the parallel middle body have detected relatively insignificant effect of the ship's length on the ice resistance the former changing only through the change of the length of the parallel middle body (**B** = const). So, the increase of length of an icebreaking ship by 40 % results in the increase of the ice resistance by 14 - 15 % (at full scale speed of 1 m/s). When the ship's length is increased by 80 % the ice resistance increases by 28 - 30 %. These results fairly well match the data on the influence of the hull length on the ice resistance obtained earlier [15]. In the first approximation, the ice resistance/ship's length relationship (4.1) may be used for practical evaluation.

$$\mathbf{R}_i = f(\mathbf{L}^{0.4}). \tag{4.1}$$

Then, under the assumption of square resistance dependence on the ice thickness one may consider that the icebreaking capability depends on the length of ship in the following way:

$$\mathbf{h}_i = f(\mathbf{L}^{-0.2}). \tag{4.2}$$

Tests in the hydrodynamic tank permitted to obtain the result worth attention though it was anticipated. It was found out that the elongation of ship with icebreaking hull lines owing to the increase of length of the parallel middle body leads to the diminishing of the specific (per one ton of displacement) towing resistance. This resulted in the fact that towing ship power for all **L/B** versions turned out to be practically the same, this being associated with the corresponding change of ship's displacement at the variation of length of the parallel middle body.

4.3. Effect of the shallow draft and the width/draft ratio upon the icebreaking capability

Construction of cargo ice superships is associated with the perspectives of the export of raw materials from the Arctic shelf of Russia. At the same time, taking into consideration the existence of shallow water in the Russian Arctic there will be a need in the building of these ships with the restricted draft and accordingly unusual ratios of main dimensions. This necessitated the carrying out of special investigations to find out the effect of a light draft on ice properties of ships. Below the results are presented of the research on the influence of a restricted draft of large ice ships upon their hull shape and icebreaking capability. Consideration was given also to the effect of a small under-keel clearance on the propulsion characteristics, and safety of ships navigating in shallow waters.

Influence of draft on the efficiently processed power. The experience of construction and operation of domestic icebreakers shows that maximum power which may be efficiently (without aeration and cavitation) processed by propellers depends on propeller diameter and consequently on ship's draft [16, 17, 18].

Figure 4.5 shows relationships between the critical value of power N_c, draft **T** and propeller diameter **d** of the icebreaking ship with a three-shaft plant. Data on shaft power of *Taimyr*[1] and *Arktika*[1] type icebreakers are also given here.

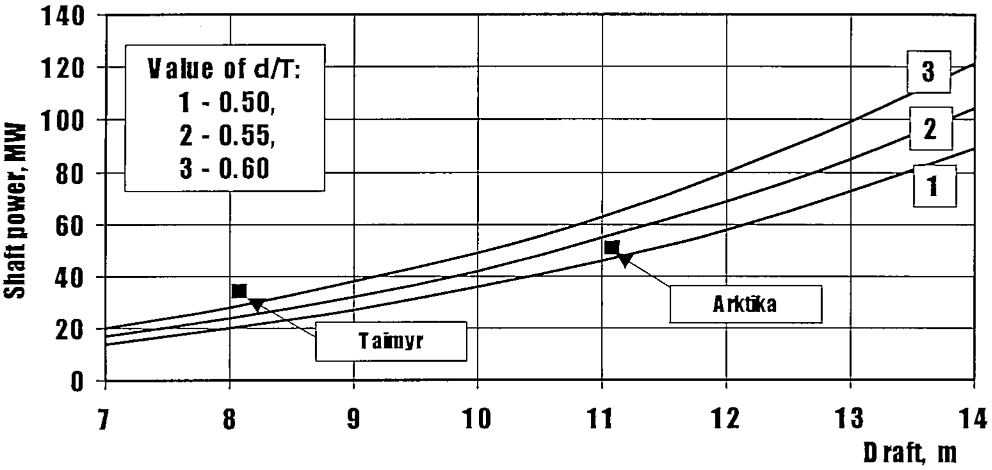

Fig.4.5. Relationship between the power efficiently proceed by propellers, ship's draft and relative diameter of the propeller

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[1] Principal characteristics of the icebreaker are shown in the Annex, Table A.2

As one can see from the plot, with the decrease of ship's draft the critical value of power is considerably reduced. Experience shows that for the reduction of the ice/propeller interaction, maximum admissible diameter of side propellers should not exceed 0.6 of the ship's draft. Bearing in mind this recommendation, for the verification in the first approximation of the possibility to process power by one propeller without cavitation and aeration the empirical formula (4.3) proposed by L.G.Tsoy may be used in which the propeller diameter is taken in meters.

$$N_c = 213\ \mathbf{d}^{2.5},\ \mathrm{kW}\,. \tag{4.3}$$

These restrictive conditions concerning power and propeller diameter, in their turn, impose substantial limitations on achievable icebreaking capability of shallow-draft ships. To increase the icebreaking capability it is necessary to further improve the ship's hull shape.

Tests of icebreaker models with different breadth. For the investigation of the effect of the dimensions of icebreaking ships upon the ice propulsion, in the model ice basin of the AARI, to order of CNIIMF, comparative tests of models of icebreaker with variable principal dimensions were carried out. Main task consisted in the construction of a series of models differing only in one of principal dimensions keeping other values unchangeable. Reference model in relation to which the investigated parameters were changed was that of the icebreaker of *Moskva*[1] type. Main characteristics of the different hull breadth models tested, are shown in Table 4.2. Tests carried out according to methods of the AARI were of the towing character in the level compact ice corresponding to a full-scale thickness of 1.2 m at constant thrust [19].

Table 4.2

Main model characteristics of the icebreaker with different values of breadth

Characteristics	Version 1	Version 2	Version 3
Length, m	1.61	1.61	1.61
Breadth, m	0.34	0.28	0.22
Draft, m	0.14	0.14	0.14
Block coefficient δ	0.508	0.535	0.568
Stem angle at design waterline φ, deg.	26	26	26
Design water line entrance angle α_0, deg.	24	24	24
Side flare angles, deg.			
• at frame line No.0, β_0	40	40	40
• at middle frame line, β_{10}	18	18	18

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[1] Principal characteristics of the icebreaker are shown in the Annex, Table A.2

Figure 4.6 shows the influence of the hull breadth. As one can see, the hull breadth appreciably affects the ice resistance. It proved the results of investigations known earlier.

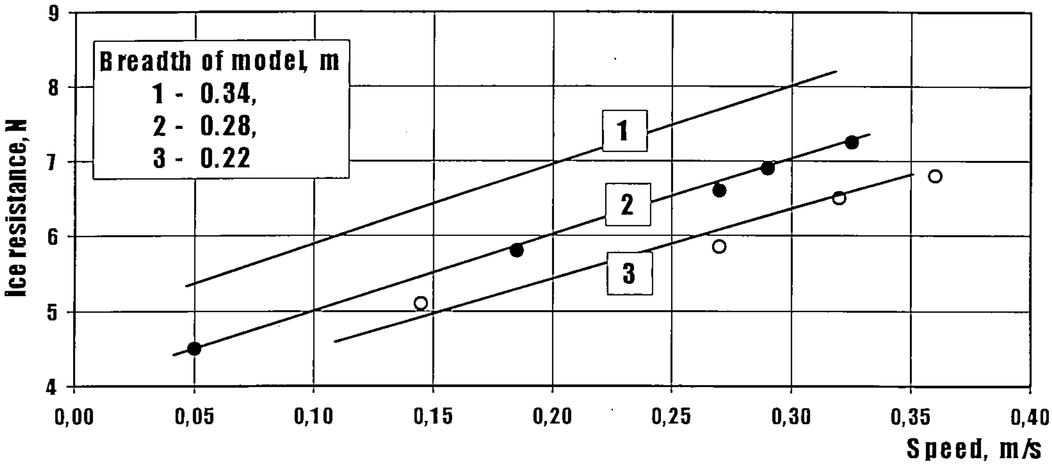

Fig.4.6. Ice resistance of icebreaker models with different values of the hull breadth

As follows from the relationships obtained, when the icebreaker breadth changes within 16 % the ice resistance changes proportionally with the hull breadth. With more substantial hull breadth changes the resistance changes to a lesser extent. Considerable change of the icebreaker breadth at a constant draft leading to a substantial change of the breadth/draft ratio **B/T** produces inevitably an effect on the geometry of bow lines even if the frame inclination angle to the design water line is kept unchanged.

Tests of models of an icebreaking cargo ship with different values of draft. In the process of tests of the above icebreaking cargo series of models the influence of the **B/T** ratio on the ice propulsion at the expense of the change of draft **T** [20]. Characteristics of models of different **B/T** ratios are given in Table 4.3.

Table 4.3

Models of the icebreaking cargo series with different values of draft

Characteristics	Version 1	Version 2	Version 3	Version 4
Length, m	3.2	3.2	3.2	3.2
Breadth, m	0.492	0.492	0.492	0.492
Draft, m	0.197	0.164	0.141	0.098
Block coefficient δ	0.657	0.664	0.674	0.666
Ratios:				
L/B	6.5	6.5	6.5	6.5
B/T	2.5	3.0	3.5	5.0
Angles, deg.				
φ	30	30	30	30
α_0	30	30	30	30
β_0	41	45	55	45
β_{10}	7	7	7	7

Models in the ice basin were tested in the level compact ice of different thickness at a constant towing force. The obtained change of the icebreaking capability of models depending on **B/T** is shown in Figure 4.7.

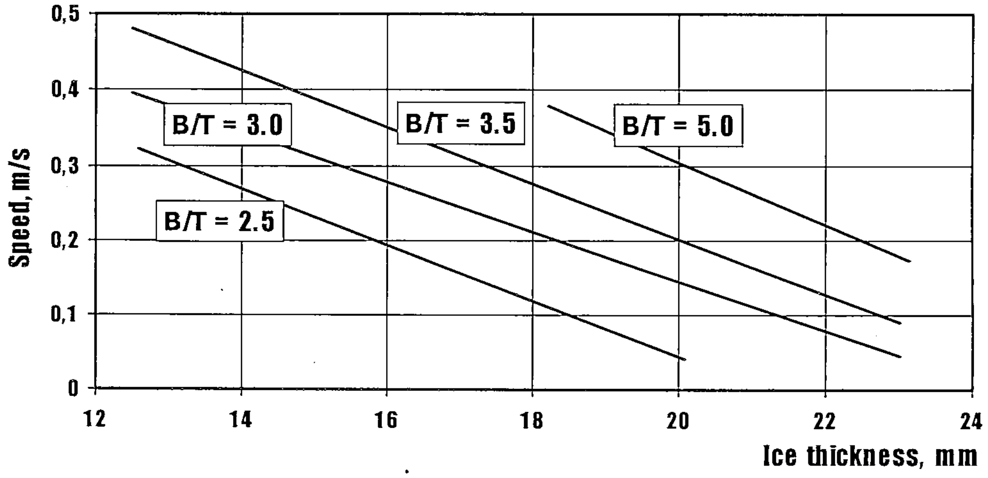

Fig.4.7. Relationship between the model towing speed with different **B/T** values and ice thicknesses

It may be seen from figure that the relative breadth affects materially the ice propulsion. The increase of **B/T** at the expense of draft reduction results in the reduction of ice resistance and accordingly in the increase of ship's icebreaking capability. In this case a new lines drawing was constructed for each of the varying drafts and though the angle of bow rake and design water line entrance angle remained constant and equal to 30°, the forebody frame flare noticeably changed and increased with the increase of **B/T**. That affected favourably the decrease of ice resistance. Consequently, when the **B/T** ratio is increased only at the expense of breadth (at constant draft) the adverse effect of breadth on the icebreaking capability may be also compensated by the positive influence of greater side flare near the entrance. The result obtained makes it possible to come to the conclusion that a forced increase of ship's breadth with draft restrictions for the purpose of increasing its cargo-carrying capacity may lead to the selection of more rational hull bow lines in relation to the reduction of ice resistance.

5. INVESTIGATION OF THE EFFECT OF THE SHALLOW WATER ON THE SAFETY OF NAVIGATION AND THE PROPULSION OF SHIPS IN ICE

When ships sail in conditions of shallow water, from the point of view of safety of navigation, it is necessary to consider minimum possible under-keel clearance. Besides, while moving in shallow water the propeller thrust loss and reduction of the icebreaking capability should be taken into account. Shallow water also adversely affects the longevity of stern tubes, and the reliability of work of the ship's power plant cooling system.

Minimum admissible under-keel clearance. As calculations have shown, under clean water conditions the minimum navigational under-keel clearance for large ships according to the Russian Codes of the Technological Design of Seaway Channels may be 1.4 - 1.5 m.

In order to determine a margin for trim of the icebreaker in operation in compact ice the analysis of the test data of the Krylov Institute, CNIIMF and AARI which were gathered during full-scale and model tests of various icebreakers has been made. The analysis has shown that the movement of the icebreaker in compact ice is of a cyclic pattern and is accompanied by the periodical crawling of the forward end over ice and its falling through with the destruction of ice cover. The periodical submersion of stern accordingly occurs, this submersion being 2 - 3 times less than the crawling of the forward end over the ice. On the average, the icebreaker's trim by the stern is practically commensurable with the thickness of the surmounted level ice. Thus, the icebreaker *Arktika* in the movement through ice of a thickness of 2.3 m, maximum for this icebreaker, will have a trim by the stern of about 1° which corresponds to 2.4 - 2.5 m. Figure 5.1 shows an experimental relationship between the trim by the stern and the thickness of level compact ice for the icebreaker *Arktika*.

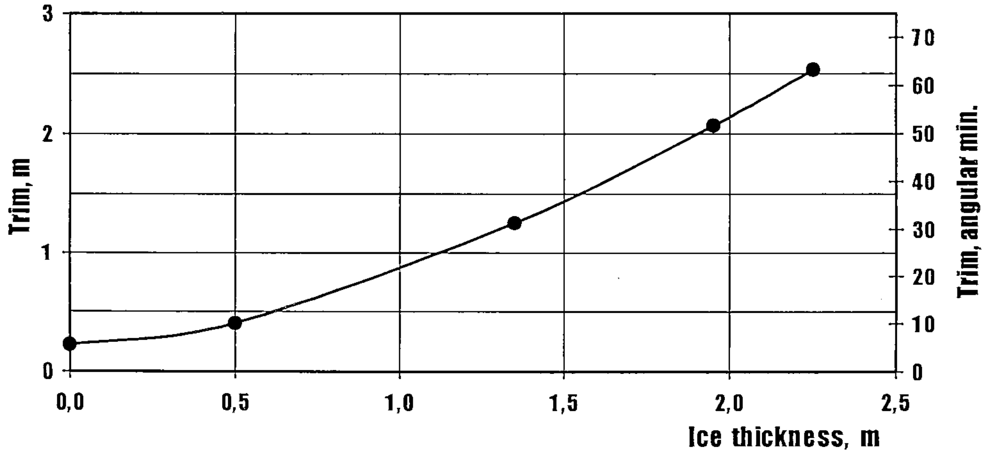

Fig.5.1. Dependence of the icebreaker trim by the stern on the thickness of the compact ice

From the above reasoning it should be expected, that for icebreaking ship with an icebreaking capability of 2.5 m the stern sinking will make up not more than 0.7 - 0.8 m. It is also known that an icebreaker while moving in compact ice makes regular rocking motions rolling over from one board to another. According to the operational experience of domestic icebreakers of the *Arktika* and *Ermak*[1] types the maximum angle of roll at such heeling tests does not exceed 2°. However, as it is shown by rough drawing, the above roll will not bring about additional increase of the ship's draft by the stern with allowance made of the roundness and elevation of the stern frames of icebreaking ships. Consequently, when an icebreaking ship continuously moves in the first-year fast ice with a maximum design thickness up to 2.5 m the draft increment of the stern will not exceed 0.8 m. The submersion of stern of the icebreaker can be considerably deeper only in operation by rammings in heavy ice of a thickness beyond the limiting value. In this case, speeds of rammings should be restricted (what is being done in practice) under shallow water conditions, even if there is a sufficient depth under the keel, proceeding from the condition of preventing the ship's sticking. Usually the ramming speed does not exceed 8 knots.

<u>Influence of the under-keel clearance on the propeller thrust.</u> The Krylov Institute has developed methods for the determination of the reduction of the total propeller thrust in shallow water depending on the under-keel clearance. These methods are based on specially carried out investigations of the effect of shallow water on the water resistance to the motion of ship with icebreaking hull lines and the propeller/ hull interaction coefficients. Major attention was paid to the study of the propeller thrust drop in the mode of operation close to bollard pull conditions.

As the calculations made for the icebreaker speed equal to 3 knots have shown, at a minimum under-keel clearance of 1.5 m the propeller thrust drop is only about 4 %. This corresponds to the decrease of the icebreaking capability not more than by 2 %. Consequently the effect of shallow water on the propeller thrust is insignificant. Really observed more substantial reduction of the icebreaking capability under conditions of shallow water is apparently associated first of all with change of the character of the ship's hull/ ice interaction: in particular when the ice thickness is commensurable with the under-keel clearance. So, the investigations carried out by the A/O *Wärtsilä Marine* confirmed the fact of more significant effect of the increase of the ice resistance during the motion of icebreaker in shallow water on the reduction of the icebreaking capability.

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[1] Principal characteristics of the icebreaker are shown in the Annex, Table A.2

Figure 5.2 shows the relationship between the ice resistance of icebreakers *Taimyr* and *Kapitan Sorokin* and the water depth at a speed of 2 knots in level compact ice 1.5 m thick. As one can see from figure, at an under-keel clearance of 1.5 - 2.0 m the icebreaker ice resistance increases approximately twice.

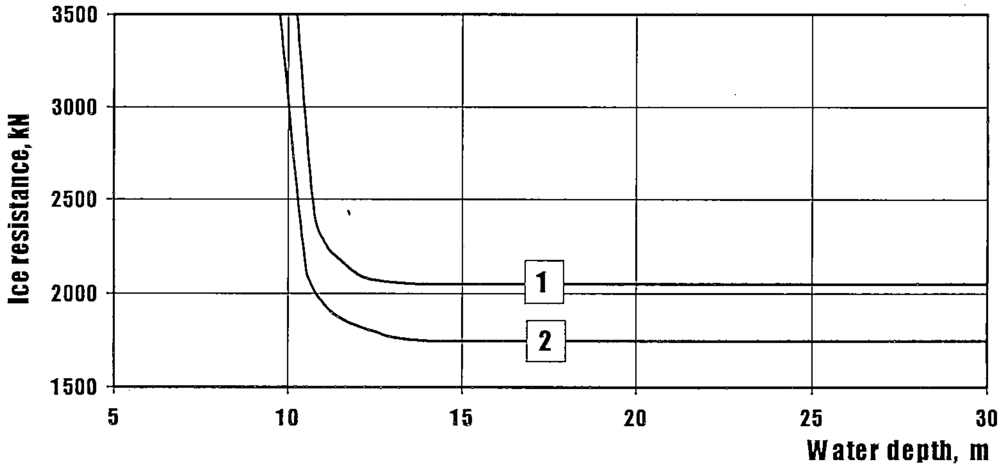

Fig.5.2. Ice resistance of icebreakers *Taimyr* (1) nd *Kapitan Sorokin* (2) plotted against the water depth

Effect of shallow water on the ice propulsion . Shallow water influence on the ships' ice propulsion manifested itself in the reduction of speed of motion over small depths was for the first time found out during the tests of the icebreaker *Murmansk* of *Moskva* type in the autumn-winter navigation 1973-1974 [21, 22]. Tests were performed in compact ice 60 - 120 cm thick with snow cover and in the channel proper at different stages of freezing of broken ice in it.

The most pronounced influence of the shallow water is to be found at depths less than a double draft of ship. Salient feature is that the shallow water manifests itself at modes of operation close to that of the bollard pull, that is during the movement in ice of maximum thickness.

Under conditions of shallow water also icebreaker *Taimyr* after its construction by the Finnish *Masa-Yards* in 1990, icebreaker *Kapitan Nikolaev* after conversion by the same company in 1990 and icebreaker *Kapitan Sorokin* after conversion by the German company *Thyssen Nordseewerke* in 1991 were tested. All these tests were carried out in the fast ice of the Yenisei Gulf.

Table 5.1 contains comparative data on ice tests of icebreaker *Taimyr* in deep and shallow water. The icebreaking capability was compared at the same power of electric engines equal to 33.5 MW and a speed of steady motion of 2 knots.

Table 5.1

Icebreaking capability of icebreaker *Taimyr* in deep and shallow water according to full-scale tests in 1990

Test conditions	Deep water	Shallow water
Water depth $\mathbf{H}_w$, m	≥ 21.0	11.2 - 11.4
Average draft $\mathbf{T}_a$, m	8.4	8.8
Ratio $\mathbf{H}_w/\mathbf{T}_a$	≥ 2.5	1.28
Icebreaking capability, m	2.21	1.98
Reduction of icebreaking capability, %	–	10

As one can see from the table, the icebreaking capability of icebreaker *Taimyr* in shallow water ($\mathbf{H}_w/\mathbf{T}_a = 1.28$) decreased by 10 %. This decrease turned out to be less than it was expected by model tests.

Results of the analysis of ice tests of the above mentioned icebreakers *Kapitan Nikolaev* and *Kapitan Sorokin* under conditions of shallow water are presented in Table 5.2.

Table 5.2

Reduction of the icebreaking capability of icebreakers *Kapitan Nikolaev* and *Kapitan Sorokin* during the tests in deep and shallow water

Test conditions	Deep water	Shallow water
Icebreaker *Kapitan Nikolaev*		
Water depth $\mathbf{H}_w$, m	≥ 21.0	9.4 - 11.3
Average draft $\mathbf{T}_a$, m	8.3	8.3
Ratio $\mathbf{H}_w/\mathbf{T}_a$	≥ 2.5	1.25
Power of electric engines, MW	17.4	17.4
Icebreaking capability, m	1.80	1.63
Reduction of icebreaking capability, %	–	10
Icebreaker *Kapitan Sorokin*		
Water depth $\mathbf{H}_w$, m	≥ 21.0	10.6 - 11.4
Average draft $\mathbf{T}_a$, m	8.5	8.5
Ratio $\mathbf{H}_w/\mathbf{T}_a$	≥ 2.5	1.29
Power of electric engines, MW	16.6	16.2
Icebreaking capability, m	1.90	1.66
Reduction of icebreaking capability, %	–	13

One can see from the tables that icebreaker *Kapitan Nikolaev* has similar reduction of the icebreaking capability as icebreaker *Taimyr*. The loss in the icebreaking capability of icebreaker *Kapitan Sorokin* practically under the same shallow water conditions turned out to be somewhat more (13 % instead of 10 %). Thus latest tests have also confirmed the reduction of the icebreaking capability of ships under conditions of shallow water. However this reduction in the presence of reasonable safe under-keel clearance within 2.0 - 2.5 m can scarcely have serious consequences relative to operational and economical characteristics of the work of ship.

On the basis of the carried out investigations concerning the effect of small draft and shallow water on ice qualities of large icebreaking ships one may come to the conclusion that as far as the provision of ice propulsion is concerned the main problem is the possibility of the efficient processing of high power when constructing shallow draft ships. Expected comparatively small reduction of the icebreaking capability during the sailing under conditions of shallow water can scarcely be considered as related to most important problems requiring solution during the design of ships with restricted draft.

The investigations made have corroborated principal feasibility of the construction of large shallow draft ships for the Arctic. Main attention here should be paid to problems of the guarantee of ice strength of hull and reliable work of the screw-rudder system, stern tubes and the sea water power plant cooling system. Experience of the construction and operation of the Russian icebreaking fleet shows that these problems are practically soluble.

6. STUDY OF THE EFFECT OF THE STATE OF SHELL PLATING ON THE ICEBREAKING CAPABILITY OF SHIPS

The construction of powerful nuclear icebreakers and the renewal of the icebreaking cargo fleet in Russia enabled to considerably extend the duration of navigation in the Arctic and to navigate in the western area all the year round. At the same time, certain problems were brought to light associated with the particular winter operation conditions, such as sticking of a snow-ice mass onto the hull resulting in a sharp reduction of speed of the icebreaker until the complete stoppage of the latter; frequent and protracted jammings; decrease of the icebreaking capability progressing in time and caused by rapid corrosion of the outer plating and accordingly by the increase of its roughness. These phenomena lead to considerable economic losses necessitating in the design of icebreakers and icebreaking cargo ships to provide for special technical facilities of the improvement of the passability in ice assuring the protection against sticking and jamming as well as maintaining the icebreaking capability in the course of the operation of ship at a specification level. Among such facilities there are heeling and trimming systems, washing devices, ice-resistance coatings, steel clad with a stainless layer for the outer underwater hull plating, electrochemical protection etc. For the assessment of the efficiency and advisability to utilize certain of the above means of the improvement of the passability in ice, CNIIMF has performed special investigations on the study of the effect of roughness of the shell plating upon the ice propulsion of ships.

Generalization and analysis of information on the operational experience and also on the full-scale trials of icebreakers in the Arctic testify to the continuous and substantial reduction of the icebreaking capability of icebreakers with the increase of their age. To illustrate this, in Figure 6.1 comparisons are given of icebreaking capability curves of nuclear icebreaker *Arktika* obtained from the results of delivery trials of the nuclear ship in May 1975 and specially performed control tests of this nuclear icebreaker in the same area in May 1983, that is after 8 years. From the graphs shown one can see that the icebreaker icebreaking capability curve of 1983 at the same power is appreciably lower than that of 1975. This fact accounts for heavy corrosion damages of the shell plating and sharp increase of its roughness. As a result, the icebreaking capability of icebreaker *Arktika* decreased by 27 % which is equivalent to the icebreaker loss of power (as it follows from the graph in Figure 6.2) by 54 %.

Such high losses were a cause for carrying out special investigations on roughness of the ship's surface and of its influence upon shell plating/ice friction coefficient [23, 24].

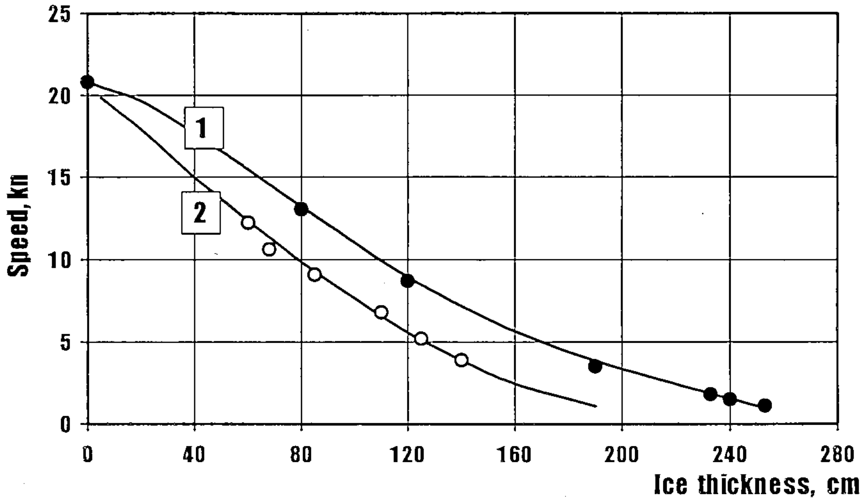

Fig.6.1. Icebreaking capability of icebreaker *Arktika* in May 1975 (1) and in May 1983 (2)

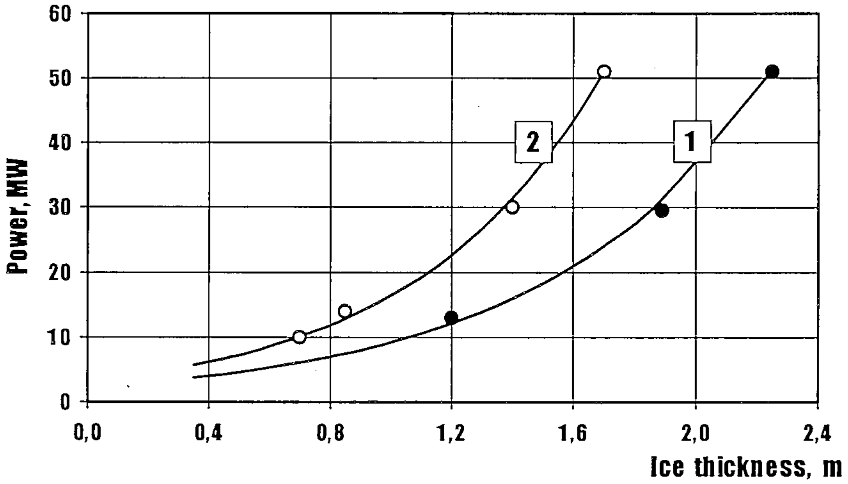

Fig.6.2. Relationship between thickness of level ice broken through by icebreaker *Arktika* and power at a speed of 2 knots in May 1975 (1) and in May 1983 (2)

Study of the state of icebreaker plating has brought to light the following:

1. Roughness of the shell plating after several years of the operation of icebreaker due to corrosion and erosion wear may be many times higher than the initial one. Roughness of a new painted or prepared for painting icebreaker hull is usually within 50 - 200 μm by parameter $\mathbf{R}_{max}$ (maximum height of profile irregularities within the basic length).
2. Level of roughness and speed of its growth considerably depend on the hull's material. So, roughness of high-strength austenitic steel of AB type used on nuclear icebreakers grows more quickly and reaches approximately twice higher values of $\mathbf{R}_{max}$ if compared with ordinary carbon steels. This proves the fact that for powerful nuclear icebreakers, problems of retaining icebreaking capability in the process of operation are of primary importance.

Figure 6.3 represents dependencies of $\mathbf{R}_{max}$ on the time of operation and hull's material. Roughness of the icebreaker plating sharply increases during the first 6 - 8 years and then its level having reached maximum values after 8 - 10 years of operation, stabilizes.

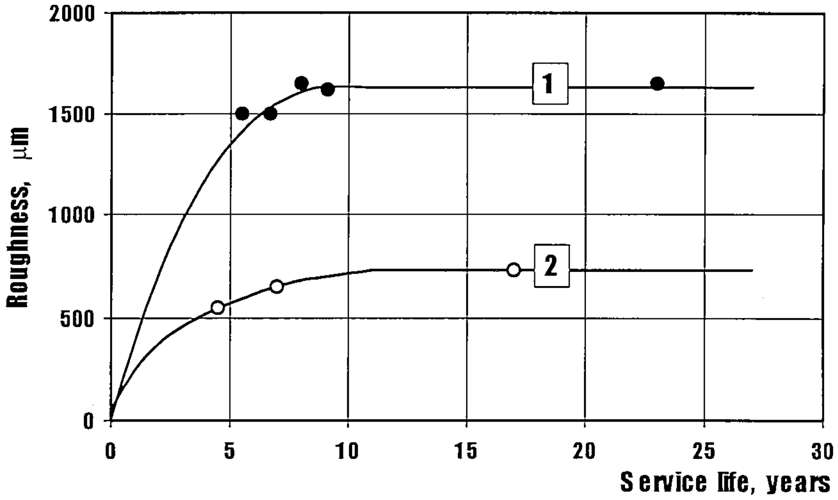

Fig.6.3. Relationship between the roughness of shell plating, time of operation and hull materials of icebreakers: steel of AB type on nuclear icebreakers (1) and carbon low-alloy steel (2)

Dependence of the icebreaking capability on the coefficient of plating / ice dynamic friction obtained as applied to icebreakers *Arktika* and *Kapitan Sorokin* is shown in Figure 6.4. As one can see, the revealed considerable reduction of the icebreaking capability of icebreakers with the increase of hull's roughness during the service life requires the adoption of special measures for the prevention of this adverse phenomenon in the course of icebreaker operation.

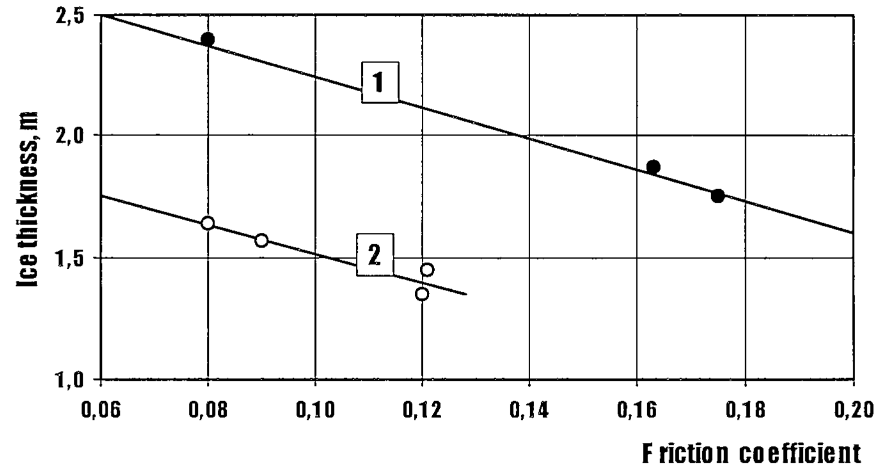

Fig.6.4. Effect of the friction coefficient upon the icebreaking capability of icebreakers *Arktika* (1) and *Kapitan Sorokin* (2)

Additional factor reducing the icebreaking capability under winter conditions is the sticking of snow and ice upon the icebreaker's hull. Along with the reduction of movement speed this may result in emergency situations while escorting ships. Observations have shown that during the first year of the operation of icebreaker the sticking and jamming either do not occur or are of episodic short duration each succeeding year becoming more and more intense and of longer duration. This points to the dependence of these factors upon the roughness of shell plating. Consequently, to fight them it is also necessary to search for methods and means for the prevention of corrosion and erosion wear of the hull plating of icebreakers. For the compensation of the negative influence (or complete neutralization) of the shell plating roughness the application of means affecting friction coefficients will be required. According to the nature of this effect all the means improving the passability in ice may be conventionally divided into active (controlling the sticking and seasonal increase of the friction coefficient) and passive ones preventing the growth of roughness and retaining icebreaking capability at a specified level in the process of long operation of ship. Figure 6.5 shows principal means for the improvement of the passability in ice which have been studied and may be used for icebreakers and ships to be built in the future [25].

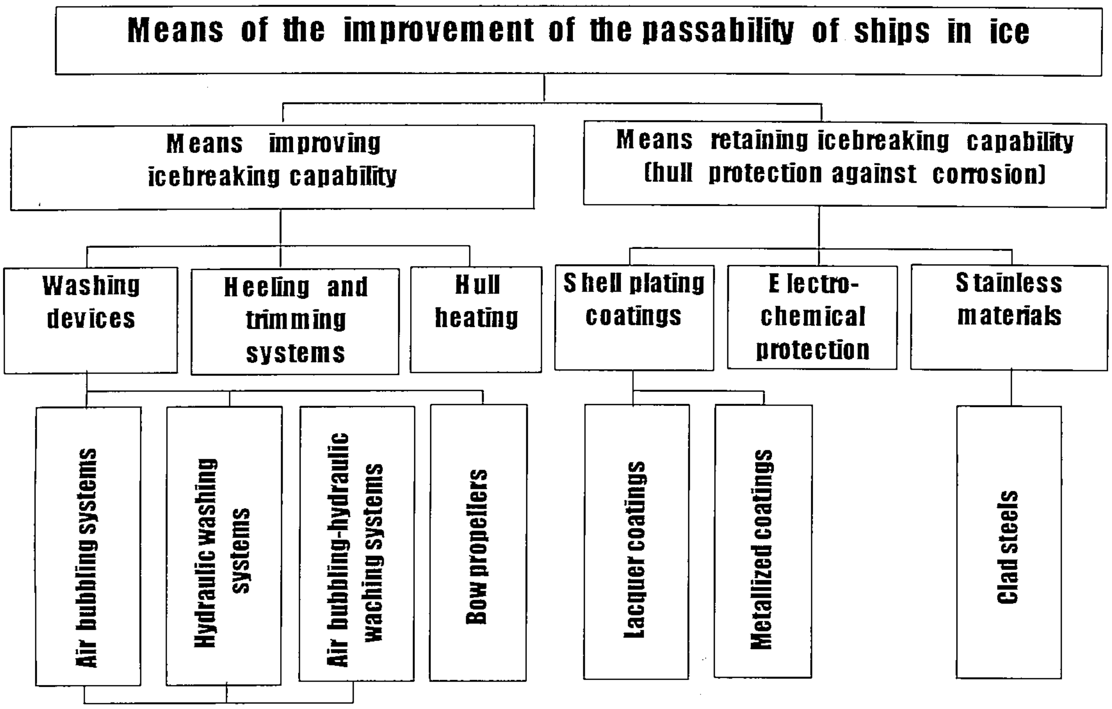

Fig.6.5. Classification of means improving the passability in ice

Assessment of the comparative efficiency and advisability of the application on ice ships of different purposes of means improving the passability in ice performed by technical and economic analysis has permitted to come to the following conclusions:

1. The use of active means (air-bubbling system, hydraulic washing, hull heating etc.) enables to decrease negative effect on the ice propulsion of low temperatures, snow cover over ice, sticking phenomenon, but this does not make up for the strongest factor causing the reduction of the icebreaking capability associated with the shell plating corrosion wear. Out of the considered means improving the passability in ice in winter those using the principle of hull air-bubbling are most efficient [26].
2. To retain the specification icebreaking capability of icebreaking ships in course of operation it is necessary to use ice-resistant lacquer coatings and for the ice strake area – also the double-layer steel with a stainless outer layer combined with the electrochemical protection. It has also been found out that for icebreaking cargo ships the use of stainless steels is not justified. Better economical indices are achieved using ice-resistant coatings.

The above conclusions were the basis for the drawing up of technical and operational requirements to means improving the passability in ice of the prospective icebreakers and icebreaking cargo ships.

7. ASSESSMENT OF THE NEEDED ICEBREAKING CAPABILITY OF ARCTIC SHIPS OF THE PROSPECTIVE CONSTRUCTION

The long-standing experience of the operation of Russian ships in the Arctic and the accumulated statistic data on the duration of arctic navigation depending on the power of icebreakers which escort ships through ice permit to formulate requirements to the icebreaking capability of these icebreakers. The knowledge of this value is necessary for the reliable and safe navigation of ships in a given area of the Arctic during a particular season. This applies to the traditional way of sailing in the Arctic of cargo ships under the assistance of icebreakers. And in this case, when choosing principal parameters of ships their power and icebreaking capability is optimized depending on the purpose of ship, navigational conditions and capabilities of a leading icebreaker.

When selecting parameters of an icebreaking cargo ship of independent ice navigation without the assistance of icebreakers one should bear in mind that cargo ships as to their ice performance and maneuverability are substantially worse in comparison with specialized icebreakers.

Cargo ship while navigating in ice, if compared with an icebreaker, under other similar conditions (the same icebreaking capability, number of propeller shafts etc.) will have worse parameters related to:

- turning ability (gyration in ice, "herring bone" turn);
- ability of getting released from sticking;
- propulsion under conditions of ice compacting.

Worsened maneuverability of a cargo ship principally accounts for the presence of a parallel middlebody and relatively larger length. It is apparent that no shipowner would agree to cut the hull length of a merchant ship for getting dimensional ratios characteristic of icebreakers, because this would result in a considerable reduction of cargo-carrying capacity and economical efficiency of the ship. Therefore this limitation should be considered as inherent to ice cargo ships. At the same time, latest achievements in the field of icebreaker building raise hopes for the possibility to substantially improve ships' maneuverability in ice thanks to the use of turning propeller steering systems of *Aquamaster* and *Azipod* type, if their structural reliability and efficiency during the operation under heavy ice conditions is demonstrated in practice. The use on ice ships of turning screw-rudders will apparently enable solving also the problem of sternway movement and improvement of the ability to get released from sticking. With the help of turning screw-rudders a possibility will emerge of rocking and swinging a stuck ship that would substantially assist in its getting released. When on a transport ship there are fast-acting heeling and trimming systems, such a ship with the turning propulsion unit will be able to maneuver in ice and to get released from sticking independently.

Fundamental disadvantage of cargo ice ships is their inherently worse propulsion under the ice compacting. Loss of speed at the ice compacting might be compensated only by the increase of power.

The investigations performed [27] and processing of the statistic data on the operation of ships in the Arctic show that general frequency of compacting during the sailing through ice with a concentration of 9/10 - 10/10 reaches 55 - 60 % (Figure 7.1).

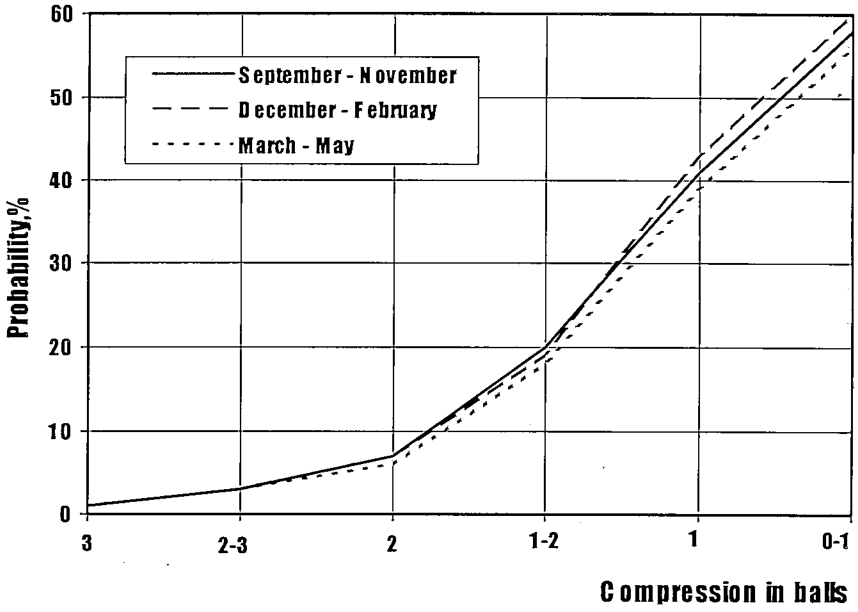

Fig.7.1. Cumulative probability of ice compression

Significant ice compacting (numbers 1 - 2) leading to the reduction of speed approximately twice occur on ice route stretches amounting to about 20 % of the total length of way through the concentrated ice.

Study of the effect of ice compacting upon the speed of ships navigating along the Northern Sea Route has permitted to find out the difference in propulsion between icebreakers and icebreaking cargo ships. With due account of the ice compacting and of other unfavourable weather conditions in independent navigation the speed of a cargo ship on the NSR is reduced on the average by 14 - 15 % in comparison with an icebreaker. It was also established that relative changes in the ship's speed under the ice compacting of moderate intensity in the first-year medium ice was approximately proportional to the ship's length/breadth ratio (**L/B**). It is known that difference in **L/B** of icebreaking cargo ships and icebreakers may reach 30 - 40 %. Similar value should be anticipated in the loss of speed of a cargo ship in comparison with an icebreaker under conditions of the ice compacting with an intensity of 1 - 2.

Statistical data on the probability of occurrence of the ice compacting of different intensity and its effect on the propulsion of ships enabled to produce simulation of the movement of ships in ice taking into account compacting in the independent sailing and under the assistance of icebreakers.

By means of the model developed the comparison was carried out of the time consumption of an icebreaking cargo ship and icebreaker having the same icebreaking capability for the independent passage of the ice route 20 % of which falls on the conditions of the ice compacting its average statistical intensity being 1 - 2. As it was mentioned, under these conditions the speed of icebreakers on the average decreases twice and of an icebreaking cargo ship of *Amguema* type by further 25 - 30 % relative to an icebreaker. It is to be supposed that for the achievement of the same efficiency and safety in the transportation of cargo the ships with different **L/B** ratios should provide for the same turn-round time, i.e. have equal speed of movement averaged over the whole ice route. For this purpose and bearing in mind that under the ice compacting a ship with increased **L/B** has considerable speed losses, to compensate for these additional losses while moving along the route on stretches without ice compacting (80 %) the speed of ship should be accordingly increased at the expense of the power increase of a propulsion plant and consequently of the ship's icebreaking capability. Value of this increment is to be determined from the condition of obtaining equal time consumption (or equal average speed) for the covering of the whole route. These initial presuppositions were used for the calculations of average speeds of movement of ships along the NSR according to different versions.

Results of calculations are presented graphically in Figure 7.2 showing the required increase of the icebreaking capability of a cargo ship with **L/B** = 6.5 for the achievement of the averaged speed over the whole ice route equal to the speed of an icebreaking cargo ship with **L/B** = 5.1. As the statistics shows, in the first year medium ice on the NSR the ships escorted by icebreakers develop average speeds of 8 - 10 knots. At such speeds the increase of ship's icebreaking capability in the transition from **L/B** = 5.1 to **L/B** = 6.5 should be 10 - 14 %. It corresponds to the increase of power by 30 - 45 %.

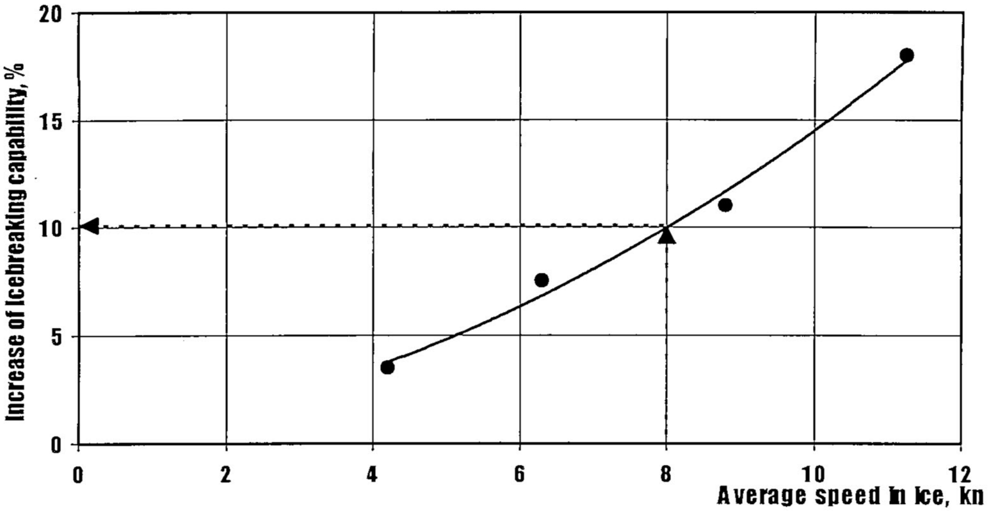

Fig.7.2. Increase of the icebreaking capability required to ensure the equality between average speed of an icebreaking cargo ship passing through the ice route in independent navigation and that of an icebreaker

Thus the investigation undertaken has shown that to provide for the average speeds of movement equal to those of icebreakers taking into account the probability of ice compacting on the NSR the icebreaking cargo ships with the standard ratio **L/B** = 6.5-7.0 should have at the same icebreaking capability, in comparison with icebreakers (**L/B** = 4.5-5.1), an additional increase of power of the propulsion plant from 30 to 50 %.

Taking into account the above stated, appropriate corrections were introduced into statistical data on the results of arctic navigations with the icebreaker support. Figure 7.3 represents the dependence of the eventually obtained guaranteed duration of the safe independent sailing in the Arctic of icebreaking cargo ships upon their icebreaking capability as applied to the traditional icebreaking hull form. It can be seen from the plot that for the safe year round navigation over the whole NSR the icebreaking capability of a cargo icebreaker should be at least 3.7 m, in the Kara Sea – 2.8 m and in the Pechora Sea – 2.1 m.

These figures corresponding to the excessively high power cast doubt on the advisability of using in the Arctic non-icebreaking transport and technological systems making provision for the use on the NSR of only icebreaking cargo ships of independent navigation without icebreakers. This matter however exceeds the limits of the present work; it should be studied by the comparative economic assessment of the competing systems using and not using icebreakers. The Russian experience shows that without the assistance of icebreakers it is impossible to provide for the efficiency of operation of the transport fleet in the Arctic. It is only necessary to determine the reasonable need in the icebreaker support in each specific case.

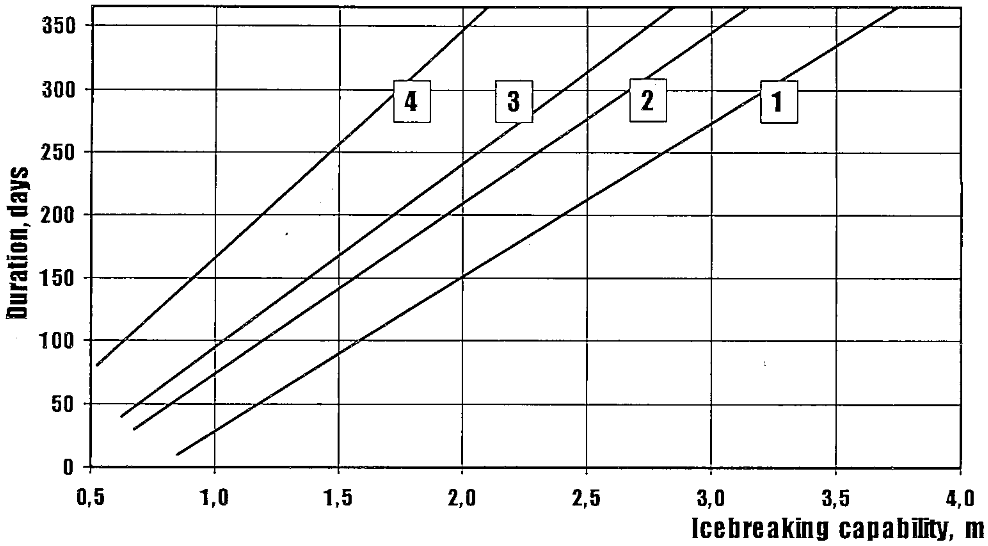

Fig.7.3. Dependence of the duration of the safe independent navigation of icebreaking cargo ships in the Arctic on their icebreaking capability (taking into account the long-standing experience of arctic operations):
1 – Eastern area of the Arctic and transit sailing through the NSR,
2 – Western area of the Arctic,
3 – western section of the Kara Sea,
4 – Pechora Sea

With a rational value of the icebreaking capability of an icebreaking cargo ship equal to 1.5 - 2.0 m, as one can see in Figure 7.3, such ship will be able to be operated independently practically the year round in the Pechora Sea, for up to 7 months in the western area of the Russian Arctic and for about 4 - 5 months in the eastern area and during the transit navigation over the entire NSR. In the remaining winter-autumn period of the year, to ensure the safety of sailing of such ship in arctic seas the icebreaker support will be required. Proceeding from this tactics of work of ships in the Arctic, the most efficient in accordance with the Russian experience, new powerful leading icebreakers were constructed and substantiated in Russia. Characteristics of prospective arctic icebreakers for the escorting of future large ships are considered below (Section 9).

8. TYPE SIZE SERIES OF SUPERSHIPS

8.1. Tankers for the export of gas condensate and crude oil

Ships of this type are most prospective as the interest to the deposits of hydrocarbons in the shelf zone of arctic seas is progressively growing. Hand in hand with Russian enterprises also foreign oil companies in a competitive way strive for the control over the right of the industrial development of mineral resources. Most investigated are the resources of the Barents, Pechora and Kara Seas with potential reserves of hydrocarbons as of 1995 being approximately equal to 54 billion tonnes [28]. Ten deposits - two oil and eight gas and gas condensate ones - were brought to light here. In the nearest future one may anticipate the following volumes of the annual export of the gas condensate from this zone of the Arctic, million tonnes:

- Kharasavei – 0.5 - 1.0,
- Novy Port – 0.5 - 1.0,
- Yamburg – 1.0 - 3.0.

Tankers for the export of gas condensate. At the Kharasavei gas deposit the average daily accumulation of the gas condensate may amount to 1400 - 2800 tonnes. For 10 days (approximate duration of one return voyage) a deposit will accumulate 14000 - 28000 tonnes of cargo the export of which may be carried out by 1 - 2 tankers with a carrying capacity of about 14000 tonnes. Annual production of the condensate in the Ob Gulf (Novy Port and Yamburg) is planned to be at the level of 1.5 - 4.0 million tonnes corresponding to the average daily production of 4100 - 12300 tonnes. At an average duration of the return voyage of about 12 days some 50000 - 150000 tonnes of cargo will be accumulated and this quantity of cargo cannot be taken away by one ship of the matching tonnage bearing in mind draft restrictions. Greater number of smaller tankers will be needed.

Preliminary analysis allows to determine boundaries of the alternative series of tankers for the export of gas condensate from the Western sector of the Russian Arctic. For the Kharasavei region of deposits one may bear in mind tankers of 6000, 10000, 17000 and 30000 tonnes. These ships will be able to work without any limits in the Ob Gulf as well because their draft does not exceed 9 m. The construction of larger deadweight tankers with a restricted draft is technically feasible, but has some peculiarities – length/width and width/draft ratios increase. Change of length results in the increase of the hull mass, makes ship more expensive and during the navigation in ice conditions deteriorates the maneuverability and the ability to get released from the sticking.

Wider ships have somewhat worse propulsion parameters in calm sea and in waves as well as in oscillation due to the decrease of its period. In this connection the length/width and width/draft ratios cannot exceed 8 and 4 accordingly. Having these restrictions in view it is possible to design tankers with a deadweight of about 40000 and 60000 tonnes. The latter would operate in the Ob Gulf with a certain underloading, but with a possibility to finalize loading up to the full draft at Kharasavei. So, to ensure the supposed volumes of the transportation of gas condensate one can consider an alternative series of tankers of two ice categories – UL and ULA – with a deadweight from 6000 to 60000 tonnes (Table 8.1). One may judge of the character of the change of main dimensions, displacement, power and speed of ships of the alternative series in question from dependences presented in Figures 8.1 - 8.5.

All the tankers in question have the isolated ballast located in the double bottom, double sides, bow deep-tank and peaks. This allows to completely combine cargo handling and ballast operations. Pumping out of the ballast may be performed directly at berth during the loading in the Ob Gulf and at Kharasavei. At negative air temperatures it is necessary to heat the ballast located in double sides. When the air and water temperature drop below 15° the cargo heating is required starting several days before the arrival in the port of unloading. For this purpose, on tankers with pumps in the pump room there are coils in tanks for the circulation of steam. Cargo heating on tankers (versions 1 and 2) with submersible pumps is carried out by heat exchangers situated on deck. It is advisable to use heat exchangers also for heating of the ballast in double sides.

Washing of cargo tanks is made during the change of cargo or once per 4 - 5 voyages. On tankers with a deadweight exceeding 20000 tonnes, stationary washing machines (two ones per a tank) are fitted and the inert gas system is arranged.

Table 8.1

Principal characteristics of ice tankers for the transportation of gas condensate

Characteristics	*Tankers of the UL ice category*					
	Version 1	Version 2	Version 3	Version 4	Version 5	Version 6
Length between perpendiculars **L**, m	105.3	133.5	154.0	203.0	237.0	246.5
Breadth **B**, m	18.3	21.0	24.4	31.0	33.6	36.0
Depth **H**, m	9.5	11.0	14.0	14.5	15.0	16.5
Draft **T**, m	6.7	8.0	9.0	9.0	9.0	11.0
Deadweight, t	5500	10600	18200	31000	40000	60000
Block coefficient	0.67	0.70	0.76	0.76	0.76	0.78
Light displacement **D**, t	3300	5500	8250	13120	15680	18040
Ratios:						
L/B	5.75	6.36	6.31	6.55	7.05	6.85
B/T	2.73	2.63	2.71	3.44	3.73	3.27
H/T	1.42	1.38	1.56	1.61	1.67	1.50
L/H	11.1	12.1	11.0	14.0	15.8	14.9
Rated power, kW	4500	6000	7600	11000	12800	14400
Service speed, kn	15.2	15.3	14.8	15.0	15.0	14.5
Number and capacity of cargo pumps, m^3/h	8×150	10×150	4×450	4×750	4×100	4×1500

	Tankers of the ULA ice category					
	Version 7	Version 8	Version 9	Version 10	Version 11	Version 12
Length between perpendiculars **L**, m	111.5	139.5	164.7	209.0	245.0	259.5
Breadth **B**, m	18.3	21.0	24.4	31.0	33.6	36.0
Depth **H**, m	9.5	11.0	14.0	14.5	15.0	16.5
Draft **T**, m	6.7	8.0	9.0	9.0	9.0	11.0
Deadweight, t	5500	10600	18200	31000	40050	60000
Block coefficient	0.66	0.69	0.75	0.75	0.75	0.76
Light displacement **D**, t	3750	5975	9600	14070	16905	20050
Ratios:						
L/B	6.09	6.64	6.75	6.74	7.29	7.21
B/T	2.73	2.63	2.71	3.44	3.73	3.27
H/T	1.42	1.38	1.56	1.61	1.67	1.50
L/H	11.7	12.7	11.8	14.4	16.3	15.7
Rated power, kW	6800	10000	14900	2x10000	2x11400	2x13500
Service speed, kn	15.2	14.8	15.0	14.3	14.2	14.0
Number and capacity of cargo pumps, m^3/h	8×150	10×150	4×450	4×750	4×1000	4×1500

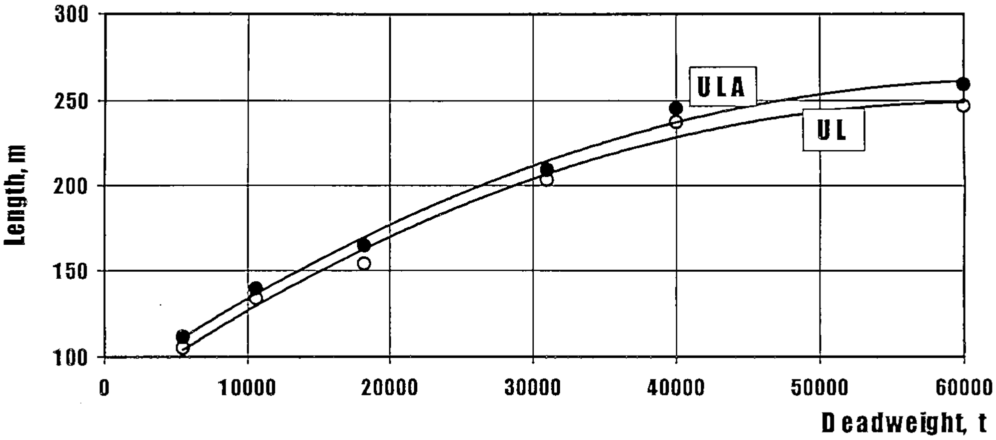

Fig.8.1. Dependence of the length of tankers of the ice categories UL and ULA on the deadweight

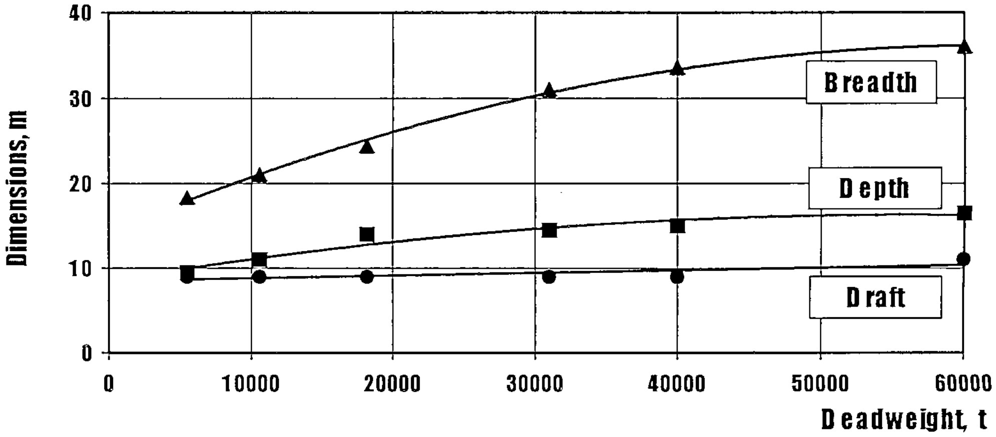

Fig.8.2. Change of width, depth and draft of ice tankers with the increase of deadweight

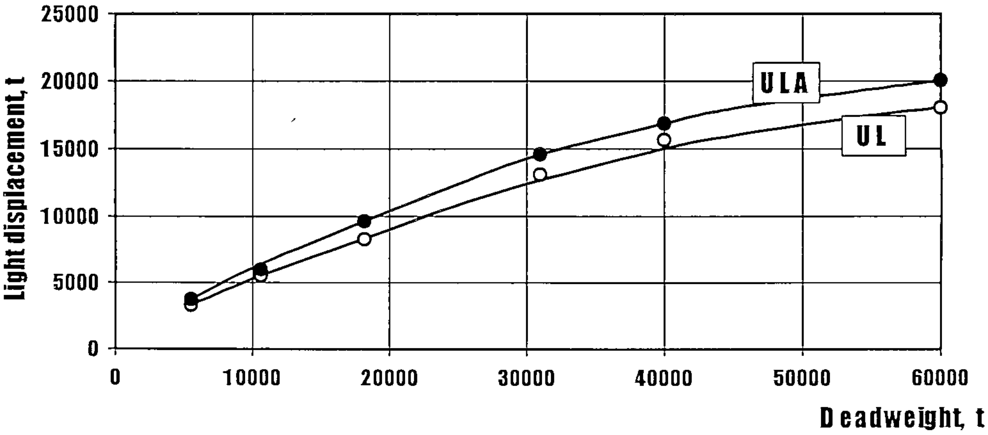

Fig.8.3. Dependence of the light displacement of tankers of the UL and ULA ice categories on the deadweight

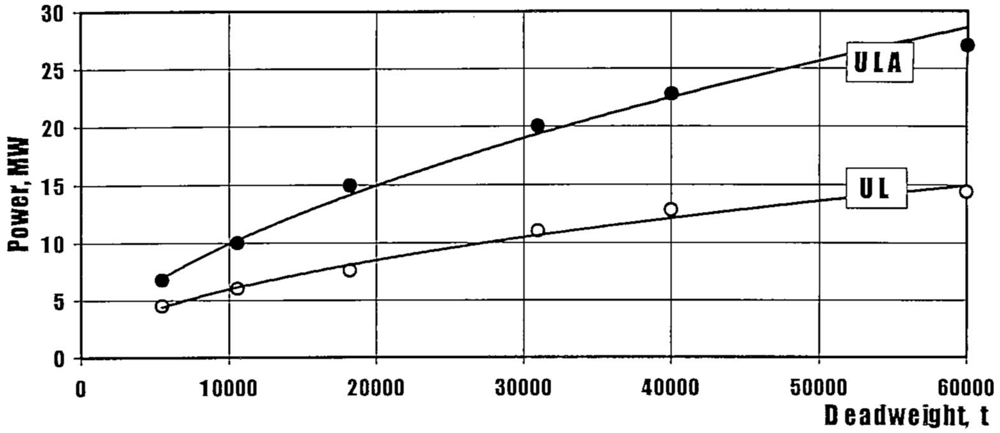

Fig.8.4. Dependence of the power of the propulsion plant of tankers on the ice category and deadweight

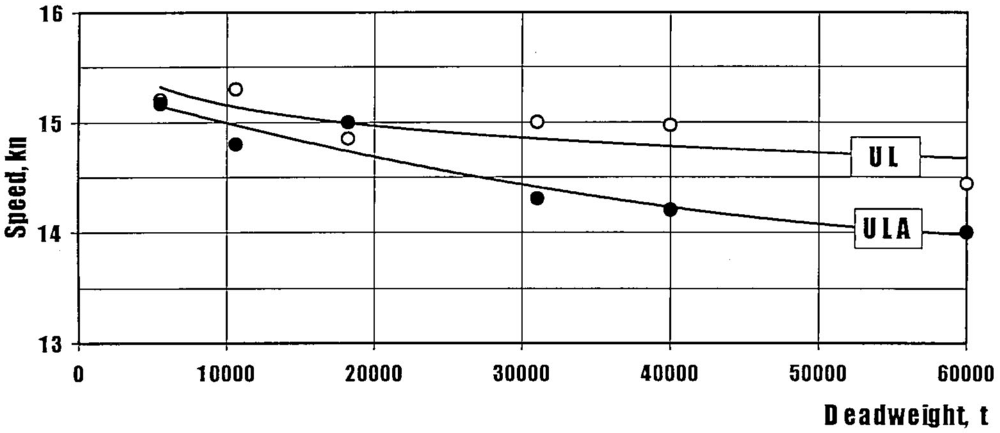

Fig.8.5. Change of operational speeds of tankers of the UL and ULA ice categories with the increase of deadweight

Tankers for the export of crude oil. Development of the alternative series of tankers was carried out using as an example ships for the export of gas condensate. The main distinctive feature of this cargo is its density equal to 0.69 - 0.82 t/m^3 unlike that (0.85 t/m^3) for the crude oil. Specification requirements for the marine transportation of gas condensate and crude oil are practically the same [29], therefore all the tankers covered by the alternative series can work as crude oil tankers. In severe ice conditions all the ships included into the alternative series will operate under the assistance of linear icebreakers of different types. Figure 8.6 illustrates the side view of tanker with a deadweight of about 17000 tonnes.

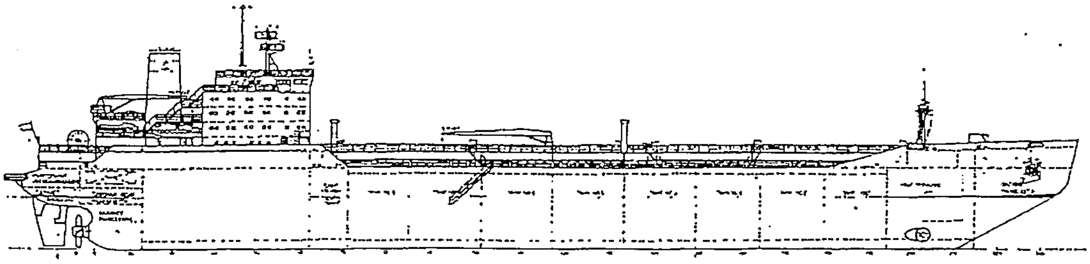

Fig.8.6. Side view of a tanker of the ULA category with a deadweight of about 17 000 tonnes

While investigating potential possibilities of the export of oil from the arctic basin an alternative version is considered of its transportation along the NSR and further on to the east by large tankers-icebreakers. Deadweight of such tankers taking into account probable restrictions in the navigation along the high latitude routes may amount to 150 000 - 200 000 t. Principal characteristics of tankers of the independent navigation are presented in Table 8.2 and a side view of one of them – in Figure 8.7.

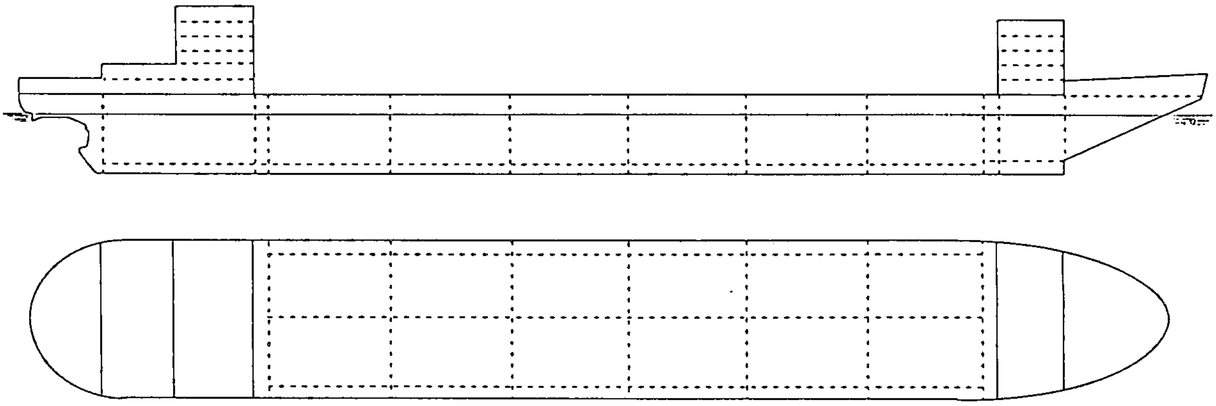

Fig.8.7. General arrangement of a tanker-icebreaker with a deadweight of about 200000 tonnes

Table 8.2

Principal elements and characteristics of tankers of the independent navigation

Characteristics	*Tankers-icebreakers*		
	Version 1	Version 2	Version 3
Length on designed waterline, m	247.0	368.0	368.0
Breadth, m	36.5	55.0	55.0
Depth, m	13.6	21.0	28.0
Draft, m	9.0	15.0	20.0
Displacement, t	61970	213100	284150
Deadweight, t	40000	143700	201550
Type of engine	Low speed	Low speed	Low speed
Power, kW	50000	50000	50000
Type of propulsion device	CPP	CPP	CPP
Number of propellers	2	2	2
Angles, deg.			
stem angle	23	25	25
entrance angle	35	35	35
midship flare angle	0	8	8
fore perpendicular frame flare	60	60	60
Block coefficient	0.77	0.70	0.70
Icebreaking capability, m	2.0	2.3	2.4

8.2. Gas carriers

The West Siberian oil and gas complex is one of the most prospective regions of the economical development of the North. In the transportation of gas from the Yamal Peninsula the sea-borne transport may well compete with the pipeline. The export of liquefied gas by gas carrying ships may be effected in two directions: to Kola Peninsula and to Western Europe. Most complicated for the navigation of ships is the section from the Yamal Peninsula to the Kara Strait which may be covered by ships assisted by icebreaker or independently. All-the-year-round independent operation will result in the necessity of the construction of a gas carrier-icebreaker.

For ships navigating during the heaviest periods under the icebreaker assistance it is sufficient to have the ULA category of ice strengthening. Architectural and structural peculiarities of gas carriers are defined by the choice of the type of cargo tanks. Comparison of two ships of the same capacity but with membrane and spherical tanks shows that the first one is of smaller plan dimensions and register capacity, the second one – of lower free board and displacement. The main drawback of spherical tanks is the weakening of the deck by cut-outs and the elevation of tanks above the deck this complicating the arrangement and servicing of equipment and pipelines. In spite of this preference should be given to the spherical version of cargo spaces because it provides for the highest reliability and safety. Inserted spherical tanks are less sensitive to the strain of hull under the effect of ice compression and when operating by ramming as well as at higher vibration in sailing through ice.

The formation of a type series of arctic gas carries is restricted by depths near the Yamal Peninsula and the extent of icebreaker servicing. Depending on the type of icebreaker the capacity of ships may change within 37 000 - 90 000 m^3 and in case of the operation without icebreaker reach 125 000 m^3 (Table 8.3). Maximum draft at which gas carriers can work on this line is about 11 m. Figure 8.8 shows the scheme of one of the ship alternatives for the export of liquefied gas from the Yamal Peninsula.

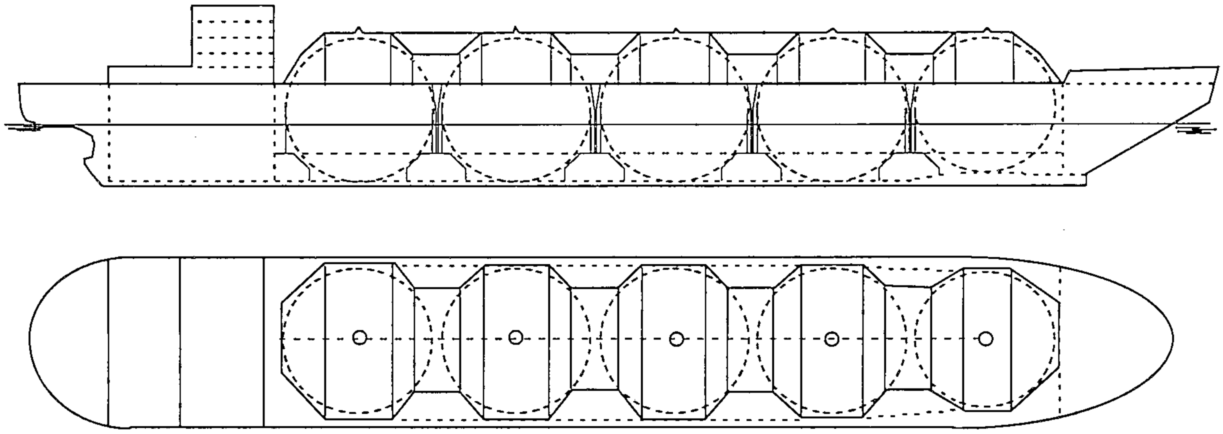

Fig.8.8. General arrangement of an ice ship for the transportation of liquefied natural gas

Table 8.3

Principal elements and characteristics of gas carriers

Characteristics	*Gas carriers*			
	Version 1	Version 2	Version 3	Version 4
Ice category	ULA	ULA	ULA	LL1
Length, m	182	216	247	321
Breadth, m	30	35	40	45
Depth, m	18	20.8	23	25
Draft, m	9.5	10.2	10.5	10.8
Displacement, t	39100	57900	78150	109900
Load carrying capacity, t	17800	30000	43500	60000
Deadweight, t	20300	33000	47000	62300
Capacity, m^3	37000	62000	90000	125000
Type of engine	Steam-turbine	Steam-turbine	Steam-turbine	Diesel-electric
Power, kW	15600	18500	23500	110000
Type of propulsion device	CPP	CPP	CPP	FPP
Number of propellers	2	2	2	3
Speed, kn	18.9	18.2	19.7	21.0
Angles, deg.				
stem angle	25	25	25	25
entrance angle	35	35	35	40
midship flare angle	0	0	0	10
fore perpendicular frame flare	60	60	60	60
Block coefficient	0.75	0.75	0.75	0.70
Icebreaking capability, m	1.4	1.55	1.7	3.0

8.3. Bulk carriers

Most probably the ships of this type will find application on the NSR in the transportation of iron ore, coal, fertilizers and ferrous metals. The possibility is not excluded of the transit transportation of bulk cargoes between foreign ports, in particular of fertilizers from Murmansk to China.

Transportation between ports situated outside the arctic basin makes it possible for bulk carriers to have draft of 15 - 20 m. The width of ships may be chosen without restrictions if they are of the ice category and operated in the transport-icebreaker mode. Otherwise, when the ice strengthening category remains at the ULA level, the icebreaker assistance is required and this imposes limits on the width of ships.

One of the factors influencing the efficiency of the icebreaker escorting is the ship's width/icebreaker width ratio. The smaller is the latter the higher is the speed of the convoy. In the escorting of ship the width of which is greater than that of the icebreaker the speed of movement is sharply reduced and the risk of getting ice damages is higher. On the basis of these considerations, preferable value of the maximum width of ship following in the channel a prospective icebreaker with a power of 110 000 kW is about 40 m. Principal characteristics of superbulkers to be operated independently in summer and under the assistance of a linear icebreaker-leader in winter are given in Table 8.4. Schematic side view of one of the ships is presented in Figure 8.9.

Table 8.4

Principal elements and characteristics of bulkers and bulk/container carriers

Characteristics	*Bulkers*		*Bulk/container carriers*	
	Version 1	Version 2	Version 1	Version 2
Length, m	260.0	260.0	184.1	186.0
Breadth, m	40.0	40.0	25.1	27.5
Depth, m	24.0	28.0	15.0	16.0
Draft, m	17.0	20.0	9.0	12.5
Displacement, t	142000	167000	36060	51880
Deadweight, t	112000	136000	25000	40000
Capacity, m^3	136000	159000	32300	34560
TEU	–	–	1408	1671
Type of engine	Low speed	Low speed	Diesel-electric	Diesel-electric
Power, kW	22400	22400	29040	31680
Type of propulsion device	CPP	CPP	Azipod	Azipod
Number of propellers	1	1	2	2
Speed, kn	14.5	14.1	14.5	14.5
Icebreaking capability, m	1.4	1.5	1.8	1.8

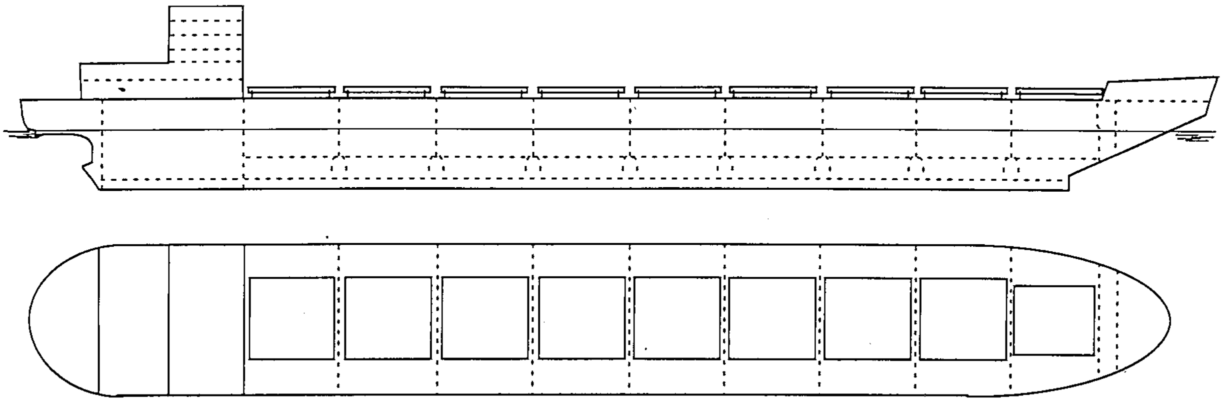

Fig.8.9. General arrangement of an arctic bulker

In the context of WP-4 of the Programme INSROP the Finnish company *Kvaerner Masa-Yards* has developed two projects of bulk/container carriers with a deadweight of 25 000 and 40 000 tonnes. Ships are designed for the export of timber and ore from the port of Dickson to ports of Japan and for the delivery of containers to Russian arctic ports on a return voyage. Principal characteristics of bulk/container carriers are presented in Table 8.4. High level of power and maneuverability enables them to independently operate on line Dickson–Japan during the summer-autumn period. During the rest of the year ships will surmount heavy ice sections under the escort of powerful icebreakers.

8.4. Containerships

Despite some stagnation phenomena and the excess of tonnage of containerships the world fleet of cellular containerships continues to grow. Ships are ordered predominantly of three type dimensions with a capacity of 1500 - 2000, 2500 - 3000 and more than 4000 TEU. Such containerships at an appropriate level of ice strength would be engaged in the transit traffic between ports of the Western Europe and those of Japan, China, USA and Canada. In this case two schemes of the organization of transportation are possible:

- independent navigation during summer and extended periods in the Arctic;
- independent operation during the summer arctic navigation and in the winter-autumn period under assistance of icebreakers with power of 63 000 and 110 000 kW.

For the realization of the first version the containerships should have ice category LL1 and as to the second one it is sufficient to have category ULA which provides for the necessary compliance between the speeds: achievable by power and that admissible by the strength of hull. In this case provision is made for the minimum risk of getting ice damages, reliability of movement along the NSR and possible economical efficiency due to the use of full power in the movement through channel behind the icebreaker. Principal characteristics of containerships of three types mostly corresponding to each of the above schemes of operation are presented in Table 8.5. Figure 8.10 shows, as an illustration, side view of the ULA category ship designed for the escorting by a leading icebreaker.

Table 8.5

Principal elements and characteristics of superlarge containerships

Characteristics	***Containerships***		
	Version 1	Version 2	Version 3
Ice category	ULA	ULA	LL1
Length, m	190	252	273
Breadth, m	28.5	32.2	39.0
Depth, m	15.8	19.5	21.4
Draft, m	10.0	11.5	12.0
Displacement, t	43150	67540	83400
Load carrying capacity, t	18000	29930	34000
Deadweight, t	31310	51000	54150
Capacity, TEU	1500	2300	3000
Type of engine	Medium speed	Medium speed	Diesel-electric
Power, kW	31140	62000	83500
Type of propulsion device	CPP	CPP	FPP
Number of propellers	1	3	3
Speed, kn	23	24	25
Angles, deg.			
stem angle	25	25	25
entrance angle	35	35	40
midship flare angle	8	8	8
fore perpendicular frame flare	60	60	60
Icebreaking capability, m	1.1	1.8	2.2

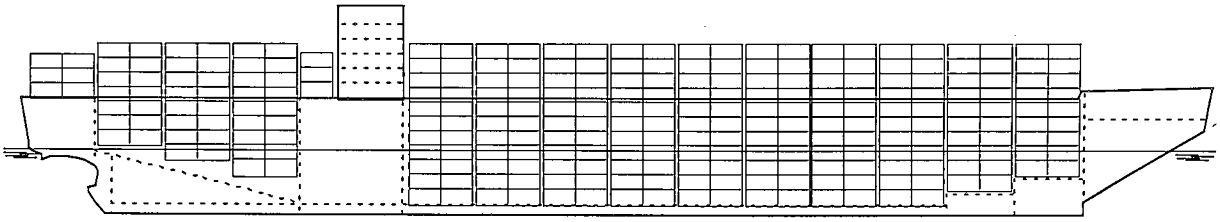

Fig.8.10. Side view of a specialized ship for the transportation of 2300 containers

Improvement of the architectural and structural type of containerships to raise their operational flexibility and economical efficiency involves the increase of the total container capacity (through the utilization of the upper deck and the greater number of deck tiers) as well as the possibility to arrange on deck and in holds containers of different type sizes and mass. 30 - 40 % of containers carried are located on the upper deck of this type of ships these containers being exposed to unfavourable environmental factors (penetration of water, wave impacts, icing etc.). An arctic containership version is possible with entirely protected deck cargo. For this purpose the ship is equipped with a covered deck superstructure in its upper part provided with light watertight hatch covers which extend over the whole stack of containers. Such alterations of the architectural and structural type of containerships will provide for the improvement of the safe keeping of cargo, elimination of the manual labour, reduction of time for cargo handling operations and increase of the carrying capacity.

Restrictions of main dimensions are due to water depths at the container terminals and width of icebreakers providing for the escort of ships through ice. For containerships 28 - 30 m wide of the first out of three considered types it is sufficient to have an icebreaking capability of 1.0 - 1.2 m and power-to-weight ratio of 0.65 - 0.75 kW/t (Figure 8.11) to successfully work with the icebreaker the power of which is about 63000 kW.

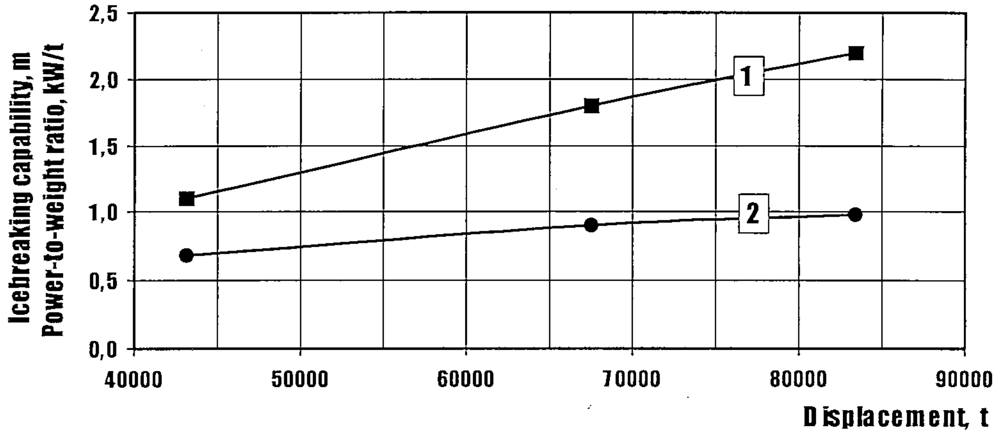

Fig.8.11. Dependence of icebreaking capability (1) and power-to-weight ratio (2) of containerships on the displacement

When the ships' width is increased up to 32 - 34 m (containerships of the second type) their icebreaking capability should be increased up to 1.7 - 1.9 m, the power-to-weight ratio - up to 0.85 - 0.95 kW/t and servicing under heavy ice conditions has to be placed on the icebreaker-leader with a power of about 110 000 kW. The last type of ships, transport-icebreaker, should have an icebreaking capability of about 2.2 - 2.4 m and power-to-weight ratio of about 1 kW/t.

9. NEW TYPES OF ICEBREAKERS TO ENSURE ESCORTING IN THE ARCTIC OF PROSPECTIVE LARGE CARGO SHIPS

The exploration of raw energy resources of the northern section of Russia planned for the nearest future and the organization of the international transit transportation of goods along the NSR by traditional methods of the escorting of ships through ice by icebreakers generate a need for appropriate development of the icebreaking fleet.

For the support of prospective large-scale cargo flows in the Arctic, principally new types of cargo arctic ships and new matching icebreakers should be developed and constructed.

For the transportation of energy raw materials out of the arctic shelf areas it is necessary to build large icebreaking crude oil tankers, liquefied natural gas carriers, tankers for the gas condensate and bulk carriers. These ships should meet specific operational and technological requirements dictated by working conditions in the Arctic (low air temperature, heavy ice conditions, shallow water near the arctic coast, transshipment operations without berths etc.) and from the viewpoint of economical efficiency they have to be of a high load-carrying capacity.

Development of the transit transportation over the shortest high-latitude sections of the NSR will require the construction of large competitive ice container ships with a capacity of up to 3000 TEU of a principally new architectural and structural type ensuring the safe carriage of containers under unfavourable weather conditions.

According to the comparative technical and economical investigations made by CNIIMF, the year round use in the Arctic of icebreaking cargo ships of active independent (without the assistance of icebreakers) navigation is not advisable. Preference is given to the traditional method of the escorting of ships by icebreakers [30, 31]. Proceeding from the above stated, the use in the Arctic of prospective superships will call for the construction of appropriate powerful nuclear leading icebreakers capable of providing for reliable, regular and safe year round navigation along the NSR including high-latitude sections.

As the experience and investigations have shown, the arctic fleet of icebreakers should be based on multi-purpose route ships adapted for the operation in shallow water areas of the Arctic and equipped with means of the improvement of the efficiency of work under these conditions. Taking into account requirements on the restriction of principal dimensions and, primarily, of draft of icebreakers, as well as the necessity at the same time to provide for practically unrestricted endurance regarding the stock of fuel, mobility and accordingly high reliability of arctic operations, the investigations proved the utility of the construction of powerful arctic nuclear icebreakers.

Thus on the basis of the above mentioned investigations, the advisability of the construction of prospective arctic icebreakers of the following two type sizes was substantiated:

- Superpowerful leading icebreakers of the *LK-110Ya* type with an icebreaking capability of 3.5 - 3.6 m and design waterline draft of 13 m and minimum operating draft of 11 m intended for the support of prospective large ships to ensure all the year round transportation of raw materials extracted on the shelf of arctic seas and the assured through transit carriage of cargoes along the NSR between the Western Europe and the Far East [32];
- Linear double-draft universal icebreakers of the *LK-60Ya* type with an icebreaking capability of 2.8 - 2.9 m, design waterline draft of 11 m and minimum operating draft of 9 m intended for the support of ships' convoys on traditional sections of the NSR during traditional periods of the arctic navigation as well as for the year round escorting of ships as a part of complex convoys behind an icebreaker-leader and for carrying out operations under heavy ice conditions in coastal areas including estuaries of Siberian rivers [33].

In the substantiation of principal dimensions of these icebreakers along with the escorting through deep water sections of the NSR of prospective superships the necessity of the interchangeability of icebreakers in areas with restricted depths was born in mind. Minimum operating draft without ballast of powerful icebreakers of each type size was selected taking into account the possibility of their use under extreme ice conditions in areas attended by less powerful icebreakers. This would allow making the escorting of ships in the Arctic safer taking into consideration variation of ice conditions. The efficiency of prospective arctic marine transport and technological systems will to a large extent depend upon the stability of shipping on the given directions of transportation.

Anticipated characteristics of prospective arctic icebreakers based on the design and feasibility study are shown in Table 9.1. and general arrangement plan of a nuclear icebreaker-leader of the *LK-110Ya* type – in Figure 9.1.

Table 9.1

Principal characteristics of prospective icebreaker types to support superships in the Arctic

Characteristics	*LK-110Ya*	*LK-60Ya*
Length, m		
• overall	224.0	177.0
• at design waterline	210.0	164.0
Breadth, m		
• overall	44.0	35.0
• at design waterline	42.0	33.0
Depth, m	22.0	18.0
Draft, m		
• overall	13.0	11.0
• specified (without H_2O ballast)	11.0	9.0
Displacement, t	68400	36500
Type of engine	Nuclear	Nuclear
Propulsion plant power, MW	130	74
Shaft power, MW	110	63
Number of propellers	3	3
Total bollard pull, t	950	630
Open water speed, knots	24.0	22.0
Icebreaking capability, m	3.5	2.8
Endurance, days	unlimited	unlimited
Crew	140	105

The universal duty and multi-purpose application of future icebreakers predetermine the use of traditional but improved shape of hull lines permitting to provide for a considerable gain in power (up to 50 %) while retaining the efficiency of operation practically under any ice conditions as well as to ensure the acceptable seaworthiness when sailing in open water. To improve ice performance including the maneuverability in ice, prospective icebreakers should be equipped with new progressive propeller-rudder systems, air bubbling and thruster devices and other means of the improvement of the icebreaking capability, such as the use of clad steels with a stainless outer layer for the underwater hull plating.

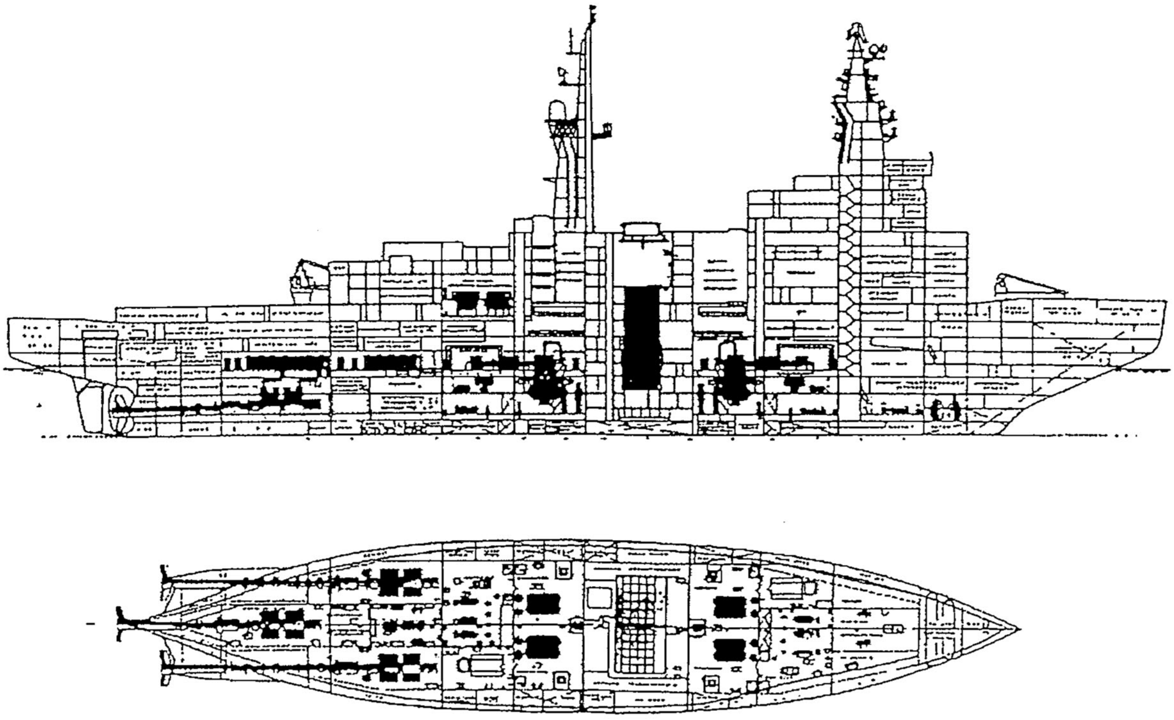

Fig. 9.1. General arrangement plan of icebreaker-leader with a power of 110 MW

10. REQUIREMENTS TO THE ICE PERFORMANCE OF PROSPECTIVE ARCTIC SHIPS

Requirements given below to the ice performance (ice impact strength and ice propulsion) of ships to be built in the future for the Arctic are based on the experience of design, construction and operation of Russian arctic ships as well as on the experimental investigations of ice propulsion and seaworthiness of ships with an icebreaking hull shape. In view of the negative conclusion obtained earlier by the results of the comparative analysis of the data of full-scale tests and experience of operation of refitted domestic icebreakers *Mudyug*, *Kapitan Nikolaev* and *Kapitan Sorokin* equipped with new forebodies of *Thyssen-Waas* and *Wärtsilä* systems, the present requirements have been drawn up as applied to ships with the traditional (wedge-like) bow shape [11, 12]. As the investigations have shown, traditional icebreaking hull lines may be substantially improved without a detrimental effect on the seaworthiness. Just these lines are recommended for future icebreaking cargo ships and arctic icebreakers.

As to ice classes of prospective ships it should be noted that at present specialists of the polar countries concerned have prepared and submitted to IMO a draft of the International Code on the safety of ships navigating in polar waters. This Code is supposed to be approved and implemented in 2001. At the moment within the common international ice classification used as a basis of the Code, requirements to arctic ships of different ice classes are formulated. It was considered advisable to distinguish seven principal ice classes of ships capable to operate under certain conditions (Table 10.1).

According to the Russian experience of the operation of ships in the Arctic the first three classes should be assigned to icebreakers, the last three - to cargo ships corresponding to the following ice classes of the Russian Marine Register of Shipping: PC5-ULA, PC6-UL, PC7-L1. International class PC4 may be assigned both to icebreakers and icebreaking cargo ships with additional hull strengthenings as compared with the existing strengthening category ULA. The practice shows that for the reliable operation in the Eastern region of the Arctic during extended periods of navigation the MRS requirements to the ULA strengthening are inadequate.

Proceeding from the Polar Code subdivision of ships into ice classes and the existing MRS classification the present requirements to ice classes of future arctic ships have been developed.

Table 10.1

Project of the subdivision of polar ships into classes

Class	Ships designed for the operation under ice conditions up to and easier than:
PC1	Year round operation without limitation in all polar areas of the world ocean
PC2	Year round operation in moderate multi-year ice conditions
PC3	Year round operation mainly in the second-year ice
PC4	Year round operation mainly in the first-year thick ice
PC5	Year round operation in the first-year medium ice
PC6	Summer/autumn operation in the open floating residual ice with a conventional design thickness of the first-year medium ice
PC7	Summer operation in the open floating ice and ice cake with a conventional design thickness of first-year thin ice

10.1. Ice class, ice strength of structures, material of hull

Recommended ice classes

As the experience of many years of work of the domestic transport fleet has shown, level of the ice damageability of ships is decisively influenced by the compliance of the ice class (category of ice strengthening) with the area and season of the operation of ship in the Arctic. The right choice of the ice class (corresponding Rules imposed on ships of the class in question being met) considerably reduces the probability of heavy ice damages.

Analysis of the experience gained by the present time allows to formulate the following recommendations on the use of ships of different ice classes in the Russian Arctic:

- Western region of the NSR (Kara Sea)
    - Summer - independently: PC6 (UL), PC5 (ULA);
    - Autumn - independently: PC5 (ULA);
      - under the icebreaker assistance: PC6 (UL);
    - Winter-spring - under the icebreaker assistance: PC5 (ULA).

- Eastern region of the NSR (Chuckchee, East Siberian and Laptev Seas)
    - Summer - under the icebreaker assistance: PC6 (UL);
    - Summer-autumn - under the icebreaker assistance: PC5 (ULA);
    - Winter-spring - under the support of powerful nuclear icebreakers: PC4 (ULA-Super).

Hull ice strengthenings

As it was often noted [1, 2, 3], the peculiar feature of ice damages of the hull framing of arctic ships are local bucklings (bulges) of the framing web areas adjoining the shell plating. Such strains form the major portion of ice damages of the hull framing of arctic ships.

In order to reduce sizes and number of such ice damages, Russian and Finnish specialists [34] have elaborated recommendations directed towards the improvement of the reliability of structure elements being under the effect of concentrated ice loads. In so doing the following constructional measures should be envisaged:

- for the purpose of ensuring the stability of diaphragm and platform areas adjacent to the shell plating as well as of framing webs under the action in their plane of concentrated ice loads, additional stiffening ribs should be fitted in such a way that the ratio between thicknesses of strengthened plates and inter- rib distance would be not less than 0.025 thicknesses of the indicated plate structures having to be not less than 14-16 mm;
- it is advisable to fix longitudinal stiffeners running through bilge brackets (Figure 10.1) over the bilge of PC5 (ULA) ships the distance between stiffeners not exceeding that between frames; other means of bilge strengthening may be also applied - for instance, extension of intermediate frames onto the bilge and the adjoining bottom areas.

At present there is no doubt about the necessity to provide double bottom on arctic cargo ships this fact being reflected in the running Rules of Navigation along the NSR [4]. The use of double sides for ships navigating in the Arctic is still being discussed. The MRS Rules now in force contain recommendations as to the use of double sides on the ULA class ships [35], but the installation of double sides on ships of other classes is not specified.

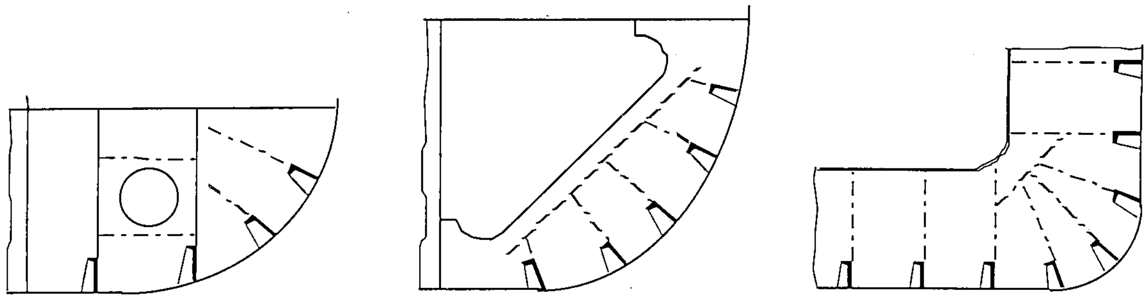

Fig.10.1. Strengthenings of framing webs and diaphragms

In accordance with the MARPOL requirements [36], on large tank ships with a deadweight of over 30 000 tonnes the installation of double sides is compulsory. Bearing in mind the environmental hazard of the probable spill of toxic substances overboard in the case of heavy ice damages this being especially dangerous in view of large dimensions of prospective cargo arctic ships, double sides have to be installed on all cargo arctic ships within cargo spaces and engine rooms. It is also necessary to introduce restrictions on the use of double bottom compartments for the storage of fuel. To improve the environmental safety the following constructional and organizational measures should be taken:

- strengthening of bottom and bilge strakes (of plating and framing) in way of bottom fuel cisterns and cargo tanks;
- complete elimination of the transportation of petroleum products in double bottom and double side compartments located towards the bow from the midship;
- double sides on tankers should be arranged in such a way as to overlap the bilge, better up to the beginning of the flat bottom.

One should note the positive role of double sides in the case of ice compression. This compression results in ice damages of side structures of the ship's midbody encompassing (as it was stated above in section 1.1) considerable sections of ice strengthened areas even on modern ULA class ships (of *Norilsk* type). Compression in heavy ice of the Eastern region of the NSR often causes heavy ice damages of the structures of ships without double sides and sometimes is even the reason of their loss (ships of the *Pioner* type). At the same time there were no emergency events in ice compression of the damage of side grillages of ships with double sides. The presence of double sides in the middle part of hull substantially increases the compressive strength of the ship's hull and reduces rates of the permanent strain through the involvement in work of the grillage of the second side structures.

For the reinforcement of sides at ice compression in the area of the arctic waterline in double sides it is recommended to fit horizontal permeable platforms. Besides, double sides prevent holds from flooding when cracks and holes in the shell plating are produced this being especially important for superships with large cargo holds.

Taking account of the wear of the shell plating

Peculiarity of the wear of the shell plating of ships navigating along the NSR is the great abrasive component associated with the shallow water of the route and consequently with the presence of a quantity of abrasive materials (sand). This circumstance is reflected in values of ships' plating wear allowances regulated by the Rules of the MRS.

In the process of the development of text of the Unified International Rules of Polar Ships by the American Bureaü of Shipping (ABS) it was suggested to assign allowances taking into account in a simplified form the availability of the surface coating – $\mathbf{C}\,\Delta\mathbf{t}$. If a protective coating is applied onto the plating, $\mathbf{C} = 1$; if there is no coating, $\mathbf{C} = 2$.

Value Δt is determined depending on the ship's class and the hull area. For ships of the highest ULA category and linear icebreakers the Russian Register Rules specify the allowances which are 1.5 - 2 times as large as those for corresponding classes of the ABS. At the same time, it should be noted that the way of assigning wear rates set forth in chapters 3.10 and 3.11 of the MRS 1995 Rules is not free of disadvantages. Recommendations on the wear rates for cargo ships (L1 - ULA) poorly comply with the recommendations for icebreakers (classes LL4 - LL1). The influence of steel grades on the corrosion resistance of structure is not taken into account.

Analysis of data on the wear of hulls of ice ships shows that the intensity of the wear of plating substantially depends on the type of ship (cargo ship, icebreaker) and the character of its operation in ice (all the year round independently, all the year round under the icebreaker support or sailing only during summer navigation). So, if for MRS L1, UL ships and port tugs the wear of the bow shell plating is 0.2 - 0.3 mm/year, for linear icebreakers it may reach 0.4 - 0.5 mm/year and more.

The generalization of the operational experience made by CNIIMF permits to take additionally (as to the ABS proposals) into account the following factors:

- purpose of ship (icebreaker or cargo ship);
- influence of the steel grade on the wear rate;
- shallow water effect for ships with a restricted draft.

As to the protective hull coatings it should be stressed that these should be ice resistant coatings of the *Inerta-160* type. At the same time, as the experience shows, even such coating on cargo ships should be reapplied at least once in 2 - 3 years and on powerful icebreakers –

annually. In the assessment of the intensity of the corrosion wear of plating one should take into consideration the presence or lack of the electrochemical protection of the ship's hull.

While designing superships, it is necessary to pay special attention to the hull bilge area and adjacent bottom sections as due to the increase of draft and the shallow water of the NSR one can anticipate larger abrasive plating wear of such ships in the indicated areas.

It is recommended to take allowances for the shell plating wear of future large arctic ships not less than values given in Table 10.2.

Table 10.2

Abrasion and corrosion wear allowances of the shell plating Δt depending on the area, mm

Hull area	PC1, PC2 and PC3	PC4 and PC5	PC6 and PC7
Bow and intermediate areas of the ice belt	4.0	3.0	2.0
Side areas below the ice belt	3.0	2.0	1.5
Bottom and other hull areas	2.0	1.5	1.0

In addition to the taking into account of the abrasive wear of bottom and bilge strakes of the plating due to the shallow water one should bear in mind that the ground touching by the plating directly or through the "cushion" of ice debris entrapped under the hull during the movement over the shallow water results in the considerable increase of loads on these sections, especially in the forebody and midship hull areas.

As the statistics shows, just in the areas indicated the bulk of ice damages of arctic ships is concentrated. In the works of CNIIMF performed earlier the advisability of regulation by specification documents of the design ice loads upon bottom hull sections and the bilge has been substantiated. Frequency and high cost of repairs of hull after heavy structural ice damages in these areas lead to the necessity of assigning here design ice loads. Since 1990 the MRS Rules specify ice loads of these areas in fractions of design loads on the applicable area of the ice belt. So, in the forebody of the ULA class ships they are 65 % of loads on the ice belt for bilge, 50 % – for bottom; as to the LL3 class icebreakers these values are 60 % for bilge and 50 % for bottom accordingly.

Considering the above stated and the probability of the episodic operation of superships as icebreakers it is advisable to bring design ice loads upon the bottom and bilge of these ships to the level of requirements (as a percentage ratio) for the LL3 (PC4 - PC5) class icebreakers, that is to at least 50 - 60 % of the design loads upon the ice belt.

Selection of the steel grade

Experience of the operation of the Russian fleet in the Arctic shows that cases of the occurrence of cracks in structures under the effect of negative temperatures are very rare. Nevertheless, there were reports of such cases and materials with their description were analyzed by CNIIMF. So, for the period from 1973 to 1979 the MSCO noted 7 events of the emergency structural damages caused by the effect of low temperatures: 1973 – 1 event, 1976 – 4 events , 1979 – 2 events. Damages observed within this period occurred mainly in January and December when ships were in the Yenisei Gulf and Yenisei River. Cracks emerged at low negative temperatures (–35...–40°C in areas of the concentration of stresses and higher vibration.

The analysis has shown that such damages occur, as a rule, as a result of the combined influence of a number of factors sharply enhanced at low temperatures (higher vibration, fatigue stresses etc.).

Therefore recommendations on the selection of the steel grade of hull structures of ice ships should deal not only with the class and loading of structures, but also with the calculated values of negative temperatures for the ship being designed. In this respect the methodical approach to the selection of steel for hull structures stated in section 1.2.3. of the running Rules of the Russian MRS adequately takes account of factors affecting the reliability of work of hull structures in the Arctic.

However taking into consideration relative complexity of the methodology adopted by the Russian MRS for the selection of the steel grade with due regard for its cold-resistance, one may use a simplified procedure of the selection of steel developed by the international working group within the framework of the preparation of IACS requirements to polar ships. This procedure is based on the proposals of ABS submitted in 1996-1998. Under this technique, values of the outdoor negative temperature in areas of the operation of ship being designed are not explicitly taken into account. However in an indirect way this is reflected in polar classes of ships of the international ice classification and accordingly in the recommended classes of steel. Therefore such approach may be considered as justified.

The application of cold-resistant steels for the plating and framing is regulated for hull structures located above the level of the "lowest waterline".

Bearing in mind proposals considered at meetings on the Harmonization of Polar Rules as well as the Russian experience on the ordering and construction of icebreakers and icebreaking cargo ships for the Arctic it is recommended to use cold-resistant steels only of the highest categories D and E for ice strengthenings of ships embraced by the group of polar classes PC1-PC5 because these ships are intended for the year round operation in polar waters. For ships of polar classes PC6 and PC7 intended for the summer-autumn navigation in ice it is admissible to use steels of lower categories B and A.

The used steel grades should have the cold-resistance not worse than steels presented in Table 10.3 based on proposals of participants of the International Working Group on the

Harmonization of the Polar Rules. Classes of structures exposed to sea and weather conditions are determined depending on the location of structure (Table 10.4).

Table 10.3

Steel grades for the structures of ships of different classes

Thickness **t**, mm	Classes of structures								
	I			II			III		
	PC6, PC7	PC4, PC5	PC1, PC2, PC3	PC6, PC7	PC4, PC5	PC1, PC2, PC3	PC6, PC7	PC4, PC5	PC1, PC2, PC3
$t \le 10$	A	B	B	B	B	B	B	D	E
$10 < t \le 15$	B	B	D	B	D	D	D	E	E
$15 < t \le 20$	B	D	D	B	D	D	D	E	E
$20 < t \le 25$	D	D	D	D	D	D	D	E	E
$25 < t \le 30$	D	D	D	D	E	E	E	E	E
$30 < t \le 35$	D	D	E	D	E	E	E	E	E
$35 < t \le 40$	D	E	E	D	E	E	E	E	F
$40 < t \le 45$	D	E	E	E	E	E	E	E	F
$45 < t \le 50$	E	E	E	E	E	E	E	F	F

Table 10.4

Classes of structural elements of polar ships

Structural elements	Classes of structures
Shell plating in the area of hull ice strengthenings. All framing members attached to the weather/sea-exposed plating including any contiguous inboard member within 600 mm of the shell plating.	I
Weather-exposed plating and attached framing in cargo holds of ships which by nature of their trade have their cargo hold hatches open in cold weather operations.	
Weather and sea exposed structural members outside 0.4 **L** amidships.	
Shell plating within the bow and bow intermediate ice belt; bilge strake.	II
Stem and stern frames, rudder horn, rudder, propeller nozzle, shaft brackets, ice skeg, ice knife and other appendages which can be under ice impact loads.	
All weather and sea exposed , structural members within 0.2 **L** from FP.	
Sheer strake, deck stringer of the strength deck, deck plates in corners of cargo hatchways, continuous longitudinal coamings in the middle portion of the ship.	III

10.2. Ice propulsion, hull shape and principal dimensions ratios

Icebreaking capability

Division of ships into polar classes adopted in the IMO Draft Polar Code as well as in the unified IACS requirements to ice ships being now developed gives only some idea on the admissible conditions of the operation of ships of a certain class. At the same time, experience of the development of requests for proposal while ordering icebreaking cargo ships and that of their design and operation show that along with the determination of conditions of the safe navigation, ice class should characterize ship's operational capabilities of each ice class. Just by an operational criterion enabling to estimate the efficiency of the use of ship and the economical indices of its work, a shipowner issues order on the construction of ship. Such criterion for the ships capable of actively navigating in ice is a maximum thickness of the level compact ice through which a ship can move at a continuous steady speed, that is icebreaking capability. This convinces of the necessity to apply to ships of each polar class of the common international ice classification the requirements to the icebreaking capability sufficient to ensure satisfactory ice propulsion and operational safety under specified conditions of the unrestricted navigation. Suggested values of the icebreaking capability are given in Table 10.5.

Table 10.5

Relation between polar classes and needed icebreaking capability in the ice classification of ships

Ice class	Icebreaking capability, m	Unrestricted independent navigation	Examples of Russian arctic ships	
			name	MRS category
PC1	3.0 - 3.7	year-round in all polar areas of the world ocean	Design of the *icebreaker-leader* with a power of 110 MW	LL1
PC2	2.3 - 3.0	year-round in moderate multi-year ice	nuclear icebreaker *Arktika*	LL1
PC3	1.7 - 2.3	year-round predominantly in second-year ice	icebreaker *Ermak*, nuclear icebreaker *Taimyr*	LL2 LL2
PC4	1.2 - 1.7	year-round predominantly in first-year thick ice	icebreaker *Moskva,* icebreaker *Kapitan Sorokin,* barge carrier *Sevmorputj*	LL3 LL3 ULA
PC5	0.7 - 1.2	year-round predominantly in first-year medium ice	icebreaker *Mudyug,* m/s *Norilsk,* electrically driven m/s *Vitus Bering,* m/s *Ivan Papanin*	LL4 ULA ULA ULA
PC6	0.5 - 0.7	summer/autumn operation in open floating ice	m/s *Dmitry Donskoy,* tanker *Samotlor,* tanker *Ventspils*	UL UL UL
PC7	0.3 - 0.5	summer operation in open floating ice cake	m/s *Pioner,* m/s *Volgoles,* m/s *Bryanskles*	L1 L1 L1

As one can see from the table, the Russian experience of the design, construction and operation of arctic ships is in fairly good agreement with the division of polar ships into classes proposed within the scope of the Polar Code of IMO.

It should be noted at the same time that the international ice classification in question and data on the icebreaking capability of ships depending on the polar class suggested for the insertion into this classification are of a rather generalized character. While considering specific types of icebreaking cargo ships and icebreakers intended for the navigation on certain seaways of the NSR in a given calendar mode (seasonally, all the year round) and also in dependence on the type of sailing (independently, under the icebreaker assistance) for the determination of the required, as to the maintenance of the safe operation in the Arctic, icebreaking capability of icebreaking cargo ships one should use graphical functions of duration of the independent sailing of ships in the Arctic and their icebreaking capability (Figure 7.3) shown in section 7 of the present report.

For the estimation of the required icebreaking capability of icebreakers depending on duration of the navigational period and area of operation in the Arctic the values of the icebreaking capability of independently navigating cargo ships obtained in Figure 7.3, in accordance with the justification presented in section 7 should be reduced approximately by 10 %.

Hull shape and dimension ratios

Icebreaking cargo ships. On the basis of experimental investigations of ice propulsion and seaworthiness of ice ships as well as on the experience of their design, construction and operation, requirements were prepared to the rational shape of hull lines of the perspective arctic cargo ships with an icebreaking forebody of traditional type. Proposed values of entrance angles φ and α_0 and also of flare angles at the first from the forward perpendicular frame line β_1 and at the middle frame β_{10} are presented in Table 10.6.

Table 10.6

Proposed requirements to the hull shape characteristics of arctic cargo ships depending on the ice class

Ship's ice class		Angles, degrees			
IMO	MRS	φ	α_0	β_1	β_{10}
PC4 , PC5	ULA	25	35	45 - 50	0 - 8
PC6	UL	30	30	35 - 45	0
PC7	L1	40	25	20 - 30	0

Combination of angles φ, α_0 and β_0 (flare angle at station section 0) should provide for the rounded (moderately convex) shape of fore frames, straight line stem and buttocks.

As the experimental investigations have shown, these recommendations on the hull bow lines shape of perspective icebreaking cargo ships will allow either to improve their icebreaking capability by 5 - 10 % in comparison with the existing ones built for the Arctic, propulsion plant power being the same, or to provide for the saving of power up to 20 - 25 % at a set icebreaking capability.

For cargo ships of PC4 - PC5 (ULA) and lower classes it is admissible to use vertical sides amidships so permitting to increase the block coefficient and accordingly the cargo-carrying capacity practically without noticeable deterioration of the ice propulsion.

In compliance with the propulsion tests made in the hydrodynamic tank in still water and in the head regular seas of models of the icebreaking cargo ships with the recommended hull shape parameters there are no grounds to expect substantial worsening of their seaworthiness. It is obvious at the same time that the hull shape recommendations stated will require further more accurate definition by the full-scale experimental verification of their applicability in dependence on purpose and specific operational conditions of new ships being constructed.

Any special restrictions of the principal dimensions ratios of ice cargo ships from the point of view of the ice propulsion are hardly appropriate because for commercial ships the economical expediency prevails.

As to the experience of the construction and operation of icebreaking cargo ships the **L/B** ratio (length to width along the design waterline) is to be within the economically justified values, that is about 6.5 - 7.0. The implementation in the future on icebreaking ships of turning propeller systems of the *Aquamaster* and *Azipod* types will considerably improve the maneuverability of these ships in ice and accordingly the problem of choosing the **L/B** ratio will become less vital.

Practically neither the **B/T** ratio (width to draft along the design waterline) is limited by the ice propulsion requirements because, as it was shown earlier, with the increase of this ratio the negative effect of width is compensated by the positive effect of the decreasing relative draft on the choice of the rational shape of the hull entrance of the icebreaking ship. In actual practice, **B/T** is determined for each individual case proceeding from the existing draft restrictions as well as taking into account the width of icebreakers used for escorting ships.

Icebreakers. The investigations carried out permit also to formulate requirements to the hull shape of arctic icebreakers of ice classes PC1-PC4.

The improved traditional shape of the forebody lines ought to be considered as most promising for arctic multi-purpose icebreakers, parameters of the forebody meeting the following requirements:

- stem angle at design waterline $\varphi = 20°$,
- design water line entrance angle $\alpha_0 = 45°$,
- side flare angle at frame line No.0 $\beta_0 = 65°$,
- side flare angle at frame line No.2 $\beta_2 = 48 - 50°$,
- side flare angle at middle frame line $\beta_{10} \geq 10°$.

Combination of angles φ, α_0, β_0 and β_2 should provide for moderately convex form of forebody frames, rectilinear stem and buttocks. The use of the bow "ice knife" forming an integral part of the hull structure should be done away with. Instead, a step in the form of a sole in the lower part of the stem should be fitted. The height of this step should not exceed 0.3 **T**

Ratio **L/B** for icebreakers should mainly be chosen such as to provide for the satisfactory maneuverability in ice. Proceeding from this, for arctic linear icebreakers, as the experience of their operation shows, the length/width ratio should not exceed 5.1.

The above recommendations on the hull shape of prospective icebreakers for the NSR permits increasing their icebreaking capability in relation to existing icebreakers with traditional hull lines (*Moskva*, *Ermak*, *Arktika*) by at least 15 - 20 %. At a set icebreaking capability this implies the energy saving up to 50 %.

It should be also noted that the use of the recommended lines with the increased flare of bow frames will favourably affect values of ice loads on hull resulting in their appreciable reduction and accordingly in the decrease of the ice damageability of prospective icebreakers (section 2 of the present report).

Comparative propulsion tests of different icebreaker hull shape versions in still water and in the head regular seas carried out in the hydrodynamic tank have shown that icebreakers with recommended characteristics of the forebody shape do not rank below existing icebreakers with the traditional hull shape in the propulsion in open water. Improved traditional forebody lines provide for the appreciably better seaworthiness if compared with nontraditional lines put forward by foreign shipbuilders.

In the construction of future arctic superships to be escorted by icebreakers it is important to choose a rational ship / icebreaker ratio and to determine maximum power (icebreaking capability) of the cargo ship. However the solution of these problems is possible only on the basis of the economical analysis applied to specific types of cargo ships and icebreakers as well as to lines of their operation. Assessment of the economic efficiency and optimization of parameters of ships to be designed are the subject of separate independent investigation.

10.3. Technical means to improve the icebreaking capability

Study of the ice propulsion of arctic cargo ships and icebreakers in winter conditions in the presence of considerable snow cover, hummocking and ice compacting permits formulating requirements to special means of the improvement of the icebreaking capability under these conditions and also of its retaining at the specification level during the entire ship's service period.

In essence these requirements are mainly the following:

- On icebreaking cargo ships of class PC5 (ULA) and higher designed for all the year round use in the Arctic it necessary to use ice-resistant lacquer coatings (of *Inerta - 160* type) for the underwater part of hull with its regular restoration each 2 - 3 years. On ships with a draft of more than 5 - 6 m, along with the application of lacquer coatings it is recommended to install a hull air-bubbling system;
- For ships of the seasonal navigation in the Arctic with ice class PC6 (UL) under condition of their additional use on freezing seas in winter it is also expedient to apply ice-resistant coatings with a low ice friction coefficient;
- For powerful icebreakers of classes PC1-PC3 (LL1, LL2) intended to lead convoys as well as to operate within complex convoys along traditional and high-latitude seaways of the NSR throughout the year including arctic icebreakers with a restricted draft working in winter in mouth districts of Siberian rivers, the hull plating in way of the ice belt should be produced out of the double-layer steel with an outer corrosion-resistant clad layer. In so doing one should provide for the adequate electrochemical protection. Ice-resistant lacquer coating should be applied onto the remaining underwater portion of hull. Besides, icebreaker should be equipped with an efficient washing device;
- On auxiliary icebreakers of class PC4 (LL3), proceeding from the economical expediency, all the underwater part of the shell plating should be covered with ice-resistant lacquer coatings to be restored on a regular basis and at least once in 2 years. In parallel with the above, icebreakers of this group should be equipped with a washing device.

Utility and necessity of the use on icebreakers of thrusters and bow propellers should be assessed for each particular design.

CONCLUSION

Generalization and analysis of the experience of design, construction and operation of domestic icebreakers and icebreaking arctic cargo ships have permitted to bring to light specific features of the navigation along the NSR and to formulate principal technical and operational requirements which are to be imposed to these ships for their safe, reliable and efficient work in the Arctic. This concerns first of all requirements for the ice performance of ships (ice strength and ice propulsion). Therefore this work attracts attention to the study of problems associated with the ice damageability of ships' hulls, selection of rational structural solutions and principal parameters (dimensions, hull's shape, power) upon which the ability of ships to efficiently operate in ice (icebreaking capability, maneuverability etc.) mostly depends.

In view of the fact that the present work deals with the outlooks for the NSR of large, that is not traditional for the Arctic, icebreaking ships, while drawing up requirements to the ice performance, special features of their operation in the shallow arctic shelf area, all the year round, independently and under the assistance of icebreakers were considered. This primarily was reflected in the prepared requirements to the design of future new types of ships.

At the same time, it should be noted that as the recommendations contained in the report are to some extent of a generalized character, at a later time while ordering new non-traditional ships for the Arctic, additional corrections may be needed taking into account the particular purpose and conditions of the operation of ship.

REFERENCES

1. S.B. Karavanov. Analysis of the damageability of hulls of arctic cargo ships in book Prospective types of ships, seaworthiness and ice performance, Leningrad, “Transport”, 1985, p.72.
2. Karavanov S.B., Tsoy L.G. Advisability to introduce an additional category of ice strengthenings for cargo ships operating in the eastern area of the Arctic. Book: Architectural and structural type, seaworthiness and ice performance of ships. Leningrad, “Transport”, 1989, pp. 100-106.
3. S.Karavanov, Yu.Glebko. Collection and analisis of statistical data on hull ice damages of transport ship on NSR, Planning and Risk Assessment, INSROP Working Paper, No.23-1995, 1.5.5, Wol.1, p.92.
4. ANSR. Guide to navigating through the Nortern Sea Route, 3. Hull of vessel, St.Petersburg, 1996, p.319.
5. V.A. Kurdyumov, D.E. Kheisin. Hydrodynamic model of the impact of a solid against ice. Applied technology, V. 12, issue 10, Kiev, 1976, p.103.
6. V.A. Kurdyumov, V.N. Tryaskin, D.E. Kheisin. Determination of the ice load and assessment of the ice strength of hulls of cargo ships. In the Proceedings of Leningrad Shipbuilding Institute - Icebreaking capability and ice strength of sea-going ships. Leningrad, 1979. p.103.
7. L.G.Tsoy, S.B.Karavanov, Yu.V.Glebko. Assessment of ship performance and required powering based on ice conditions, Harmonization of Polar Ships Rules, IACS UR, St.Petersburg, 1997.
8. L.G. Tsoy, S.B. Karavanov, O.V. Fadeev. Estimation of the effect of the side slope in the middle portion of icebreaking cargo ships on their ice performance. In book Collected reports of the Soviet-Finnish seminar on the ice strength of ships, Leningrad, Sudostroenie, 1988, p.70.
9. L.G.Tsoy. Assessment of ships' icebreaking capability at early stages of design. *Abstracts of papers. Conference on Shipbuilding, Shipping and Offshore Technology NEVA’95.* St.Petersburg, 1995, pp. 53-54.
10. Juurmaa K., Wilkman G., Shlachkov V. The evaluation of different icebreaker concepts using the mission-based approach. International Conference, Tromso, Norway, March 30 - April 1, 1992.
11. Ierusalimsky A., Tsoy L. The Efficiency of Using Non-Traditional Hull Lines for Icebreakers. ICETECH'94. Fifth International Conference on Ships and Marine Structures in Cold Regions. Calgary, March 1994, P. S1-S10.
12. L.G. Tsoy, V.I. Kashtelian. Serial Tests of the Ice Propulsion of Models of Ice Ships with Different Hull Shapes. Collected Volume of Transactions of CNIIMF. Architectural and Structural Type, Seaworthiness and Ice Performance of Ships. Leningrad,"Transport", 1989, pp.14-19.
13. L.G.Tsoy. Investigations of the Effect of the Principal Dimensions Ratios and Hull Form on the Ship's Passability in Ice. The 10th International Conference on Port and Ocean

Engineering under Arctic Conditions (POAC89). Proceedings, Vol.3, Lulea, Sweden. 1989. pp. 1486-1492.

14.L.G. Tsoy, A.A. Bogdanov, A.A. Petrov. Influence of the Lines Shape of Ice Ships upon the Propulsion in Still Water and in the Seaways. Collected Volume of Transactions of CNIIMF. New Types of Ships and their Seaworthiness. Leningrad, "Transport". 1987. pp. 14 - 19.

15.V.I. Kashtelian, O.V. Faddeev, L.G. Tsoy. Selection of Principal Parameters of Icebreaking Cargo Ships. Sudostroenie. N 12. pp. 4 - 6.

16.Belyashov V.A, Boitsov V.P, Prishchemikhin Yu.N (1978). "Cavitation of icebreaker propellers in the mode of forcing the ice". *Scientific and technical book Problems of shipbuilding*, issue 19, pp. 64-69.

17.Belyashov V.A , Shpakov V.S (1983). "Choice of the minimum icebreaker propeller diameter". Scientific and technical book Problems of shipbuilding, issue 37, pp.94-98.

18. Alekseev Y.N., Beljashov V.A., Sazonov K.E. Hydrodynamic Problems of Propellers for Icebreaking Ships. POAC 93. Proceedings of the 12-th International Conference on Port and Ocean Engineering under Arctic Conditions, Vol.1, pp. 351-358.

19.Kashtelyan V.I , Poznyak I.I , Ryvlin A.Ya (1968). "Ice resistance to the movement of ship". Sudostroenie, 238 pp.

20. Tsoy L.G. Investigations of the Effect of the Principal Dimensions Ratios and Hull Form on the Ship's Passability in Ice. POAC 89. Proceedings of the 10-th International Conference on Port and Ocean Engineering under Arctic Conditions, Vol.3, pp.1486-1492.

21.Svistunov B.N (1978). "Effect of the restricted depth on the ice propulsion of icebreakers". *Proc Gorky State University* Theory and strength of the icebreaking ship, pp.13-15.

22.Svistunov B.N. Ice propulsion of icebrea-kers in ice with snow cover and in shallow water. *Proc AARI* Performance of ships, Vol 376, 1981, pp. 41-47.

23.A.V.Ierusalimsky, B.N.Svistunov. Effect of the Roughness of the Steel Surface on the Coefficient of Dynamic Friction in Ice. Collected Volume of the Transactions of CNIIMF. Architectural and Structural Type, Seaworthiness and Ice Performance of Prospective Ships. Leningrad, "Transport", 1984, pp. 90-96.

24. A.V.Ierusalimsky, L.G.Tsoy. Investigation of the Effect of the Hull Plating Roughness on the Passability of Ships in Ice. IAHR Symposium. Hamburg, Germany.1984. pp.343-352.

25. L.G.Tsoy. The Effect of the State of Shell Plating on the Icebreaking Capability of Ships. POLARTECH96. International Conference of Development and Commercial Utilization of Technologies in Polar Regions Proceedings. Vol.B. St.Petersburg, Russia. 1996. pp.99-203.

26.V.I. Kashtelian, Yu.N. Popov, L.G. Tsoy. On the Efficiency of the Air-Bubbling System and Areas of its Application on Ships Navigating through Ice. Proceedings of AARI, Vol. 376 . Ice Performance of Ships. Leningrad, "Hydrometeoizdat", 1981. pp. 67-84.

27.T.Heideman. Influence of Ice Compression on Feasible Navigation on the NSR. INSROP Working Paper No 39-1996, I.1.8. FNI, Lysaker, Norway, 1996.

28.Exploration of the shelf of arctic seas of Russia. Theses of reports. The Second International Conference RAO-95. St. Petersburg Technical University. SPb. 1995, pp.373.

29.General and special rules of the transportation of liquid cargoes 7-M. Moskow, V/O "Mortehinformreklama", 1985. 456 pp.

30.L.G. Tsoy. Methods of the determination of rational parameters of icebreaking cargo superships. Collected volume of the transactions of CNIIMF. Prospective types of sea cargo ships. Leningrad, "Transport", 1986, pp. 106-109.

31. L.G.Tsoy. Methodology of the Determination of the Parameters of Large Ships Designed for the Independent Navigation in Ice-Covered Waters and of those Supported by Icebreakers/ Proceedings of the Second International Offshore and Polar Engineering Conference. Vol.II. San Francisco, USA, 1992. pp. 777-779.

32. L.G.Tsoy, I.A.Stoyanov, V.V.Mikhailichenko, S.G.Livshits. Perspective Types of Arctic Icebreakers and their Principal Characteristics. POAC'95. Proceedings of International Conference on Port and Ocean Engineering under Arctic Conditions. Vol.I. Murmansk. Russia. 1995. p.13-26.

33. L.G.Tsoy. Feasibility Study of a Nuclear Icebreaker of *Arctica* Class of New Generation. ICETECH'94. Fifth International Conference on Ships and Marine Structures in Cold Regions. Calgary. Canada. 1994. P1-P8.

34.Miroshnichenko I.P., Tsoy L.G., Karavanov S.B., Haapanen M., Korri P. Joint recommendations of A/O "Rauma-Repola" and CNIIMF on ice loads on hulls of ice tankers. Book: Collected reports of the Soviet-Finnish seminar on the ice strength of ships. Leningrad, Sudostroyeniye, 1988, pp. 77-80.

35.Marine Register of Shipping. Rules of the classification and building of sea ships. St. Petersburg, 1995.

36. IMO, Marpol 73/78 convention, Regulation 13F. 1994.

ANNEX

Table A.1

List of ships of the SA-15 type

	Name	Year of construction	Shipowner
1	*Norilsk*	1982	MSCO
2	*Nizhneyansk*	1983	FESCO
3	*Igarka*	1983	FESCO
4	*Tiksi*	1983	MSCO
5	*Okha*	1983	SakhSCO[1]
6	*Monchegorsk*	1983	MSCO
7	*Arkhangelsk*	1983	MSCO
8	*Bratsk*	1983	FESCO
9	*Kola*	1983	MSCO
10	*Amderma*	1983	FESCO
11	*Kemerovo*	1983	SakhSCO
12	*Kandalaksha*	1984	MSCO
13	*Nikel*	1984	MSCO
14	*Anadyr*	1984	FESCO
15	*Anatoly Kolesnichenko*	1985	FESCO
16	*Kapitan Man*	1985	FESCO
17	*Yury Arshenevsky*	1986	MSCO
18	*Vasily Burkhanov*	1986	FESCO
19	*Kapitan Danilkin*	1987	MSCO

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[1] Sakhalin Shipping Company

Table A.2

Principal characteristics of icebreakers

Characteristics	*Arktika*	*Taimyr*	*Ermak*	*Moskva*	*Kapitan Sorokin*			*Mudyug*	
					1	2	3	4	5
Length, m									
overall	148.0	150.0	135.0	122.1	129.4	141.4	135.5	88.6	111.4
on design waterline	136.0	140.6	130.0	112.4	121.3	130.2	125.8	78.5	89.8
Breadth, m									
overall	30.0	29.2	26.0	24.5	26.5	30.5	26.5	21.2	22.2
on design waterline	28.0	28.0	25.6	23.5	25.6			20.0	
Draft, m									
maximum	11.0	9.0	11.0	10.5	8.5			6.5	
design	11.0	8.1	11.0	9.5	8.5			6.0	
Depth, m	17.2	15.2	16.7	14.0	12.3			10.5	
Displacement, t	23460	19600	20240	13290	14900	17270	16020	5560	6880
Open water speed, kn	20.8	20.2	19.5	18.3	19.0	18.0	18.7	16.5	16.1
Icebreaking capability, m	2.25	1.95	1.80	1.45	1.35	1.90	1.80	0.95	1.50
Type of propulsion plant	Nuclear	Nuclear	Diesel-electric	Diesel-electric	Diesel-electric			Diesel reduction	
Total shaft power, kW	49000	32500	26500	16200	16200			7000	
Total bollard pull, kN	4700	2900	3140	2200	1770			900	
Power distribution by shafts	1 : 1 : 1	1 : 1 : 1	1 : 1 : 1	1 : 2 : 1	1 : 1 : 1			1 : 1	
Type of propeller	FPP	FPP	FPP	FPP	FPP			CPP	
Number of propellers	3	3	3	3	3			2	

Note:

1. Icebreaker *Kapitan Sorokin* with original forebody.
2. Icebreaker *Kapitan Sorokin* after the refitting of forebody by the West-German company *Thyssen Nordseewerke* in 1991.
3. Icebreaker *Kapitan Nikolaev* after the refitting of forebody by Finnish company *Masa-Yards* in 1990.
4. Icebreaker *Mudyug* with original forebody.
5. Icebreaker *Mudyug* after the refitting of forebody by the Weat-German company *Thyssen Nordseewerke* in 1986.

Evaluation of INSROP paper, by Dr. Loly Tsoy, et. al. Design Requirements for Future NSR Ships

By
Dr. Arno Keinonen

The paper is an excellent review and summary of Russian icebreaker and icebreaking cargo ship design, structural safety and operational experience. The Russian experience in this area is known to be the longest and by far the most extensive in any Arctic region or route. Furthermore this is all specifically relevant, and directly addresses the Northern Sea Route.

The paper is highly informative, documenting in a compact fashion, the vast experience and most important issues and aspects related to it. The influencing factors related to the structural safety of hulls of vessel, the general operability on the Northern Sea Route and specific sections of it, as well as the key design parameter influences on various aspects of ship performance are dealt with in the report.

The authors have chosen to take an approach, which directly implies direct application of the information in this summary paper into the transportation projects for Arctic offshore developments of energy, and their transportation out of, or through the Russian Arctic, the Northern Sea Route.

The report gives a considerable number of indications of how the traditional technology, on which the paper is based, works and how it can be extrapolated into bigger and better icebreakers for support of arctic transportation, as well as associated commercial vessel design and design parameter selection. It also gives some indications as to the applicability of new technology. The area of the report dealing with the new technology is considered by current reviewer to contain the most promise for future development of Arctic shipping, on the Northern Sea Route, as well as in other Arctic waters. Regrettably that is given only a minor role in the report.

The authors give a concise summary of the results of experimentation that has been performed, applying new icebreaking technologies, namely the Thyssen and the Kvaerner variations of bow designs, built into full scale arctic icebreakers. The authors have adopted hands on experience as their means of evaluating what any old or new technology can do for their future arctic shipping developments. This is worthy of high recognition, and not seen elsewhere in the World in the Arctic development.

The authors also make the point that this paper is not an answer to any Arctic marine transportation project, through the Northern Sea route. The direct involvement of high level experts can not be replaced by such general guidance as presented in current summary paper. The reviewer full heartedly agrees with this assessment.

The key areas, where the paper could be further improved on its communicative aspect, and communicate its message in an even clearer fashion, are:

1. A clear statement is required, in respect to the adequacy of the new Arctic internationally harmonized regulations in respect to dimensioning vessels for safe navigation in various regions of Northern Sea Route.
2. In section 3.1 for formulas, give all parameters and their values, in order for reader to be able to apply formulas presented.
3. It should be pointed out that the trends shown in Figures 3.2, 4.3, 4.4, 4.6, 4.7, are specific examples, not universally applicable general trends for all ship designs.
4. A comment on influence of squat of vessels in shallow water, pulling stern down at higher speeds, would enhance the shallow water operability evaluation.
5. A key comparison between a new and older vessel in their performance, between 1975 and 1983, needs to also report any similarity or difference between the ice strength, snow cover and surface temperature. This would make it possible to separate the influence of hull roughness from other potential influences, which may be hidden in Figures 6.1, 6.2.
6. It appears that the authors may have used 8 – 10 knots average speed in even the most difficult ice season as criteria for ship icebreaking capability determination. This needs clarification, as this assumption alone, if indeed used, could singularly push size, power and price of arctic marine projects out of economic reality.
7. The need for higher icebreaking capability required from a commercial vessel is not in agreement with North American experience. Further question here is; whether it has been taken into account in this assessment that Azimuth thrusters offer full thrust in backing direction will reduce ahead icebreaking performance requirements? Normal propulsion offers only most 2/3rds astern thrust in comparison to ahead thrust. Further, azimuth propulsion will help flush and clear ice away from the hull, and thus further improve maneuverability and reduce risk of getting stuck.
8. In Figure 7.3, the indication of safety based season, and indication of independent operability should be treated separately, as their criteria is clearly different. Suggestion is to indicate ice class based operational season. The performance based season should be left to specific projects to assess and evaluate.
9. Table 8.2, icebreaking capabilities appear to be in a no logical order? The smallest vessel, version 1, should have highest icebreaking capability? Similar conflicting icebreaking capability numbers appear also in other tables.

The major concern that current reviewer has with the main message, that is communicated through current paper, is that this summary paper leaves an impression that Arctic shipping becomes prohibitively expensive and requires practically Arctic superships, to efficiently and safely perform Marine transportation on the Northern Sea Route. The indication given in the report, of a need to build large new super icebreakers, and/or very expensive commercial vessels, appears to be due to the direct extrapolation from the Russian Arctic ship design and operational experience. The reviewer suggests that a more realistic statement would be that commercially viable approach must be taken for each project individually. Any successful approach to shipping in the Russian Arctic Waters must use Russian experience, including every aspect of the new experimentation with new icebreaker concepts and bow shapes. Current reviewer also suggests that, for an economically viable Arctic marine transportation project, needs to also take into account the latest icebreaker and arctic shipping related international development, outside of Russia.

The key characteristic of an Arctic Marine transportation project is that it needs to be both technically and economically successful. Project specific requirements will determine the optimum combination of commercial vessel parameters, and their ice capabilities, as well as justifiable icebreakers in support of such project. Mission and project specific evaluations of merits of various vessel parameter combinations will substitute general comparisons of the qualities of ships, such as presented in Table 3.2. It may well be that the politically, technologically and economically feasible development starts from a stepwise development, which makes justification of projects on a shorter time economic outcome possible. At this time, in this World, any large scale super projects are dead, and interest in spending money at such minimal.

Discussion of INSROP Paper. "Design Requirements for Future NSR Ships", by L.G.Tsoy et al.

By
Dr. Robin P. Browne.

Dr. Keinonen has already commented upon many aspects of this paper. Since I agree very largely with his comments, I will not repeat them. However, it is indeed fitting to acknowledge the high level of design and operational experience and technical expertise which exists in Russia and is evident in this work.

My discussion will concentrate on the application of the extensive information given in this paper, and upon the current process of developing IACS Unified Requirements for icegoing vessels within the context of the Polar Code of IMO. I have worked within this process for the Government of Canada for approximately six years.

The IACS Unified Requirements for the Hull Construction and Machinery Protection of Icegoing vessels, of classes IPC 1-7, are being developed by Classifications Societies and all National Administrations with Polar waters. The requirements are nearing completion.

Two principles were adopted unanimously at an early stage.

1. The Unified Requirements are entirely related to the Safety of Life and of the Environment. Any item not clearly identified as such is omitted.

2. The Unified Requirements should state what the vessel is to be designed for, and not what the design should be.

A result of principle #1, is that the performance and powering aspects of icegoing vessels are <u>not</u> to be included in the Unified Requirements. Extensive discussion on this matter has taken place on a number of occasions. The international consensus has been that icegoing performance and powering are principally commercial factors, although individual administrations may choose to apply additional requirements, such as minimum powering, within their national waters, in order to cover particular operational aspects and practices.

The result of principle #2 is that the Unified Requirements are structure and machinery performance related. Design loads and conditions are prescribed, depending upon the ice class, vessel dimensions, hull shape etc., and the structural performance to be achieved under these loads are specified. All of the structural items discussed expertly and at length in the INSROP paper, have been investigated by the international working groups and are included in the Requirements. The Unified Requirements will not tell the owner or designer how to design his vessel, but will ensure that the design it safe.

It is my opinion, and I believe that of most of the participants in the IACS process, that the above principles reflect the importance of regulating only as far as is absolutely necessary, in order that economic development, which thrives upon freedom and innovation, should not be impeded.

In this respect, and bearing in mind the Canadian approach and experience regarding arctic transportation, I do not share in the author's conclusion that a new fleet of very large, powerful icebreakers is a pre-requisite to expanded marine activity on the Northern Sea Route. The future will be driven by economics, and other possible solutions may well be the answer.

Future Ice Class vessels will be built to at least the minimum standards laid down in the Unified Requirements. This INSROP paper, I believe, provides an overview of the expert information available to the owner and designer to help them in arriving at the optimum design for the particular requirements.

Authors' Reply to the Reviewers

Authors of Project I.1.4 *Design Requirements for Future NSR Ships* have attentively familiarized themselves with the review of Dr Keinonen (AKAC Inc. Calgary, Canada) and are very grateful for his thorough examination of the report and the appreciation of work performed on the Project as well as for valuable comments directed towards its improvement. Specific comments on separate items have been taken into account in the final wording of the report. Comments which need certain explanations are considered below.

As to remarks of the reviewer about the not sufficiently full consideration in the present report of the outlooks of the development of shipping on the Northern Sea Route and in other arctic waters one should bear in mind that special Sub-Program III *Trade and Commercial Shipping Aspects* deals with this issue within the framework of the INSROP Program where prospects for the development of the cargo traffic in the Arctic are extensively elucidated.

As far as comments of the technical character are concerned the authors note the following:

1. Unfortunately, at the moment it is impossible to give full assessment of the adequacy of new international harmonized regulations to provide for the safe navigation in the Arctic. Unified IACS requirements for polar ships have not yet been developed and there is even no draft of such requirements. In 1998 the developed draft of the IMO Polar Code was circulated for the consideration among all interested states and appropriate comments and proposals will be collected and summarized during 1999. There are also proposals on the improvement of the Polar Code on the part of the delegation of the Russian Federation. It seems therefore premature assessing the adequacy and correctness of the international requirements for the safety of navigation in polar waters being prepared.
2. Authors agree with the comment on section 3.1 and accordingly all the parameters of formulas (3.1), (3.2) and (3.3) are given in the report.
3. Figures 3.2, 4.3, 4.4, 4.5 and 4.6 represent results of systematic tests in the ice tank of ships' models differing by certain parameters. In the opinion of authors, the resulting trends on the effect of separate parameters on the ice propulsion of ships may be used in the first approximation while making design studies of new ice ships.
4. The reviewer with good reason mentions the known fact of the squat of ship moving in the shallow water due to the particular character of wave formation. This effect, however, is very much pronounced during the movement of ship in open water at high speeds. Apparently this phenomenon is inherent to all ships both of ice and ice-free navigation. At the same time, according to the experience of operation of ships with an icebreaking shape of hull lines the following empiric formula may be used for the estimation of the stern squat ΔT_k depending on speed and relative draft of ship:

$$\Delta T_{\mathbf{k}} = 0.024\left(14.8 - \frac{L}{B}\right)\frac{V^2}{g}\sqrt{\frac{T}{H}}\text{, m}$$

where L/B - ship's length/ breadth ratio,
V - speed in m/s,
g - acceleration of gravity in m/s^2,
T - ship's draft in m,
H - water depth in m.

The experience shows that during the movement through ice cake of the channel made in compact ice the icebreaker stern squat is considerably smaller (by 20-25 %) than in the ice-free water at the same speed. It is known that in practice navigators in both cases reduce the speed depending on the under-keel clearance.

5. Comparison of the icebreaking capability of icebreaker *Arktika* depending on its age shown in Figures 6.1 and 6.2 is based on full-scale trials of the icebreaker at the same place of the Yenisei Gulf and in the same season (in May). The air temperature was practically the same (within 6-10° C below zero), snow cover was about 20-25 cm deep with equal density. This provides grounds to assume with certainty that the reason of the substantial reduction of the icebreaking capability of the icebreaker after 8 years was the roughness of the hull shell plating because of the intense corrosion. The results obtained were confirmed by laboratory tests in the ice tank of AARI of samples of the shell plating with different roughness. In summer 1983 the hull of icebreaker *Arktika* was puttied and covered with ice-resistant painting *Inerta-160*. As a result, its icebreaking capability was completely restored.
6. As the statistics of ice navigation of ships on waterways of the Russian Arctic shows, average speed of escorting ships by nuclear icebreakers in drifting first-year ice of a medium thickness (70-120 cm) is 8-10 knots. It is obvious that while escorting ships in drifting ice the most use is made of cracks and fractures in ice around heavy hummocking stretches on the route. Just as applied to the conditions of medium first-year ice (and not to the heaviest ice conditions) an example of calculation in section 7 of the report is given permitting to assess the difference in the required power of a cargo ship and icebreaker for the movement at the same speed along the ice route taking into account ice compacting with average statistical intensity. In accordance with calculations an icebreaking cargo ship distinctive of its elongated hull thanks to the parallel middlebody should possess by 30-50 % greater power to reach the efficiency of operation in the independent sailing similar to that of the icebreaker. It is an isolated example of calculation not pretending to final conclusions. Nevertheless, attention is drawn to the necessity of taking into consideration the indicated drawback of cargo ships while evaluating possibilities of their independent (without icebreaker assistance) navigation in the Arctic, especially in all the year round mode of operation. However this does not exclude detailed investigations of alternatives in each particular case and their comparison by economical criteria.
7. The use on icebreaking cargo ships of Azimuth thrusters should really improve the maneuverability of ship and reduce risk of getting stuck bearing in mind the possibility of turning the screw by 180° and thus using the full thrust. It is not clear however, what additional effect could be expected from *Azipod* in the ahead movement of ship under conditions of ice compacting? Besides, for the correctness of comparison, one should remember that *Azipod* can be used both on cargo ships and on icebreakers.

As to the North American experience it is difficult to judge. The authors only know that in the Canadian Arctic there is no all the year round navigation.

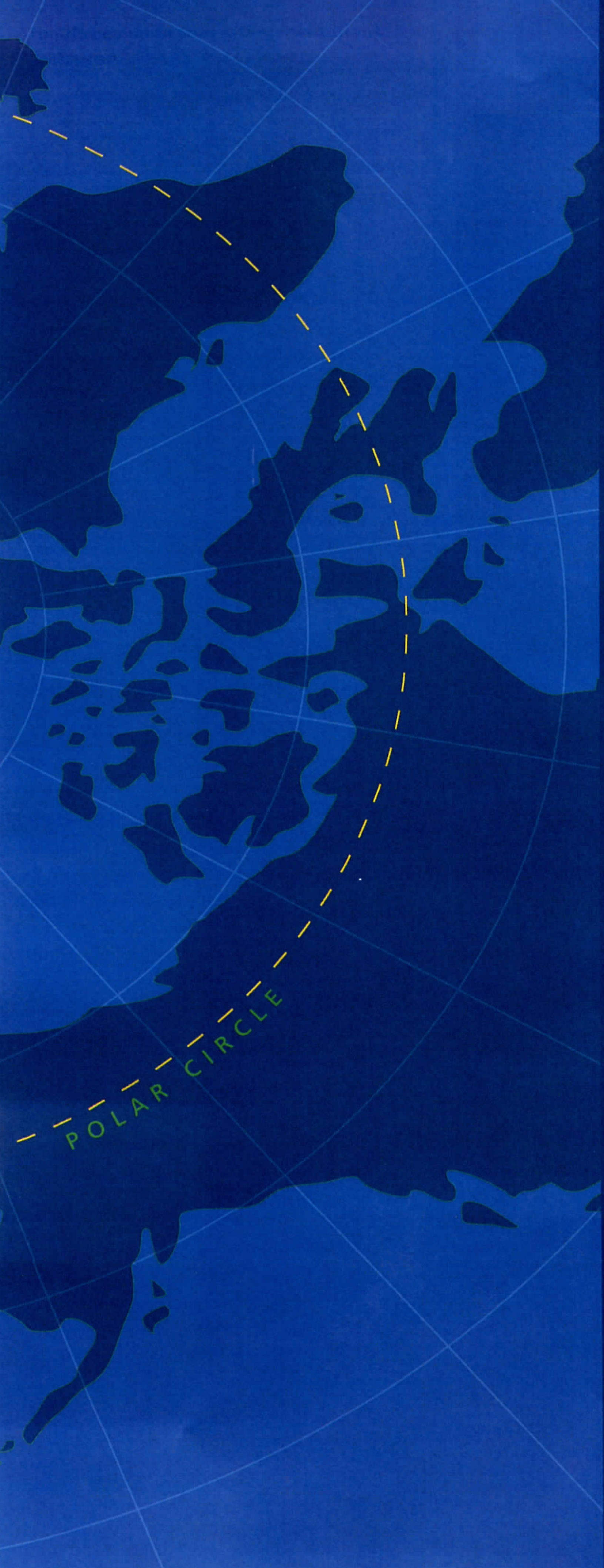
8. Graph in Figure 7.3 demonstrates the relationship between the operational season and ship's icebreaking capability based on the experience. Therefore the reviewer's suggestion to relate the operational season with ice class using the ice class/icebreaking capability criterion dependence seems to be real and advisable. In other words, each ice class should correspond to a certain level of the ship's icebreaking capability which in turn defines the admissible season and area of the independent operation of ship, as it is shown in Figure 7.3 of the report. Beyond the admissible season of the independent operation the sailing of ship is possible only under the assistance of the icebreaker having a higher class and accordingly higher icebreaking capability.

9. Reason of the increase of the icebreaking capability of icebreaking tankers with the increase of their sizes and deadweight (Table 8.2) was the increase of draft enabling to accept propellers of larger diameter (in proportion to draft) and to achieve higher thrust at the same power as well as somewhat improved hull lines shape of versions 2 and 3 and significantly greater mass of tankers with enlarged dimensions.

As to the reviewer's concern about possible expensiveness of the arctic shipping it is worth noting that problems of economics should be dealt with in the application to particular cases using different alternative solutions. It is quite natural that one should pay for the breaking through ice. These costs however are to be minimized by taking optimum technical and tactical solutions.

Already in the foreseeable future, along with traditional supply operations, in the Russian Arctic demand in the large- scale sea traffic for the taking out of the hydrocarbon raw material from deposits of the arctic shelf will arise. These operations should be reliable, safe and efficient. Authors of the report hope that the requirements formulated to arctic ships of promising construction will contribute to the solution of the raised problem.

Sincerely Yours,
Loly Tsoy
Supervisor of work, Head of the Laboratory of Icebreaking Technology
15 March 1999



The three main cooperating institutions of INSROP

Ship & Ocean Foundation (SOF), Tokyo, Japan.

SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Nippon Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.

CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stockholding company.

The Fridtjof Nansen Institute (FNI), Lysaker, Norway.

FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multidisciplinary approach, entailing extensive cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.