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STUDY OF SPECIAL FEATURES OF WINTER NAVIGATIONS IN GoF AND DEVELOPMENT ALGORITHMS AND MODELS FOR CALCULATIONS OF THE SHIP MOVEMENT IN ICE WITH THE AIM TO USE THEM IN RISK MODEL WHEN EVALUATING THE RCO EFFICIENCY WITHIN THE FRAME OF THE WINOIL PROJECT WORKS

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ABBREVIATIONS

ASP BPSPb	Administration of the sea port “Bolshoy port of St-Petersburg”;
FSA	Formal Safety Assessment;
GM	Generic Model;
GOFREP	Reporting System of GoF;
HAZID	Hazard Identification;
IMO	International Maritime Organization;
MRCC	Marine Rescue-and-Coordination Center;
RS	Russian Maritime Register of Shipping;
RR	recommended route;
VTCS	Vessel Traffic Control System;
WP2	Working Package #2 of the WINOIL project.

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ABSTRACT

This work is fulfilled in accordance with the South-East Finland-Russia ENPI CBC PROGRAMME 2007-2013 and the project SE680 “WINOIL” – Winter navigation risks and oil contingency plan.

The WP2 of the project provides for holistic risk management of winter navigation in Gulf of Finland (GoF). Part of this WP is focused on the development of an advanced model for ship performance in ice (Task 2.3). This model should be used to define operational limits for vessels and to study navigational aspects of ship operation in ice (minimal safe distance between vessels in caravan, ship performance in various ice conditions, stopping distance and others).

The first object of study was the navigation system in the east part of GoF in winter time and the selection of generic ship types in the region in winter navigation in the context of the most hazardous oil spill. The second object of study within the frame of the Task 2.3 was development of the physical and mathematical models for calculation of ship ice performance.

In the course of the work on Task 2.3 the description of the winter navigation in the GoF and the analysis of the winter navigation system in GoF as for the route limits and navigating fairway dangers were performed. Then the set of models of ship performance in ice in a form of physic and mathematic algorithms for the evaluation the ship movement in ice conditions was developed and calculations of ice performance for the selected generic ships was implemented and results of this calculations were forwarded to the WP2 lead partner.

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1. INTRODUCTION

The general purpose of WINOIL project is defied as: “Extension of the concept on oil pollution prevention measures as well as diminishing the risks regarding navigation under ice conditions of the Gulf of Finland”. In short the problem to be considered may be defined as “risks of navigation in the Gulf of Finland (GoF) during winter period”.

Within the framework of package WP2 of project WINOIL it is envisaged to perform works for the assessment and control of risks of winter navigation in the Gulf of Finland by the methods stated in the “Guidelines for Formal Safety Assessment” (FSA) developed and recommended by the International Maritime Organization (IMO). In the WINOIL project it is assumed that on the basis of the initial identification of hazards (HAZID) a holistic model of the risk management (Risk Management Model = RMM model) will be developed.

The object to be investigated as a source of hazards is not a single ship, but system of the navigation formed in the closed area of the Gulf of Finland in winter. Briefly this system is characterized by a set of different routes and fairways, by high level of the intensity of navigation of various ship types including a number of large tankers with the weight carrying capacity and draft limiting for the Baltic Sea that increase the hazard of oil spillage under conditions of winter navigation in the gulf. This system in a general way is described in the present report.

Along with the consideration of the above system the report, as it was provided for the work on package WP2, contains description of the model for the calculated estimate of the performance of ships under ice conditions. This model has been developed on the basis of theoretical investigations and statistics of shipping in the Gulf of Finland for the latest years as predominantly applied to the severe and medium ice navigations, as well as taking into account the analysis of performed earlier works [1, 2, 3].

Besides, within the framework of works on package WP2 the analysis was made of the types of ships and of their dimensions to identify a set of representing ships from the viewpoint of potentially most hazardous ones at the selected worst scenarios as far as oil spillage is concerned. For these ships their ice characteristics are calculated using the developed model and the results are presented in the present report.

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2. DESCRIPTION OF THE PECULIARITIES OF WINTER NAVIGATION IN THE EASTERN PART OF THE GULF OF FINLAND

Within the above problem not a separate ship is considered but combination of ships of different types under winter conditions in the GoF. In this case one should consider the functioning of a system description of which is to be done from the view of oil spill hazard under conditions of the system functioning. This description will allow to define the so-called "Generic Model" (GM) for its further usage within the frameworks of the considered problem.

Principle components of the system are considered below:

- winter conditions in the eastern part of the GoF ;
- main ports;
- organization of the traffic of ships;
- descriptions of ships participating in winter navigation as well as intensity of flows towards the ports of the eastern part of the GoF ;
- allocation of icebreakers during winter navigation per ports and per fairways of the eastern part of the GoF;
- principles and modes of icebreaker assistance;
- system of ship traffic control;
- the most dangerous places on winter routes of the eastern part of the GoF.

2.1. Winter conditions in the Gulf of Finland

Description of winter conditions in the GoF is based on the particular characters of the heaviest winter navigation 2010-2011 (10-11) which was in the period of the last 10 years.

When comparing two heaviest winter navigations (2002-2003 and 2010-2011) for the specified period it is necessary to note the following peculiarities. During 2002-2003 navigation area of ice coverage was considerably larger than in 2010-2011. Convoys were formed in the area of Tallin, Helsinki. Ships proceeding from the west to the port of St. Petersburg independently reached Rodsher Island and buoy № 4 and even buoy №6. In spite of this fact there were delays and stoppages in expectation for the icebreaker assistance. One can consider also later navigations in comparison with 2002-2003 navigation which can also

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referred to as heavy ones. However, ice conditions of “10-11” were very heavy despite the smaller area of ice coverage.

In February 2011 under thaw conditions strong western winds pressed 10/10 ice massif of grey-white and white ice from the meridian of Tallinn to the meridian of Gogland. Subsequent cold weather caused freezing this mass by the end of February up to the state of fast ice. Hummocked ice was estimated as 4 according to 5-point scale. The fairway section from the ice edge to receiving buoy of St. Petersburg became practically impassible for the independently navigating ships of any power, i.e. ice conditions during separate periods of winter navigation “10-11” can be estimated as anomalously heavy.

Beginning on December 2010 the administration of the ports of the GoF introduced the navigational restrictions for ships. During January and up to middle of February 2011ice conditions follow the light pattern with transition to the average conditions in the middle of February. The practical ice situation in the middle of February of 2011 was easier than for the same period of 2010.

Throughout the February of 2011 the prevailing west winds resulted in the intensive ice drift on the basin of GoF and all mass of ice was concentrated eastward of the Gogland Island. The law temperatures caused the freesing of the hummocked ice. Difficult passable ice conditions were formed at the approach fairways in the region of islands Seskar and Sommers.

In the beginning of the February the edge of ice shifted westward from the Tallin meridian at 130 miles. The low temperatures keeping throughout the long period caused the permanent increasing of ice thickness that reached to 45-50 cm in the end of February and in hummocks – up to 1.0 m.

From the beginning of March 2011 the ice situation in Russian ports of the east part of GoF continued to worsen due to permanent west winds. This resulted in shearing the ice, its compacting (compression) and hummocking. The channels behind the icebreaker closed. Icebreakers could convoy not more than 2-3 vessels in a caravan and the only individual guiding (assistance) by the linear icebreaker was possible for large tankers. In some cases one tanker could be guided by two linear icebreakers to/out the port of Primorsk.

All in all, the total duration of unfavorable western winds amounted 23 days or 74% in March 2011.

2.2. Main ports

The state control under fulfilling the national legislation and international treaties of the Russian Federation as to navigation safety, safety of the human life at sea and protection of the environment against pollution is implemented by the Federal State Enterprise “Administration of the sea port “Bolshoy port St.-Petersburg” (ASP BPSPb).

Moreover the ASP BPSPb organizes the ship traffic control as well as provides with the navigational info, pilotage, towing and icebreaker assistance of ships. It incorporates as its subsidiaries the ports of Primorsk, Ust-Luga, Vysotsk, Vyborg and the passenger port in St.-Petersburg (see Figure 2.1).

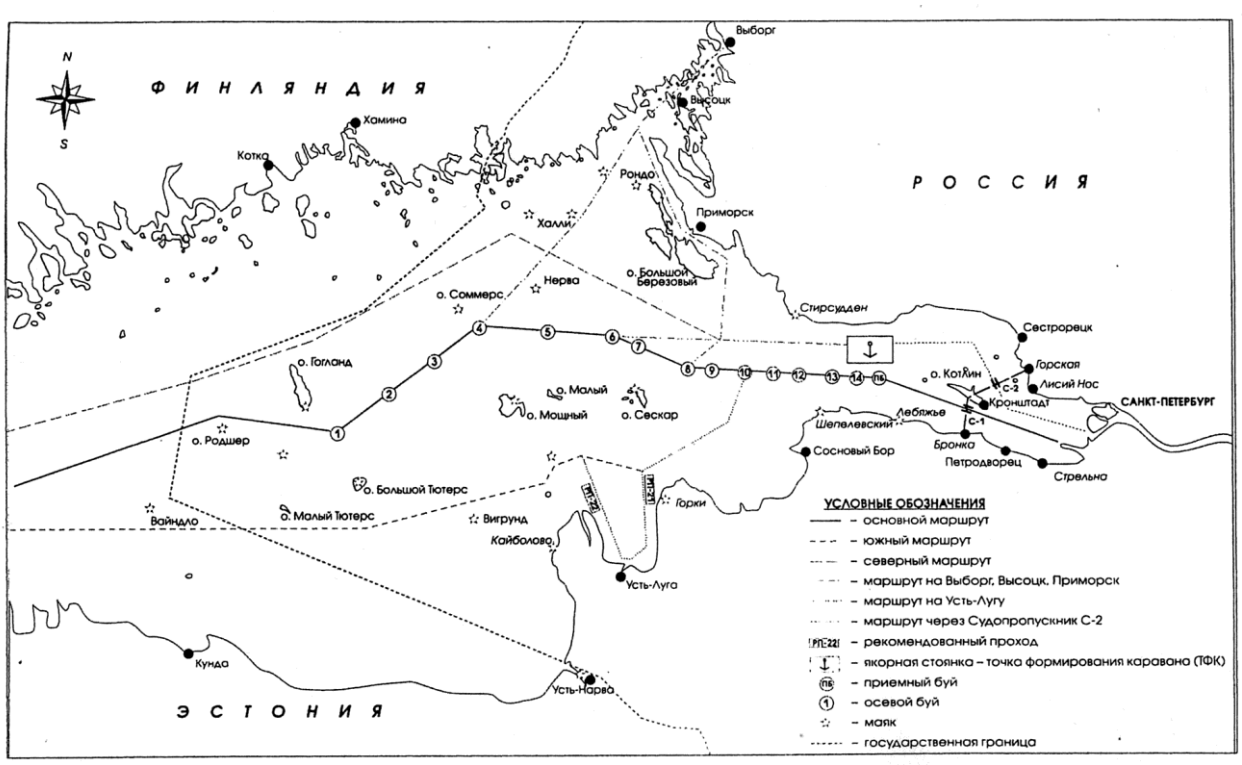

Figure 2.1. The scheme of routes and recommended fairways for ships under icebreaker assistance in the east part of GoF

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Port of St.-Petersburg

- It specializes in: cargo handling of the dry cargo vessels and tankers as well as in the cruise ships.
- Cagro turnover in 2011: 620 million ton of cargo; about 800 thousand of passengers (about 280 cruise ships).
- Restrictions: dimensions of the accepted vessels: length L ≤ 320 m; draft T = 10-11 m.

Port of Primorsk

- It specializes in: export shipment of liquid cargo at the specialized sea terminal for transshipment of crude oil.
- Cagro turnover in 2011: 75 million ton (including 70 million of crude oil)
- Restrictions: speed of vessels V ≤10 kn: wind speed while approaching of vessel V_w ≤ 15-18 m/s.

Port of Ust-Luga

- It specializes in: transshipment and additional handling more than 20 sorts of cargo.
- Cagro turnover in 2011: 22.7 million tons (29 % of oil products, 55 % of coal).
- Restrictions: dry cargo vessels DW ≤ 75 000 t; tankers DW ≤ 150 000 t; depth in the port basin and at the approaching channels from 7.6 to 16.0 m.

Port of Vyborg

- It specializes in: transshipment of export cargo (general, bulk, chemical).
- Cagro turnover in 2011: 1,1 million ton.
- Restrictions: the minimal depth of the sea channel of Vyborg is 6.9 m, ship dimensions L ≤ 135 m, draft T ≤ 6.5 m.

Port of Vysotsk

- It specializes in: the main terminals are for coal and for crude oil.
- Cagro turnover in 2011: 13,4 million ton.
- Restrictions: at coal terminal L≤230 m, T≤11.9 m, at crude oil terminal L ≤ 260 m, T ≤ 13.2 m.

2.3. Arrangement of the vessel traffic

The Regional Vessel Traffic Control System (VTCS) of the eastern part of GoF incorporates the Coastal VTCS and the Port VTMS systems of the following ports: St.-Petersburg. Primorsk, Vyborg, Vysotsk and Ust-Luga. This system is the element of the Regional VTCS of the GoF. The last VTMS of GoF consists of the VTCS of Finland, Estonia and of the of vessel report system GOFREP.

The ship navigation is performed on the announced vessel routes (on the systems of the fixed routes, fairways, channels) and managed by the Centers of VTCS.

The vessel masters should, of necessity, address to the corresponding Center of VTCS as to the safety navigation concerns. As to shipping efficiency concerns - to the St.-Petersburg ROSMORPORT branch (in St.-Petersburg) or to a department of corresponding port.

Vessels sailing to the ports of Russian Federation from the state border (the border of territorial sea) should follow the traffic separation system in the Rodsher island area or the fairway #4 (Figure 2.2).

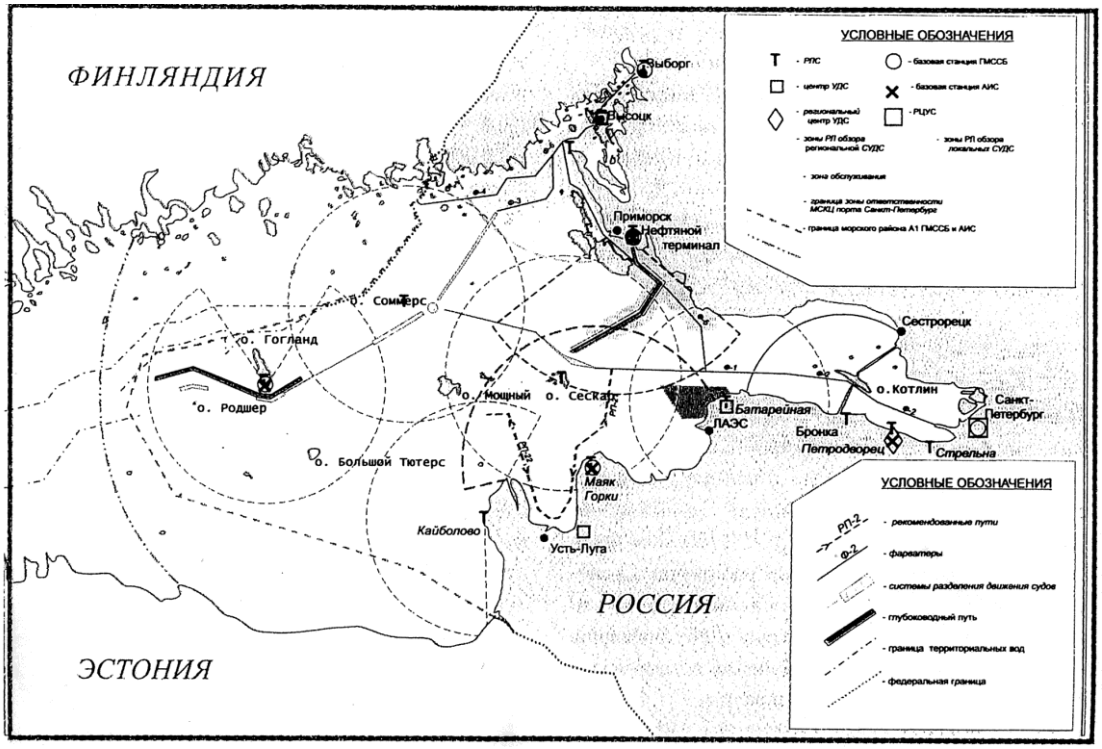

Figure 2.2. The regional system of the safe ship traffic control in the east part of the GoF

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2.3.1. The fixed routes of ship traffic, fairways and channels

The fairways from the Gogland island area and from the State border with Finland to the eastern ports of GoF make up the basis of the fixed routes of ship traffic. The most extended fairway (about 80 miles) is the Large Ship Fairway (LSF; buoys 1-14).

The Traffic Separation Systems (Schemes) are foreseen and used as follows (Figure 2.2):

- in the Rodsher island area (the lane width Bs =1.0 mile);
- in the Gogland island area (Bs =1.0-1.25 miles);
- in the Sommers island area (Bs = 1.0 mile);
- in the Seskar island area (Bs = 0.75-1.0 miles);
- by the approach to the Gulf of Vyborg (Bs = 0.3-0.5 miles).

The deepwater routes (DWR) are as follows:

- DWR-1 from Gogland island till Rodsher island; intended for the large tankers with the draft 15 m;
- DWR-2 to the inner roadstead of Vysotsk, the least depth 12.2 m;
- The recommended routes (RR-21 and RR-22) are destined to follow in the Luzhskaja inlet and to go out of it.

Fairways and channels:

- for approaching the port of St.-Petersburg (fairway #1: from the buoy # 8 to receiving buoy of SPb), (fairway #2: the ship fairway of the Kronstadt and the sea channel of SPb);
- for approaching the ports Vysotsk, Vyborg and Primorsk the fairways # 4, #5, #5a, #6, #6a (F-4, F-5, F-6) are used;
- for approaching the port of Ust-Luga the Ust-Luzhskiy channel is used.

2.3.2 The sailing order of ships through the fixed routes and fairways

Sailing through the fixed routes is controlled by the Coastal VTCS and by the VTCS of ports. Sailing through the fairways and channels is regulated by “International Regulations for Preventing Collisions at Sea – 72” (IRPCS-72); by General Rules of Navigation and Moorings in sea ports of the Russian Federation and at approaching them; by the Bylaws of

the sea port “Bolshoy port St.-Petersburg”; by Regional Rules of sailing through the navigational routes of the North-West basin.

As regards peculiarities of arrangement of navigation in ice conditions in the Baltic Sea region under review, it should be marked that in the time being the provisions stated in the chapter XII “Information on ice navigation in sea port” of the Bylaws of the sea port “Bolshoy St.-Petersburg” are in force (http://www.pasp.ru).

2.4. Ships participating in winter navigation in GoF: ship stream intensity to the ports of eastern part of GoF and distribution of icebreakers on routes

The types and characteristics of merchant ships calling ports of the Russian Federation in GoF are given in table 2.1. The cargo turnover and the number of calls to the Russian ports are presented in table 2.2 with the actual figures for the year 2011 and the planned figures for the year 2012.

Table 2.1.

Ports	Vessel type	Deadweight, т
Vyborg	General-purpose vessels	Less than 5 000
Vysotsk	Bulkers	30 000 – 70 000
	Tankers	Less than 100 000
Primorsk	Tanker (the news, with ice class)	50 000 – 120 000
St.-Petersburg	Dry cargo vessels	Less than 50 000
	Tankers	Less than 100 000
	Passenger vessels	
Ust-Luga	Bulkers	30 000 – 70 000
	General-purpose, Ro-ro, container vessels	Less than 30 000
	Ferries	Less than 10 000

Table 2.2.

Ports	Cargo Turnover, thousand tones			Number of vessel calls		
	2010	2011	2012	2010	2011	2012
St.-Petersburg	3 889	4 138	4 138	343	372	370
Primorsk	6 298	6 053	6 053	66	64	90
Lukoil terminal	800	800	875	21	26	40
Vyborg, Vysotsk	474	569	570	52	33	
Ust-Luga	868	1 071	2 231	50	69	90
Total	12 329	12 632	13 867	532	564	590

Taking into account turnover estimation and the long-term forecast for winter navigation “10-11”, “The Icebreaker Distribution Plan” was developed. The number of icebreakers necessary for operation in the Great port of St.-Petersburg in winter navigation was determined taking into account the following:

- the expected number of vessel calls to port;
- the expected type of winter conditions (light, average, hard);
- the icebreaker operative fleet in GoF and the possibility to involve the additional icebreakers from other basins.

In accordance with the Plan it was foreseen the possibility to transfer the icebreaker “Kapitan Dranitsyn” to GoF in the second period of winter navigation. Besides, the nuclear icebreaker “Vajgach” was also re-dislocated later to the GoF after the ice conditions became too worse there.

In this way, in the most complicated period of the winter navigation “10-11” fourteen icebreakers operated in the east part of GoF, of which there were 6 linear icebreakers and 8 - port icebreakers (table 2.3).

Table 2.3.

No	Icebreaker name	Type of power plant	Icebreaker type	Shaft power, MW
1	Ermak	Diesel/el	Linear	26.5
2	Moskwa	Diesel/el		16.0
3	Vajgach	Nuclear		32.5
4	Sankt-Peterburg	Diesel/el		16.0
5	Kapitan Sorokin	Diesel/el		16.2
6	Kapitan Dranitsyn	Diesel/el		16.2
7	Mudjug	Diesel/reduct	Port	7.0
8	Tor	Diesel/el		5.6
9	Karu	Diesel/el		4.1
10	Semjon Dezhnev	Diesel/el		3.4
11	Ivan Krusenstern	Diesel/el		3.9
12	Yuri Lisjansky	Diesel/el		3.4
13	Kapitan Izmailov	Diesel/el		2.5
14	Kapitan Zarubin	Diesel/el		3.3

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The placing (distribution) of the icebreaker fleet on the routes of guiding the merchant ships in winter navigation “10-11” in accordance with the Plan is represented in table 4 together with the actual distribution in the previous year.

Table 2.4.

No	Icebreaker	Region of operation	
		2010	2011
1	Ermak	Ice Edge - Primorsk	Ice Edge – Primorsk
2	Moskwa	Ice Edge - Primorsk	Ice Edge – Primorsk
3	Sankt-Peterburg	Ice Edge – Vysotsk	Ice Edge – Vysotsk / Appr. buoy SPb
4	Kapitan Sorokin	Appr. buoy SPb – Ice Edge	Appr. buoy SPb – Ice Edge
5	Mudjug	Appr. buoy SPb – Ice Edge	Appr. buoy SPb – Ice Edge
6	Tor	Buoy #8 –.Vyborg	Buoy #8/#9 –Vyborg/ Vysotsk
7	Karu	Appr. buoy SPb – buoy #9	Island of Seskar – appr. Buoy Ust-Luga/SPb.
8	Semjon Dezhnev	Appr. buoy SPb – road of timber mole	Appr. buoy SPb – road of timber mole
9	Ivan Krusenstern	Island of Gogland – Ust-Luga	Appr. buoy SPb – Ust-Luga
10	Yuri Lisjansky	Appr. buoy SPb – road of timber mole	Appr. buoy SPb – road of timber mole
11	Kapitan Izmailov	Ice Edge – Vysotsk, Vyborg	Ice Edge – Vysotsk, Vyborg
12	Kapitan Zarubin	Appr. buoy SPb – road of timber mole	Appr. buoy SPb – road of timber mole

Note: Appr. Buoy SPb = approaching (= receiving) buoy of St.-Petersburg.

2.5. Navigation under icebreaker’s guiding

2.5.1. Principles and modes of icebreaker’s guiding (assistance)

I. Selection of routes with a high priority as a function of

- Strategic status of route (line);
- Type of ice and meteorological conditions;
- Level of danger of transported cargo;
- Number of vessel calls to a certain port.

II. Attachment of the icebreakers to a port, line, part of line:

- Port icebreaker;
- Linear icebreaker;
- Attached to a section icebreaker.

III. The guiding conditions:

- The caravan guiding speed Vk ≥ 5 kn;
- The number of ships in caravan Nk ≤ 5.

IV. The modes of icebreaker's guiding regulations (control):

- The typical (usual) mode : the captain of port forms (makes up) daily caravans taking into account the queue for the icebreaker assistance, time of approaching the point of caravan formation, vessel restrictions etc..
- The operative control: this is implemented by the staff (headquarter) of icebreaker assistance (the time and the order of advancement through ice; making alterations in case of unusual situations etc.),

V. Independent (solo) icebreaker assistance: a ship may inquire individual icebreaking assistance in case she is not able to go in caravan. The request is satisfied given if there is free icebreaker.

2.5.2. Independent navigation of ships in ice.

Such a navigation is possible given the following concurrent conditions:

- ice conditions on the route of east part of GoF correspond to vessel's ice class of Russian Maritime Register of Shipping (RS);
- gross tonnage GT ≥ 30 000 t;
- the vessel age ≤ 15 years.

2.5.3. Modes and restrictions of winter navigation

Depending on the ice thickness and the vessel ice class, two following modes of ship navigation in east part of GoF are determined:

- Mode 1: it is permitted for a ship to navigate in ice under icebreaking assistance and solo,
- Mode 2: it is permitted for a ship to navigate in ice only under icebreaking assistance.

Ships are not allowed to navigate in ice under the following ice situations:

- Ice thickness 10-15 cm; tugs and tows;
- Ice thickness 15-30 cm; ships without ice class, tugs and tows;
- Ice thickness 30-50 cm; ships without ice class, tugs and tows;
- Ice thickness more than 50 cm; ships without ice class, ship ice class notation Ice1 (RS), tugs and tow.

2.6. Vessel traffic control system

The Regional Vessel Traffic Control System (VTCS) (Figure 2.2) is in operation in eastern part of the GoF. It incorporates the following parts:

- the Coastal VTCS;
- the Port VTCS of the ports St.-Petersburg, Primorsk, Vyborg and Vysotsk, Ust-Luga;
- the VTMS systems inside the ports St.-Petersburg, Vyborg and Vysotsk.

The functions of the VTCS Centers are as follows:

- analysis of the observation data;
- identification of the detected vessels;
- getting in touch with ships;
- receiving and registration of data about any detected ship; this data are further used according to the VTCS purposes.

The VTCS purposes are as follows:

- ship traffic management on the routes within the 2 miles lane on each side of the midline;
- ship position control while on anchorage, in area of waiting: control and observation ships that are outside the fairway after the fact of contact with the ship;
- rendering the help in navigation;
- transmission of the navigational, operative and other information.

Besides, the VTCS Centers organize the following:

- interaction with the Marine Rescue-and-Coordination Center (MRCC), with the pilot, dispatcher, tow and icebreaker services of the ports;

- interaction with the State Bodies of the Russian Federation;
- co-operation in making contacts (getting in touch) with other ships coast services;
- interaction with the Centers of the system GOFREP.

2.7. The most dangerous places of the GoF

These are as follows:

- From the Gogland Island to buoy #6 (due to high traffic intensity on the fairway);
- The buoys #1, #4 and #6 (due to the bends of the fairway in the vicinity of buoys);
- The section of the fairway to Primorsk in the direction of the Ermilovskiy alignment (due to the frequent hummocked ice formation).

The fairway sections with the hummocked ice represent the considerable difficulties for shipping in winter time. The appearance of such sections is caused by the compacting of the drift ice. The intensity of compacting is caused by prevailing the strong winds of west and north directions. In the region of the Seskar Island, occurrence rate of the wind of 5-8 m/s in moderate winter season in March accounts for about 8%. These winds result in as a rule the ice compression of 1-2 points strong. The winds of 9-14 m/s account for about 3% and it results in the ice compression of 2-3 points strong. The probability of dangerous (from the compression point of view) wind directions exceeds 16 %. The ice compression of up to 2-3 points strong on the route sections between islands Moshny, Gogland and Bolshoy Tjuters occurs in January and February. The greatest danger (hazard) caused by the ice compression as well as hummocked ice danger (hazard) bring the severe winters due to the heightened strength of ice and the greater its thickness.

2.8. Selection of generic ships for risk calculations

The data analysis of ships calling Russian ports in GoF was performed for the winter navigation “12-13” in order to select the generic ships necessary in further risk assessment calculations in GoF.

The criterion for selection was chosen the pair of values something like max{DW; KZ}, i.e. maximum calls (KZ) of ships with maximum deadweight (DW) for two lines Primorsk and Ust-Luga. What is more, the relative small vessels were taken into consideration as well. That is why two types of ships of smaller deadweight were considered as the generic too. The result of the performed selection is given in table 2.5 and characteristics of the selected ships – in table 2.6.

Table 2.5. Analyses of ships called at the ports Primorsk and Ust-Luga during the winter navigation “12-13” in GoF and selection of the generic ships

No	Line	Primorsk		Ust-luga				Note
1	Total number of calls at ports	385		360				
2	Number of ships called at ports	107		129				
3	Number of ships/calls without ice class	11/14		14/14				During December 2012
4	Ship type	Tankers		Tankers		Bulkers[1)]		1)At port Ust-Luga called also 16 container vessels DW={11000-23000 t} (75 calls), 7 Ro-Ro vessels DW={10000-18700 t} (35 calls), 4 dry cargo vessels DW={10000-21400 t}(19 calls), 3 barges and 1 ferry
5	Tonnage group, thousand tons of deadweight	20-50	103-120	37-51	103-120	10-56	75-94	
6	Number of vessels in tonnage group	50	55[2)]	12	32	31	18	2) Two vessels DW={134000; 163000 t} made 6 calls at the port Primorsk.
7	Number of calls (KZ}	136	244	25	72[3)]	48	63	3) 5 tankers DW={130000-165000 t} made 14 calls at the port Ust-Luga
8	Generic (averaged) deadweight[4)] , thousand tons of deadweight	35	111	37.6	111	29.6	78.7	4) Chosen by criterion max {DW; KZ}
9	Name of a vessel called this winter navigation at the ports Primorsk and Ust-Luga which is close to the generic one on deadweight parameter	*Torm Gyga*	*Deep Blue*	*Torm Gyda*	*Deep Blue*	*Com-modo-re*	*Zag-reb*	

Table 2.6. Characteristics of the generic vessels of a number those that called at the ports Primorsk and Ust-Luga during the winter navigation “12-13” in GoF

Vessel type, name	Deadweight, DW, thousand tons	Principal dimensions Length x Breadth x Draft L x B x D, m	Power, kW	Ice class
Tanker “Torm Gyga”	36.2	184.3 x 27.4 x11.3	9480	Arc4
Tanker “Deep Blue”	112.9	250 x 44 x 14.6	14310	Arc4
Bulker “Commodore”	30.0	171.5 x 27 x 10.1	6240	No
Bulker “Zagreb”	79.9	229 x 32.3 x14.6	11620	Ice1

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3. MODELLING THE SHIP MOTION PERFORMANCE IN ICE

Within the frame of the WP2 package it was foreseen to develop a model for ship performance in ice. This model will be used both to determine ship limits by ship movement in ice and to study navigational aspects of ship operation in ice conditions.

The developed and described in this report model for estimation of parameters and characteristics of ship ice performance is based on application of physical phenomena which accompany the motion of ship in ice. The model is a combination of analytical dependences and logic connections grouped in a number of calculation blocks (modules).

Some elements of the model (as a code complex) were used for estimation of different ship types motion in a channel behind an icebreaker by solving the problem of substantiation the new icebreaker and merchant vessel types as well as by selection of their characteristics and tactics of their application in ice conditions.

In this chapter, theoretical and methodical provisions and analytical dependences which are assumed as a basis for estimation of the following characteristics of ship ice performance:

- icebreaking capability;
- attainable speed of ship motion in ice;
- admissible speed of ship motion in ice;
- minimal safe distance between vessels in caravan.

3.1. Icebreaking capability

Principal operational parameter characterizing the ice propulsion of ship is its icebreaking capability that is maximum thickness of level compact ice broken through while moving at a minimum steady speed of about 2 knots. It is also assumed that ice has natural snow cover 20-25 cm thick and its bending resistance is at least 500 kPa. Icebreaking capability depends on a great number of parameters and ship's characteristics, main of which are power, forebody shape, draft etc.

Icebreaking capability is the principal measure when comparing icebreaking performance of ships, but it does not characterize ice propulsion in the whole range of ice thicknesses: from zero during the movement in open water to a maximum thickness when

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speed values are minimal. Starting from the assumption of the linearity of the speed/ice thickness relationship one can judge the ship's ice propulsion by two parameters: speed in open water $\boldsymbol{V}_0$ and icebreaking capability $\boldsymbol{h}_0$.

At present, while simulating the movement in ice of icebreaking cargo ships and icebreakers with traditional icebreaking (wedge-like) forward end lines, CNIIMF determines the icebreaking capability by the formula [5]:

$$h_0 = k_f \left(\frac{P_e}{B}\right)^{1/2} D^{1/n}, \tag{3.1}$$

$$k_f = \frac{0.07}{\sqrt[5]{\frac{L}{B}}\ \sqrt[2,6]{f_d}} \frac{\cos^{\frac{3}{2}}\varphi\ \sin^{\frac{1}{2}}\left(\frac{\alpha_0 + \beta_0 + \beta_2}{3}\right)}{\sin^{\frac{3}{2}}\left(90^0 - \beta_{10}\right)} \tag{3.2}$$

where: k_f – shape coefficient;
P_e – total propeller bollard thrust;
D – vessel's designed displacement;
φ – stem angle;
α_0 – entrance angle of design water line;
β_0 – flare angle of frame line No.0 (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);
β_2 – flare angle of frame line No.2;
β_{10} – flare angle amidships;
B – vessel's breadth on DWL;
n – exponent parameter.

The relationship (3.1) takes account of the influence of ten parameters characterizing the hull shape, propulsion and stopping ability performance as well as main dimensions. The field of its application extends to icebreaking cargo ships and icebreakers with traditional icebreaking (wedge-like) forward end lines.

One should bear in mind that in traditional writing, when exponent denominator $\boldsymbol{n}$ = 6, formula (3.1) is applicable only to ships with a displacement of up to 25 000 t.

For larger ships, parameter ***n*** is determined by formula:

$$n = 6.0 + 5 \cdot 10^{-6} (D - 25000), \text{ при } D \geq 25\,000 \text{ t.} \quad (3.3)$$

Character of the change of parameter ***n*** in formula (3.3) taking into account the effect of displacement ***D*** on icebreaking capability h_0 of large-capacity ships with traditional icebreaking form (without bulb) of forebody is shown in Figure 3.1.

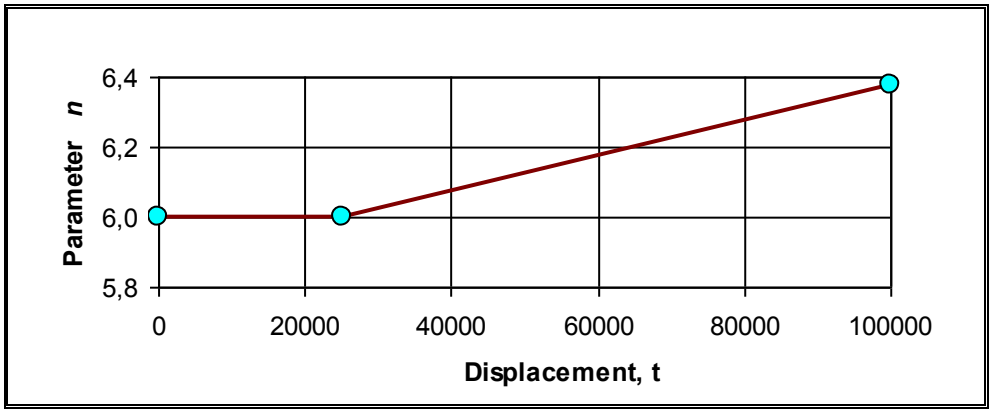

Figure 3.1. Change of exponent parameter taking into account the effect of displacement on icebreaking capability of large-capacity ships

Calculation of icebreaking capability and achievable speeds for large-capacity ships with bulbs in the forebody has certain specific features. The principal shortcoming not permitting to use formula (3.1) for the determination of the icebreaking capability of non-traditional ships is that none of the parameters takes into account the presence of bulb. Under fully loaded conditions the bulb is located below the waterline, beyond the zone of direct interaction with ice, but affects a lot the character of breaking and removal of ice. In ballast the bulb comes into direct contact with ice, but angles characterizing the hull shape at the point of impact fall outside the applicability of the formula.

These particular features were taken into account in the modified formula permitting to estimate icebreaking capability of non-ice ships with a deadweight within 40000-160000 t in compact ice [9].

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In the derivation of this new formula use was made of the results of model tests in the ice tank of cargo ships with a bulbous forward end, as well as of the results of the experimental voyage of the Aframax tanker in the Tatar Strait in 2002.

Creation of the calculation dependence was preceded by the analysis of structure of existing formulas and by the selection of parameters the effect of which on icebreaking capability is especially appreciable. In the course of the analysis it was established that such parameters are as follows: propeller thrust $\boldsymbol{P_e}$, displacement $\boldsymbol{D}$ and breadth of ship $\boldsymbol{B}$, parameters of draft under loaded and ballast conditions (average draft $\boldsymbol{T}$, forward draft $\boldsymbol{T_f}$, trim angle $\boldsymbol{\psi}$), bulb characteristic (angle $\boldsymbol{\varphi}$ between tangent at contact point and basic plane).

As a result, a formula was obtained for the calculation of icebreaking capability of cargo ships with bulb in the forebody:

$$h_0 = k_b \left(\frac{P_e}{B}\right)^{4/5} \left(\frac{T_f}{T}\right)^{-1/2} D^{1/m} \left[\mathrm{Ln}(\varphi_b + \psi) - 3.2\right]^{-1/3} \qquad (3.4)$$

where: $\boldsymbol{k_b}$ – coefficient taking into account dimension of values,

$\boldsymbol{m}$ – exponent parameter.

3.2. Calculation of ship movement speed in ice

3.2.1 Attainable speed

Among the icebreaking capability h0 the ship movement in level compact and broken ice is characterized by a dependence of speed of the movement of ship V on ice thickness h propulsion unit operating at full power; i.e. attainable ship speed while running in ice of different thickness. Thus $V = f(h)$.

To get this dependence for navigation in the level ice conditions the assumption is made that attainable speed V is a linear function of ice thickness h. Then, with given Vo icebreaking capability i.e. the pair {V ; h_0}= {2; h_0 }, and the speed of a ship in open water, i.e. the pair [V ; h}= { Vo ; 0 }, we get two points for the straight line.

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$$V = f(h, V_0, h_0). \tag{3.5}$$

Both values $\boldsymbol{Vo}$ and $\boldsymbol{h_o}$ for ships navigating in ice are specification characteristics which are indicated in the ship specification. For a ship running in the channel behind icebreaker the coefficient $\boldsymbol{k_c}$ is introduced in the formula in order to account for the influence of the relative breadth $\boldsymbol{b = B_s / B_{ib}}$ of a ship ($\boldsymbol{B_s}$ is the breadth of a ship and $\boldsymbol{B_{ib}}$ is the breadth of the assisting icebreaker) .Then the formula (3.5) will be as follows [6], [7]

$$V = V_0 \left(1 - k_c \frac{V_0 - 2}{V_0} \frac{h}{h_0}\right). \tag{3.6}$$

3.2.2 Equivalent ice thickness

By calculations of ship ice performance the main characteristic of the ice cover is the equivalent ice thickness $\boldsymbol{h}$ taking account of actual thickness $\boldsymbol{h}_f$, hummocking $\Delta\boldsymbol{h}_H$ and snow cover $\Delta\boldsymbol{h}_s$:

$$\boldsymbol{h} = \boldsymbol{h}_f + \Delta\boldsymbol{h}_H + \Delta\boldsymbol{h}_s \tag{3.7}$$

Items responsible for the ice hummocking $\boldsymbol{t}$ **(**in tenths**)** and depth of the snow cover $\boldsymbol{h}_s$ (in meters) are determined by the formulas [8]:

$$\Delta\boldsymbol{h}_H = 0.25\, \boldsymbol{t}\, \boldsymbol{h}_f \tag{3.8}$$

$$\Delta\boldsymbol{h}_s = \boldsymbol{k}_s\, \boldsymbol{h}_s \tag{3.9}$$

$$\boldsymbol{k}_s = 0.50 \text{ at } \boldsymbol{h}_s \geq 0.5 \text{ m and} \quad \boldsymbol{k}_s = 0.33 \text{ at } \boldsymbol{h}_s < 0.5 \text{ m.} \tag{3.10}$$

3.2.3. State of hull shell plating

Additional factor to be taken into account in the assessment of ship's ice propulsion is the state of hull shell plating and accordingly the hull/ice dynamic friction coefficient. As a ship becomes older, roughness of plating increases and speed at the same power and thrust characteristics of propeller is lowered. Investigations of this phenomenon on ships navigating in ice show that after 4-5 years of operation plating/ice friction coefficient may increase approximately by 50 %.

All calculations of propulsion for new ships are carried out under assumption that hull is freshly painted and friction coefficient does not exceed specification values. Later, speed losses due to the destruction of paint coating and the increase of hull roughness with time are estimated.

3.2.4. Impact of ice compacting upon ship ice propulsion

Along with ice thickness, concentration and hummocking, the ice compacting considerably affects the ship ice propulsion. The experience shows that compacting caused by the drift of ice floes is not a less significant factor than thickness and concentration of ice. Under conditions of the intense growth and formation of young ice the compacting in many cases determines the possibility of navigation and safety of ships. The ice compacting causes particular difficulties to the cargo ships following icebreaker as the hull lines of ships are less suitable for the operation in ice. Presence of the parallel middlebody most unfavourably affects the movement during compacting.

Full-scale observations of the icebreaker escorting allowed getting dependences of relative speeds of movement on the ice thickness and intensity of compacting. Application of these dependencies to large ships may give preliminary insight into the speed losses which will occur during compacting. Figure 3.2 shows (for example) the anticipated reduction of speed resulting from compacting of points 1-2 of tanker with a deadweight of about 100 000 t in channel following two icebreakers.

Application of calculation procedures taking into account the above factors allows to soundly handle the determination of speeds of different deadweight.

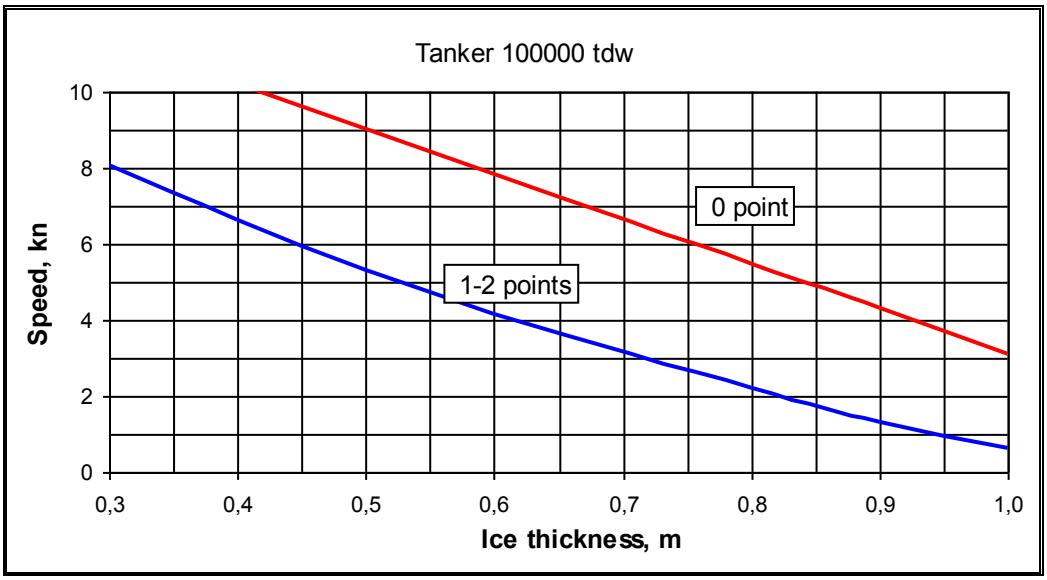

Figure 3.2. Speed of tanker escorted by two icebreakers through ice of different thicknesses when there is no compacting and with compacting of points 1-2

By estimation of the impact of the ice compacting upon the speed of the large ship movement a combination of two methods [4] was used. This is based on calculation of additional resistance R_{ic} while action of transverse forces onto shipside.

$$R_{ic} = 2\, f_d \cdot \sigma_{ic} \cdot h \cdot L_{el}\ , \text{kN} \qquad (3.11)$$

where: $\boldsymbol{f_d}$ – coefficient of dynamic ice friction,

$\boldsymbol{\sigma_{ic}}$ – normal stress in ice cover by ice compacting, кPa,

$\boldsymbol{h}$ – equivalent ice thickness,эквивалентная толщина льда,

$\boldsymbol{L_{el}}$ – equivalent parallel body length, m.

The formula (3.11) is applicable in case of independent forward run in ice of icebreaker or icebreaking merchant ship. For a ship under icebreaking guiding the formula (3.11) is applicable only in case when the channel edges close up to each other to an extent that ship's sides interact with floe.

The value $R_{сж}$ is used for computation of ice performance relative characteristics by action of ice compacting of different intencity through computing simulation of large vessels. As such a characteristic the ratio $\boldsymbol{K_{ic}} = \boldsymbol{V_c} / \boldsymbol{V_0}$ is used, where $\boldsymbol{V_c}$ is the minimal speed of ship movement at compacting of different intensity, and Vo is the speed of ship in open water.

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4. PRINCIPAL METHODICAL PROPOSALS OF COMPUTING THE SAFE SPEEDS

Safety of the navigation of ships in ice ensured by the strength of hull and propeller steering system is regulated by classification societies assigning to ship an appropriate ice category in dependence on operational conditions.

At the same time, in practice, taking into account the variability of ice conditions within one basin as well as insufficient reliability of ice forecasts, ships of low ice categories may get into heavier conditions than those admissible for a given category of ice strengthening. However safety of the navigation in ice of such ship can be improved and practically brought to the required level, if navigators are guided by the recommendations regulating necessary speed limits. These recommendations consider structural and operational characteristics of ship, ice conditions en route and availability of the icebreaker escorting. If the examination based on the calculation of ice strength shows that ship under certain restrictions is capable of operating in such ice conditions her icebreaker escorting is permitted at lower speeds ensuring the required safety of navigation in ice.

Restricted, that is safe speeds of the escorting of ships are determined by calculation in dependence on the specific structure of ship, her shape, displacement and shaft power. Results of the calculation being graphic dependencies of the admissible by strength speeds on ice conditions and parameters of the icebreaker escorting (width of channel, form and concentration of broken ice in the channel) are presented in the form of document regulating safe speeds of the movement of ship in ice.

The method of critical (ultimate) strength is taken as the basis for calculation of safe ship speed by navigating in ice. This method enables to relate (match) correctly the requirements to both hull plating and framing with requirements to strength and to stiffness of the supporting contour in the process of bumping the ship and ice.

Procedure of the calculation of safe speeds of the movement of ship in ice involves three main stages. At the first stage, ice loads on the hull plating are calculated; then the carrying capacity of side plating in the area of the application of ice loads is determined and finally, by the combination of the obtained results, curves of safe speeds are constructed. Calculations, as a rule, are performed for several forward end areas to obtain the most hazardous section.

4.1. Calculation of ice loads acting on the ship side plate

In the solution of ice loads determination problem, as input date are the following parameters:

- intention of ship;
- characteristics of ice conditions;
- parameters of ship's hull and machinery (displacement, hull form, shaft power);
- hull strength characteristics in the zone of ice loading impact.

At the ship's side/ice contact, dynamic ice edge crushing by side occurs (Figure 4.1). Depending on ice thickness and hull lines the ice edge may be broken up from bending or crushing. In the destruction of ice edge from bending maximum contact force $\mathbf{P}_{\beta\_max}$ from the condition of ice cover destruction is determined by the following formula:

$$\mathbf{P}_{\beta\_\max} = \mathbf{k} \cdot \sigma_{\mathbf{p}} \cdot \mathbf{h}^2 . \qquad (4.1)$$

where: P_{β_max} – vertical component of the total force;

k – numeric coefficient;

σ_p – ice bending strength;

h – ice thickness.

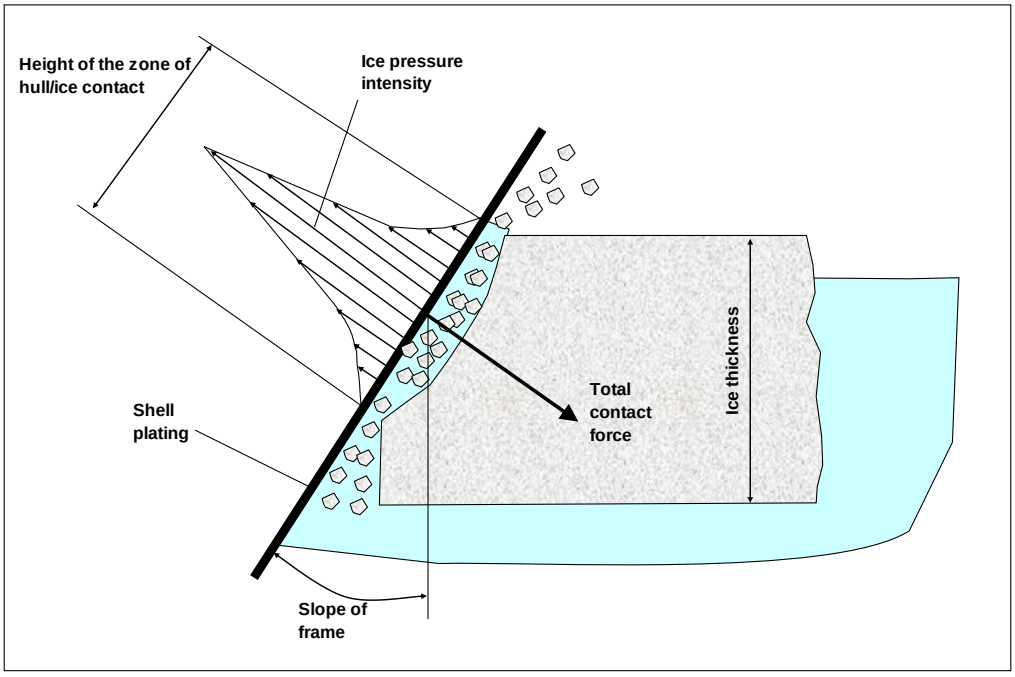

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Figure 4.1. Model for determining of ice loads at impacts with an ice floe

For the determination of loads arising at the ship/ice impact, values of added masses (brought to the point of impact) are preliminarily calculated.

According to the hydrodynamic model of the ship's hull collision with a floating ice floe [10,11], corresponding values of the total contact force ***P***, height of the zone of hull/ice contact $\boldsymbol{b_H}$ and ice pressure intensity ***p*** are determined by formulas:

$$\mathbf{P} = 0.88\ \mathbf{V}_0^{17/12}\ \mathbf{M}^{2/3}\ (2\mathbf{r})^{1/6}\ \mathbf{a}_p^{2/5}\ \mathbf{F}_P\ , \qquad (4.2)$$

$$\mathbf{b}_H = 1.25\ \mathbf{V}_0^{7/12}\ \mathbf{M}^{1/3}\ (2\mathbf{r})^{1/4}\ \mathbf{a}_p^{-2/5}\ \mathbf{F}_b\ , \qquad (4.3)$$

$$\mathbf{p} = 0.61\ \mathbf{V}_0^{13/24}\ \mathbf{M}^{1/6}\ (2\mathbf{r})^{-1/12}\ \mathbf{a}_p\ \mathbf{F}_p\ , \qquad (4.4)$$

where: $\mathbf{V}_0$ – ship's speed at the moment of impact;

M, ***r*** – ship's mass and curvature radius of the ice floe;

$\boldsymbol{a}_p$ – ice crushing strength factor;

$\boldsymbol{F_P}$, $\boldsymbol{F_b}$, $\boldsymbol{F}_p$ – shape functions depending on angles between tangents to frames $\boldsymbol{\beta}$ and waterlines $\boldsymbol{\alpha}$ and the central plane.

As an example, Figure 4.2 shows the results of the calculation of ice loads for two different sections of a large cargo ship.

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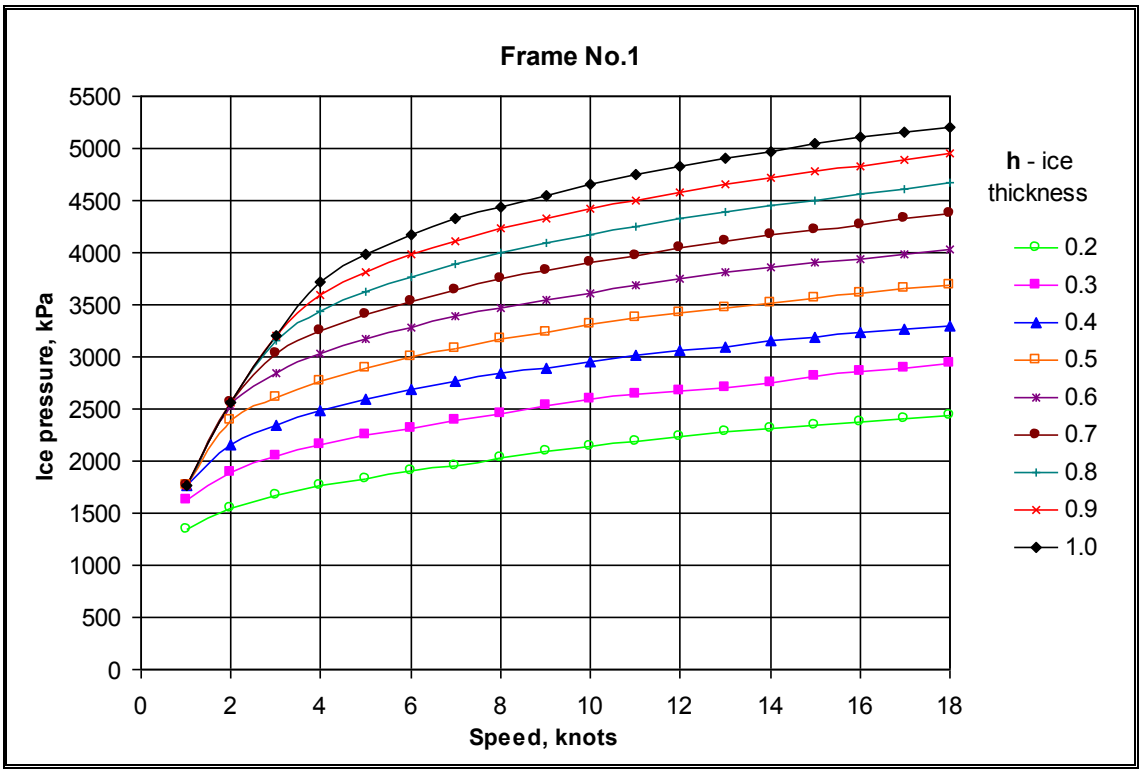
a)



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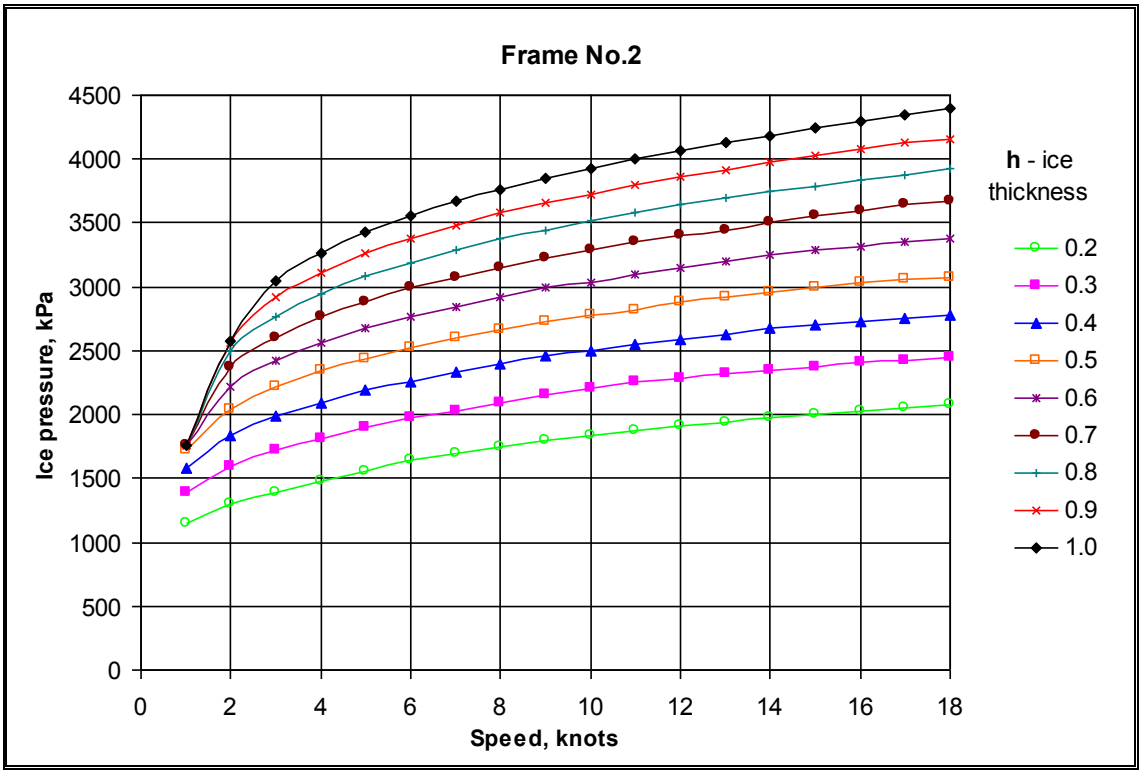

Figure 4.2. Ice pressure depending on ship's speed and ice thickness at ice floe impact against Frames Nos.1 (a) and 2 (b) cross sections

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4.2. Determination of bearing strength (carrying power) of the side plating

Ice load may be applied onto an arbitrary zone of contact. If this contact zone is presented as a rectangular, strength of the side shell plating is characterized by three parameters: ice pressure $\boldsymbol{p}$, length $\boldsymbol{l}$ and height (breadth) $\boldsymbol{b_H}$ of the contact zone, that is

$$p = p_{max}(b_H, l) \ , \qquad (4.5)$$

where $\boldsymbol{p_{max}}$ – ultimate load by a selected strength criterion.

As a strength criterion, ultimate strength criterion (taking into account plastic deformation) was selected (Figure 4.3). Curves 1 and 2 on this figure divide the whole ice load area into three sections:

I – high plastic deformations;

II – elastic-plastic deformations (fiber plasticity);

III – non-damageability (elastic work of structures).

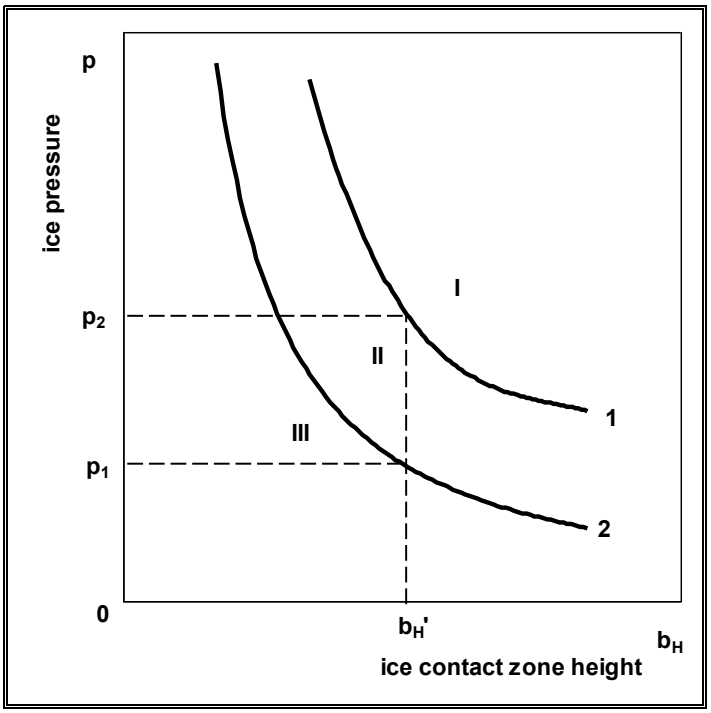

Figure 4.3. Ice load curves: 1 – ultimate strength with plastic deformation; 2 – fiber yield condition

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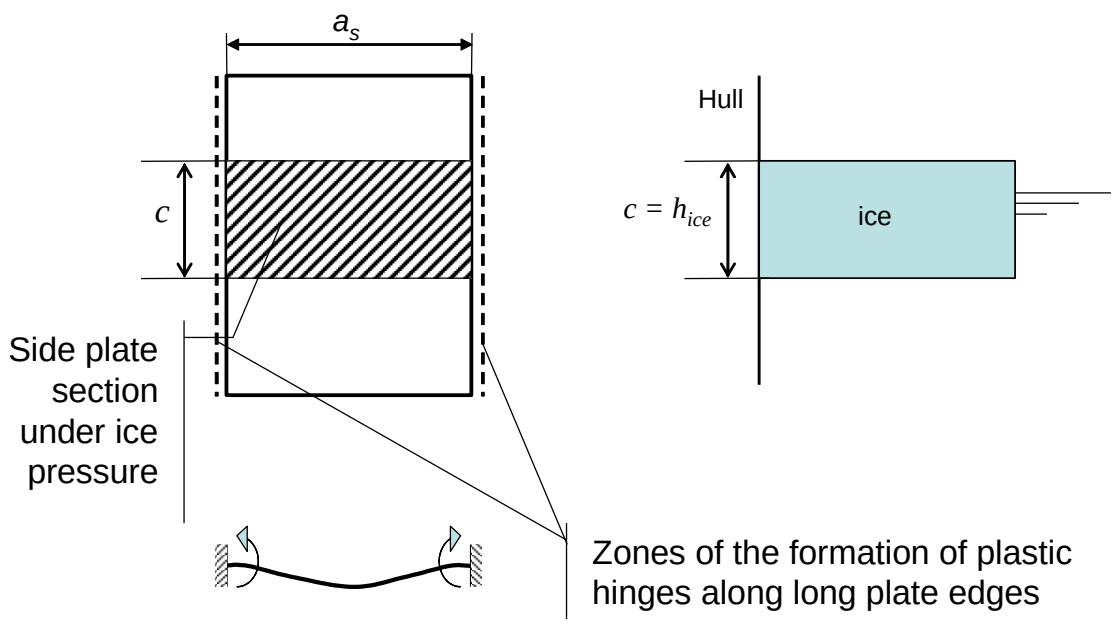
In accordance with the methodology adopted by CNIIMF when developing Ice Certificates, maximum ship's hull load-carrying capacity corresponds to the emergence of two plastic hinges in the supporting sections located on long edges of a shell plate.

Analysis of the ice damage of ships as well as former numerous calculations of the behaviour of ship's hull structure under the impact of ice load show that regions of the plastic deformation start to develop first in the shell plating and only then pass on to the framing. Adopted criterion of the admissible elastic-plastic state of the hull shell plating corresponds with the norms of admissible strains while detecting hull flaws of sea-going ships ("Methodology of the flaw detection of hulls of sea-going ships").

Scheme of the calculation of loads on a plate for the transverse framing is presented in Figure 4.4, for the longitudinal framing – in Figure 4.5. Calculations are based on the elasto-plastic solution of bending of a locally loaded plate.



a_s – transversal frame; ***c*** – height of the load application zone

Figure 4.4. Calculation scheme of a plate in the transversal framing system

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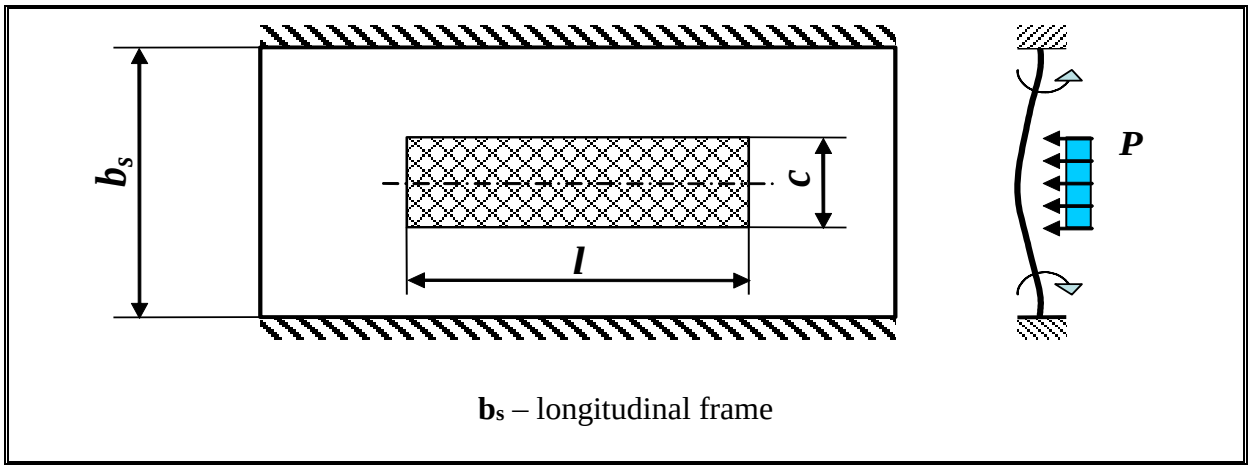

Figure 4.5. Calculation scheme of a plate in the longitudinal framing system

Calculations are made for several fore frames, for four ones, as a rule, located in the zone of anticipated ice impact. Figure 4.6 shows an example of the calculation of ultimate loads for a large cargo ship.

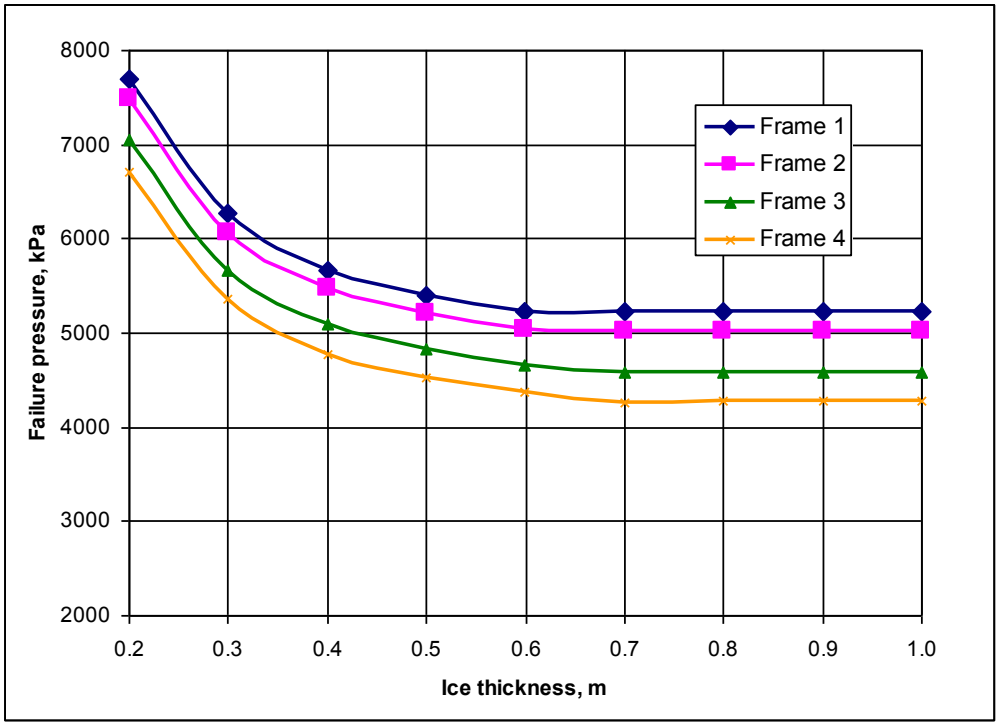

Figure 4.6. Ultimate failure loads upon hull shell plates depending on area and ice thickness

Combination of the obtained values of ice loads (Figure 4.2) depending on ice thickness and speed of the collision of ship with ice with ultimate loads shell plates (Figure 4.6) permits to estimate safe speeds of ship moving in ice of different thickness (Figure 4.7). Safe speed zone is located below the calculated curve shown in the figure.

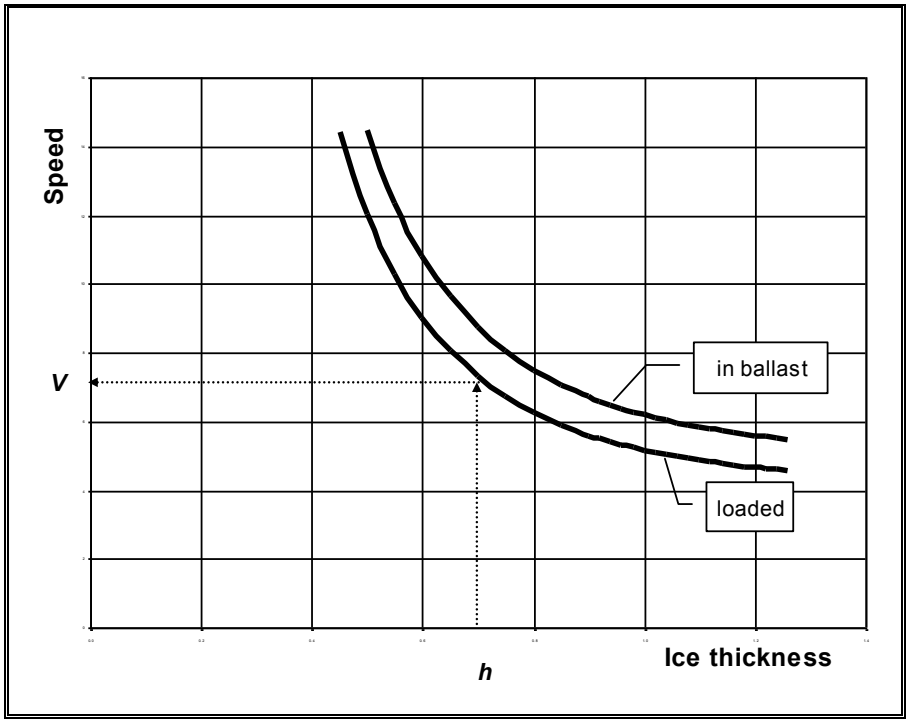

Figure 4.7. Diagram illustrating the procedure of the determination of safe speed in ice versus a given thickness

5. METHODICAL BASES OF DETERMINATION THE ADMISSIBLE SPEEDS

After obtaining calculation dependences describing ice propulsion and ice strength of ship the Ice Certificate methodology provides for the procedure of the determination of admissible speeds. Admissible speed $\boldsymbol{V}_{lim}$ is maximum speed of the ship movement under certain ice conditions corresponding to either safe $\boldsymbol{V}_s$ or attainable speed $\boldsymbol{V}_a$ whichever is lower.

This condition is mathematically expressed in the following way:

$$V_{\lim}(h) = \min\{V_a(h),\ V_s(h)\}. \tag{5.1}$$

As a result of the fulfillment of this logical operation, admissible speed $\boldsymbol{V}_{lim}$ for any ice thickness value $\boldsymbol{h}$ is uniquely determined.

Figure 5.1 shows the diagram illustrating the process.

The figure represents three zones each having its particular features:

Zone 1 – area of speeds physically inaccessible for ship; sailing at such speeds is impossible at existing power level, propulsion system parameters and hull shape.

Zone 2 – this area of speeds is accessible for ship by her technical abilities; however navigation at such speeds is of higher hazard. Considerable external loads due to hull/ice interaction could result in residual deformation or failure of hull structures.

Zone 3 – this is area of operational speeds the sailing at which is safe for ship. The ice conditions characterized by an equivalent ice thickness from h1 to h2 are of operational hazard which can be avoided reducing speed of the movement.

Consequently, red line ABCDE in Figure 5.1 characterizes the ice propulsion of ship at admissible speeds during her movement along the channel behind icebreaker.

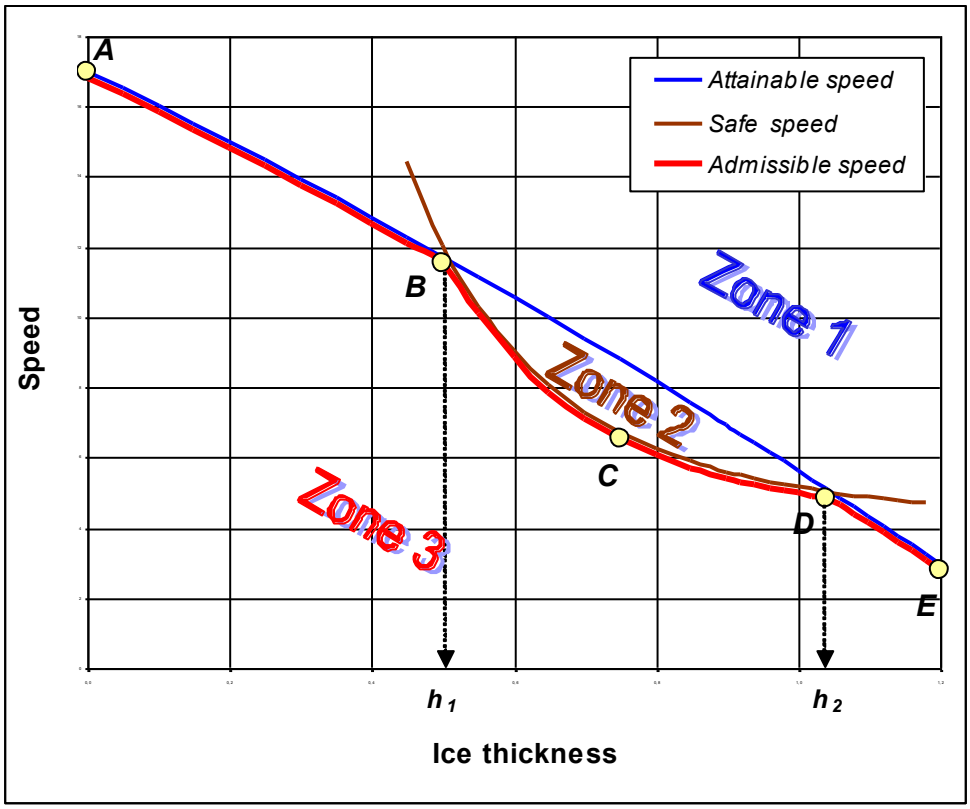

Figure 5.1. Diagram illustrating the procedure of the determination of admissible speed

As an illustration, Figure 5.2 represents a typical diagram for the determination of achievable speeds of a ship with deadweight of about 75 000 t.

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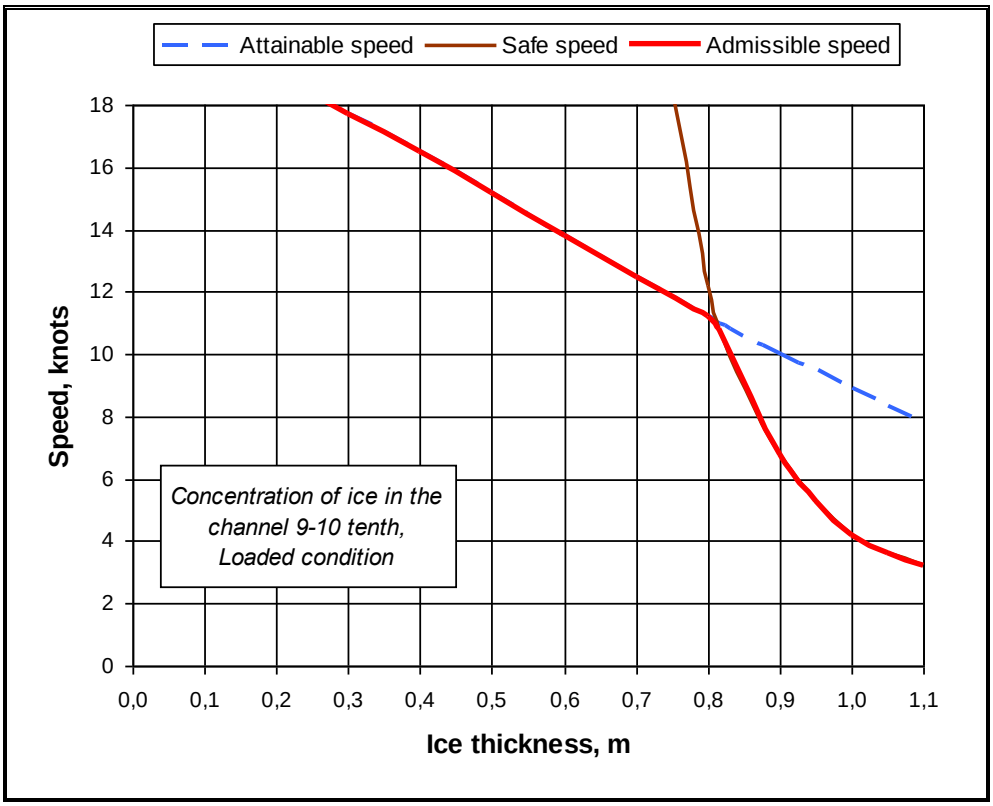

Figure 5.2. Speed restriction of 75000 tdw ship during the movement under loaded condition behind icebreaker along the channel with an ice concentration of 9-10 tenth

Blue line defines the upper limit of the zone of admissible speeds corresponding to a maximum possible speed value proceeding from the ship's running qualities. Boundaries of the zone of safe speeds due to the forward end strength is characterized by brown line. Admissible speed is defines as a minimum one out of safe and attainable speeds is shown in the figure by enveloping red line.

In some cases the relationships characterizing attainable and safe speeds may have no points of intersection and then admissible speed is entirely defined by the ship's propulsion (depending on power).

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6. CALCULATION OF MINIMAL SAFE DISTANCE

Safe distance is determined for the event of emergency braking of ship with the reversing of propeller (“crash stop”) during movement in the channel behind icebreaker, when a suddenly emerged ice obstacle results in sharp braking and stopping of a leading icebreaker. The ship should be capable of quenching inertia and stopping having avoided collision with icebreaker (Figure 6.1).

Figure 6.1. Collision of ships in convoy

At the same time, unjustified increase of the distance between ship and icebreaker leads to a reduction of escorting speed in ice due to a narrowing of the channel possible under conditions of compression, greater fullness of the channel with broken ice and accordingly the increase of ice resistance. Therefore the distance close to a safe one is optimal for the escorting. Minimum safe distance depends on an initial speed of ship, its loading (displacement), hull lines, time of reversing and ice conditions.

In the absence of the compression of ice when channel retains its properties during the long period of time, ships move at a sufficient distance from the icebreaker. In the presence of

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compression when the channel width decreases in time escorting distance may be reduced this as a rule been directly determined by navigators depending on ice conditions.

There are two approaches for the determination of safe distances – taking into account reversing of main engine and disregarding the reversing. In the practice of the operation of ice ships the second approach i.e. inertia stopping with a stopped propeller is almost never used.

In general case, the equation of a movement of ship in a channel of ice cake behind the icebreaker can be presented in a differential way:

$$(1+k)\frac{D}{g}\frac{dv}{dt} = -R - P_e, \qquad (6.1)$$

where: **D** – displacement of a vessel;

k – added water mass coefficient;

g = 9.81 m/s^2 – acceleration of gravity;

v – ship's speed;

R – total resistance to ship motion;

$\boldsymbol{P_e}$ – propeller thrust.

When calculating the stopping distance of ship with braking under the action of propeller three stages of movement are considered.

The first stage – movement for time needed for execution of "STOP" command (time from the moment of receiving the command until the stoppage of engine usually is about 5 s). Prior that stage the ship's movement was steady and took place under the action of propeller thrust $\boldsymbol{P_e}$ which was balanced by the resistance force of ship ***R***. During this period the ship's speed may be considered as constant and equal to steady speed of movement. The distance passed by ship during the first stage is determined as a product of time by steady movement of ship before reversing.

The second stage – movement of ship from the moment of engine shutdown. At this stage quick drop of RPM occurs down to the "free rotation" mode when propeller runs under the effect of incident flow as a water turbine. At the very beginning of the second stage due to the kinetic energy of the rotating engine masses the propeller still generates some positive

thrust however it rapidly decreases to zero. Therefore when calculating characteristics of the movement of ship it is assumed at this stage that propeller thrust is equal to zero, and speed reduction takes place under the effect of the resistance to the ship's movement which is a sum of water and ice resistance.

The third stage of the ship's stopping starts from the moment of the beginning of the engine reversing and lasts until the full stop of ship under the effect of the resistance of water and ice and the braking force of propeller running backward. Because of the lack of quite reliable data for the determination of thrust deduction at reversing it is assumed that propeller thrust during some period reaches a value equal to the bollard pull mode of astern movement and remains constant until full stop of ship. The analysis of the results of full-scale trials proves fairly good convergence with calculated values of speed and distance passed under such assumption.

The value of ice resistance can be obtained by the method used for arbitrary speed of ship in a channel filled with ice cake. At the same time, considering the unsteady character of movement of ship hypothesis of quasi-stationarity is taken in accordance with which the ice resistance is calculated at each moment.

As a basis of calculation of ice resistance the formula by Ryvlin for ice cake [12] was used and corrected by the results of full-scale trials of tanker "Primorye" in Tatar Strait. Resulting formula could be written down as follows:

$$R = k_1\left(\frac{B}{2}\right)^2 h\left(1 + 2 f_d \alpha_{bow}\frac{L}{B}\right) + k_2 h^{1,5}\left(f_d + \alpha_{bow} tg\,\alpha'_1\right)Fr + k_3 h^{1,5} L \cdot tg^2\alpha'_1 \cdot Fr^2, \qquad (6.2)$$

where: $\boldsymbol{h}$ – thickness of ice cake, m;

$\boldsymbol{f_d}$ – ice friction coefficient;

$\boldsymbol{L}$ – ship length, m;

$\boldsymbol{B}$ – ship breadth, m;

$\boldsymbol{\alpha_{bow}}$ – bow area water plane coefficient;

$\boldsymbol{\alpha_1}$ – waterline entrance angle at frame No.1;

$\mathbf{Fr} = \dfrac{\mathbf{v}}{\sqrt{\mathbf{gL}}}$ – relative speed;

$\boldsymbol{v}$ – ship's speed, m/s;

k_1, k_2, k_3 – non-dimensional empiric coefficients depending on ice concentration and relative channel width.

Since the water resistance to ship's movement is also proportional to the ship's speed one can calculate time and stopping distance at any set speed, thickness and concentration of ice in the channel.

As the open water zone from running propellers being formed directly behind stern of icebreaker, the margin of distance to icebreaker after the stop taken equal to about the length of ship is added to the calculated stopping distance of ship.

Figure 6.2 shows a representative diagram from which the safe distance between ship and icebreaker is determined.

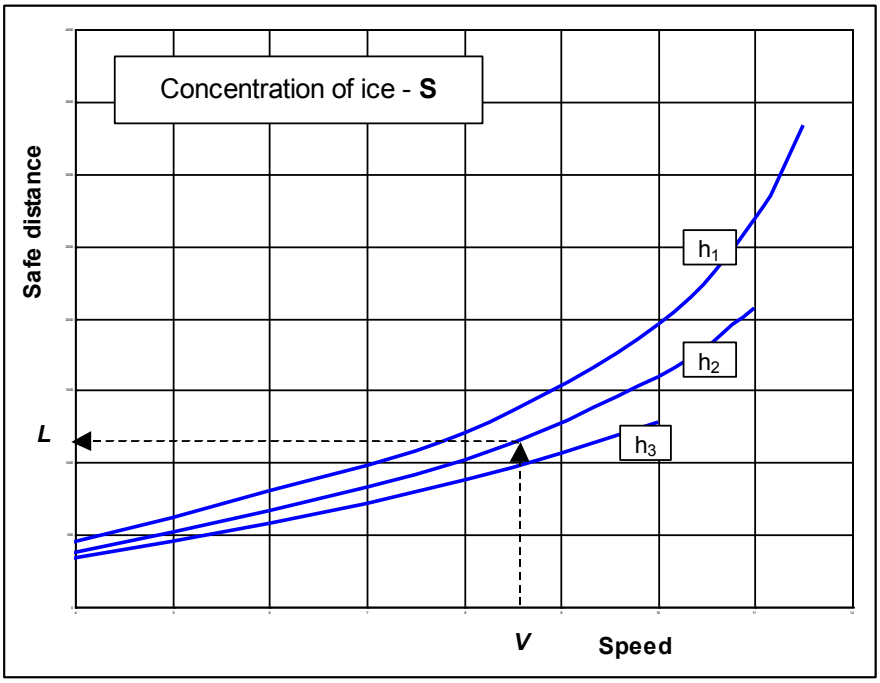

Figure 6.2. Diagram illustrating the procedure of the determination of safe distance (L) when ship is moving at a speed (V) in the channel behind icebreaker through ice with thickness (h2) and ice concentration (S)

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7. CALCULATION RESULTS

The list of generic ships together with their characteristics were given in table in the table 2.6 of this report. The obtained results of calculations of the ice performance of these generic ships are given in Figures 7.1-7.5 and in tables 7.1 - 7.3.

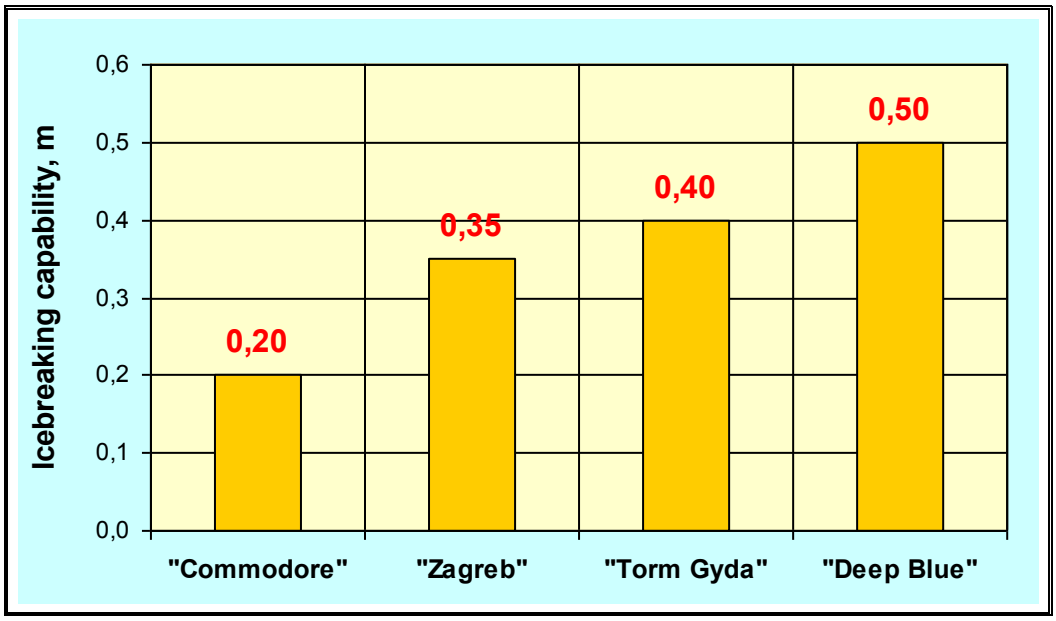

Figure 7.1. Calculated values of icebreaking capability

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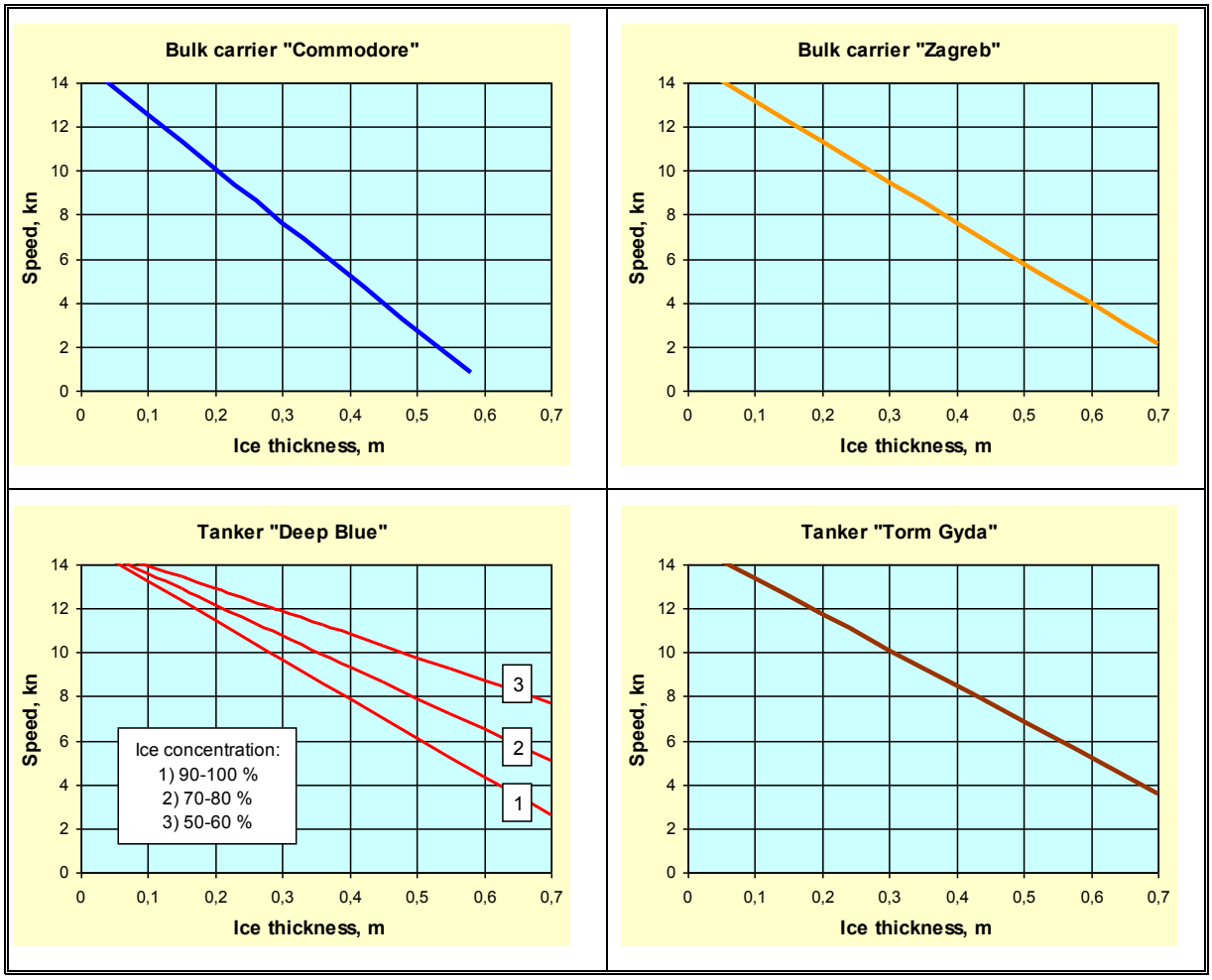

Figure 7.2. Calculated attainable speeds for laden ships while moving through the ice channel made in ice of different thickness

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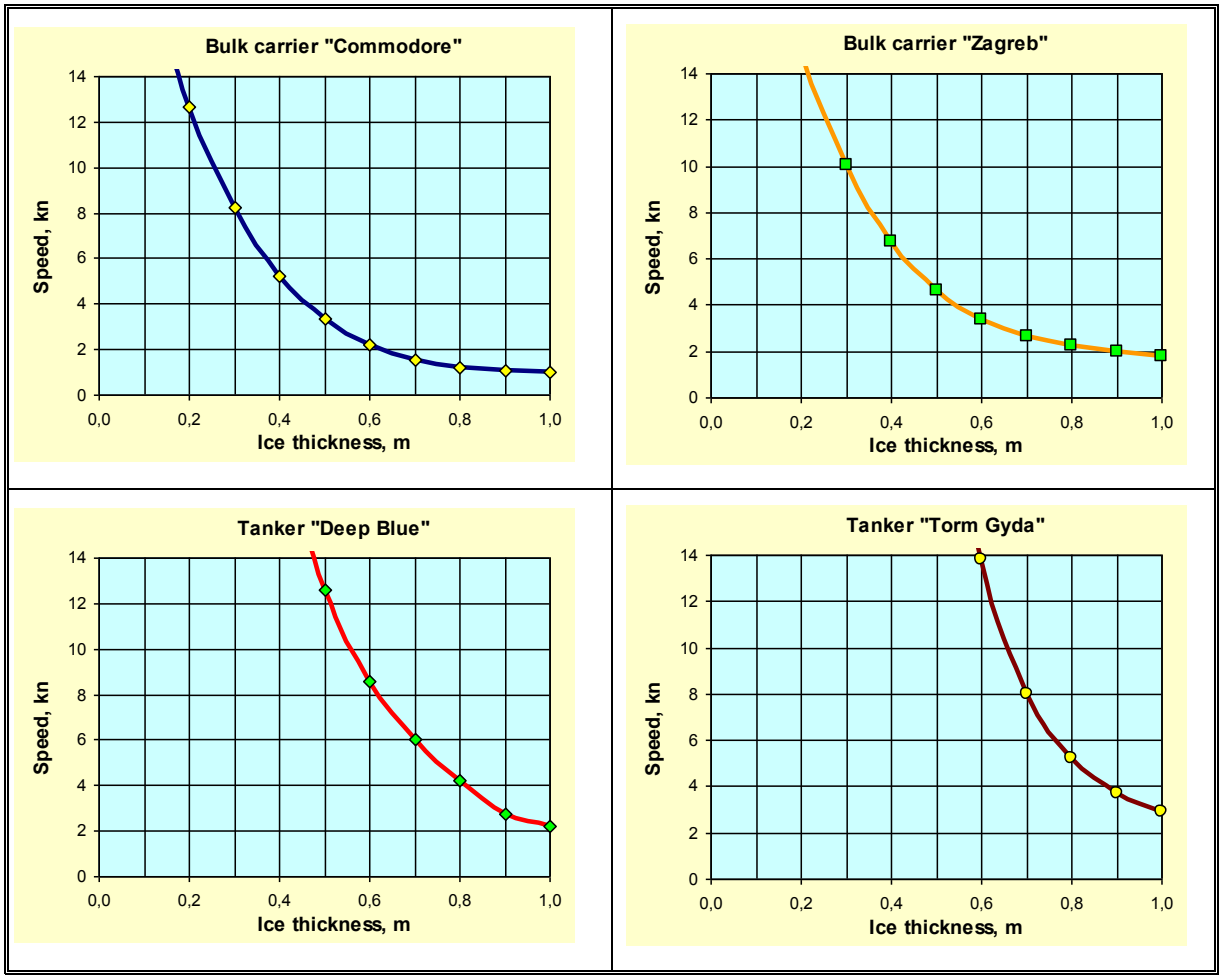

Figure 7.3. Calculated safe speeds of laden ships while moving through ice channel made in ice of different thickness

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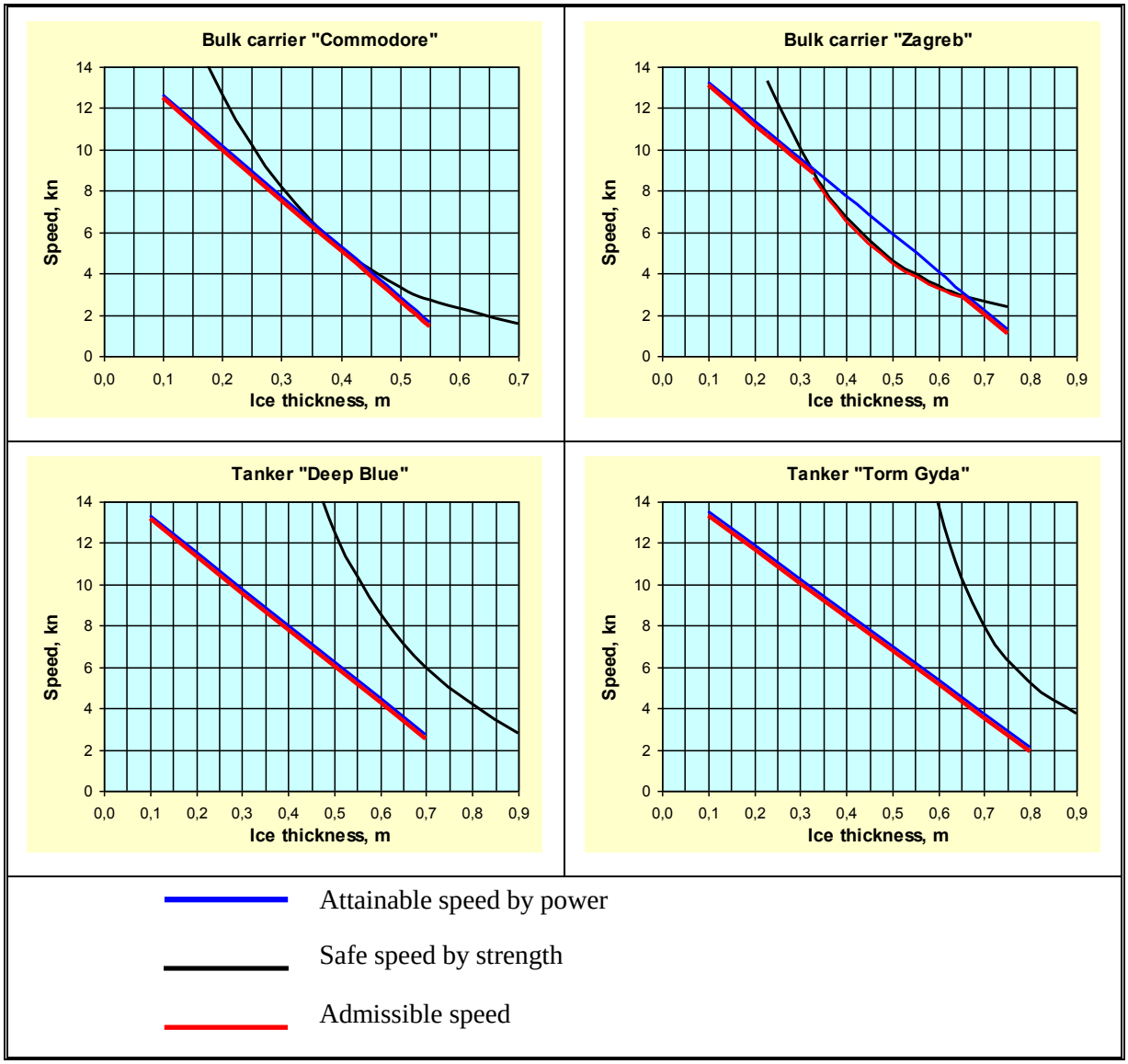

Figure 7.4. Calculated admissible speeds of laden ships while moving through ice channel made in ice of different thickness

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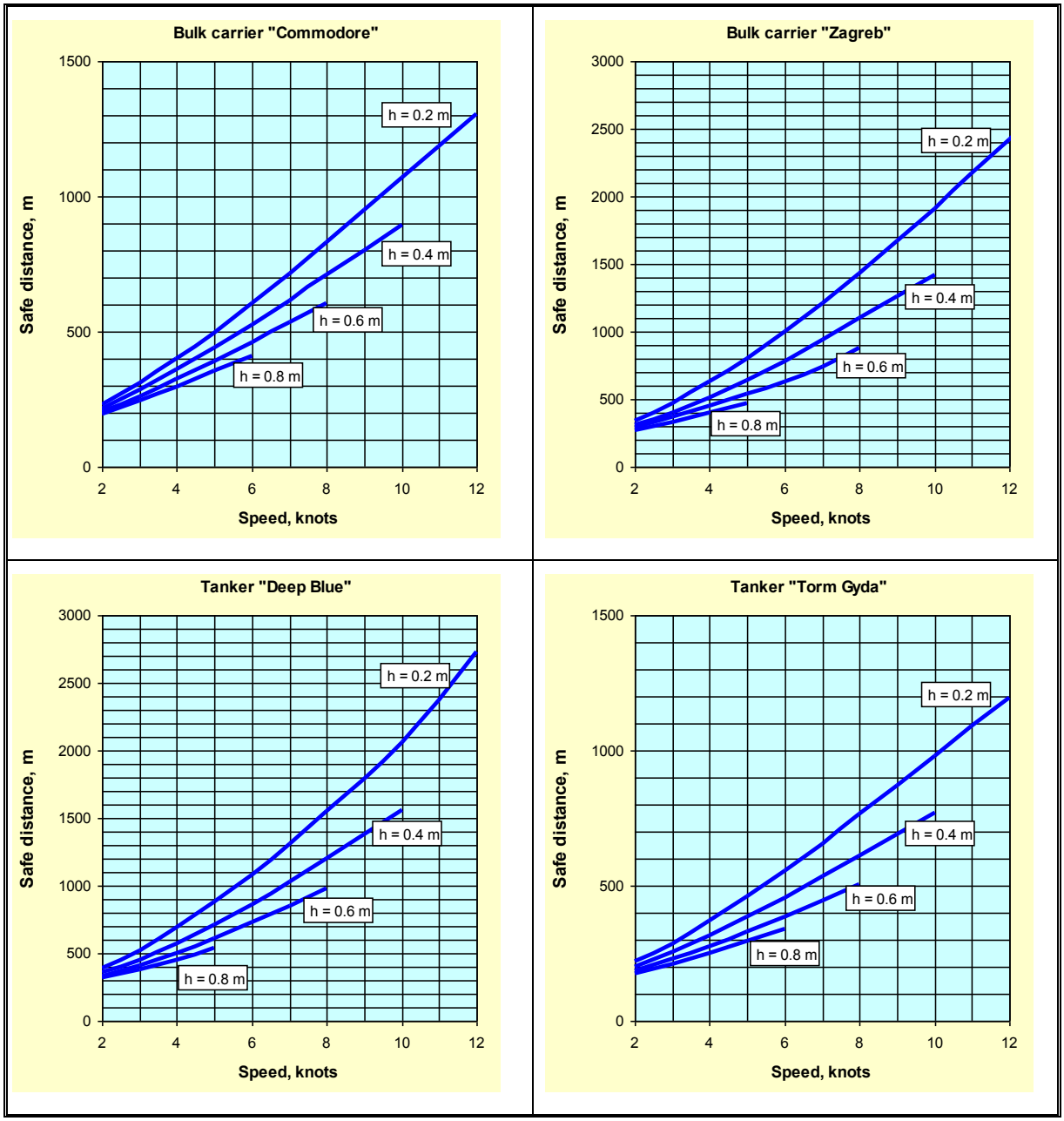

Figure 7.5. Calculated safe distances of laden ships while moving through ice channel made in ice of different thickness

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Table 7.1.Calculated attainable, safe and admissible speeds in ice (tabled Figures 7.2, 7.3, and 7.4)

Ice thickness, m	Bulk carrier "Commodore"	Bulk carrier "Zagreb"	Tanker "Deep Blue"	Tanker "Torm Gyda"
Calculated attainable speeds				
0.2	10.1	11.3	11.5	11.7
0.3	7.7	9.5	9.7	10.1
0.4	5.2	7.6	7.9	8.5
0.5	2.8	5.8	6.1	6.8
0.6	–	4.0	4.4	5.2
0.7	–	2.1	2.6	3.6
Calculated safe speeds				
0.2	12.7	15.0	–	–
0.3	8.2	10.1	–	–
0.4	5.2	6.7	19.0	–
0.5	3.3	4.6	12.6	–
0.6	2.2	3.4	8.5	13.8
0.7	1.6	2.6	6.0	8.0
0.8	1.2	2.2	4.2	5.2
0.9	1.1	2.0	2.8	3.7
1.0	1.0	1.8	2.2	2.9
Calculated admissible speeds				
0.2	10.1	11.3	11.5	11.7
0.3	7.7	9.5	9.7	10.1
0.4	5.2	6.7	7.9	8.5
0.5	2.8	4.6	6.1	6.8
0.6	–	3.4	4.4	5.2
0.7	–	2.1	2.6	3.6

Table 7.2. Calculated attainable speeds in ice of different concentrations for tanker "Deep Blue" (tabled part of Figure 7.2)

Ice thickness, m	Ice concentration		
	50-60 %	70-80 %	90-100 %
0.2	12.9	12.2	11.5
0.3	11.9	10.7	9.7
0.4	10.8	9.3	7.9
0.5	9.8	7.9	6.1
0.6	8.7	6.5	4.4
0.7	7.7	5.1	2.6

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Table 7.3. Calculated safe distances (tabled Figure 7.5)

Ice thickness, m	Speed, kn					
	2	4	6	8	10	12
Bulk carrier "Commodore"						
0.2	230	310	400	500	605	715
0.4	215	285	360	440	525	615
0.6	205	260	325	390	460	535
0.8	195	245	300	350	410	–
Bulk carrier "Zagreb"						
0.2	340	470	630	800	1000	1210
0.4	310	400	510	640	785	940
0.6	290	375	455	540	630	740
0.8	270	330	400	470	–	–
Tanker "Deep Blue"						
0.2	395	525	690	875	1085	1310
0.4	355	455	575	710	865	1030
0.6	330	410	500	610	725	850
0.8	315	380	455	540	–	–
Tanker "Torm Gyda"						
0.2	220	290	370	460	555	660
0.4	200	255	315	385	455	535
0.6	185	230	275	330	390	445
0.8	175	210	250	295	340	–

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CONCLUSION

1. It was foreseen in the WP2 of the project to solve the Task 2.3 “A model for ship performance in ice”. In other words, one part of the WP2 should be focused on the development of advanced models for ship performance in different ice conditions.
2. As a result of study on solving this task, algorithms, diagrams and calculation procedures were developed for the following parameters of ship ice performance:
   - ship icebreaking capability,
   - attainable speeds at the full engine power of a ship in different ice conditions,
   - safe speeds (from the ship hull strength point of view) of ship movement in ice of different thickness,
   - admissible speed curves as minimal values of attainable and safe speeds,
   - minimal safe distance between vessels in caravan.
3. Icebreaking capability being a principal operation parameter characterizes the ice propulsion performances of a ship. This is expressed as the maximal thickness of level compact ice broken through while moving the ship at a minimum steady speed of about 2 knots. This parameter does not characterize ice propulsion in the whole range of the operational ice thickness.

   The empiric formulae were derived within the frame of the Task 2.3 for calculation the icebreaking capability for ships of deadweight up to 160 thousand tons (including ships with the bulbous bow) by navigating in compact ice.
4. For the estimation of the ship ice performance in the ice thickness range from 0 to h_o a procedure was elaborated for determination a function “the attainable speed versus the ice thickness” with a ship propulsion unit operating at the full power.
5. The procedure of the safe speeds calculation for the ship movement in ice (from the ship hull strength point of view) was worked out. This procedure includes calculations of ice loads on the hull (with a ship moving at different speeds in ice), determination of the bearing capability of the hull side plating in the area of ice loads action and, finally, construction the curves of the safe speeds versus ice thickness.
6. The procedure for determination of the admissible speeds for safe and efficient navigation in ice of various thicknesses was developed.

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7. The ice compacting influence on the ship speed lowering by the ship movement after icebreaker was studied and empirical formulae were developed for calculation of speed lowering versus the level of ice compacting.
8. To estimate the safe distance between vessels in a caravan a calculation procedure was developed based on application of both a differential equation of ship movement in the ice cake channel behind an icebreaker and the ship ice resistance formula. The stopping distance calculation used in this procedure includes three stages of ship movement starting from receiving the “STOP” command.
9. In addition to the Task 3.2 the following works were carried out and included into report;
    - Description of the peculiarities of winter navigation in the eastern part of Gulf of Finland in hard winter navigation “2010-2011”,
    - Analyses of the ship flow to the ports of eastern part of Gulf of Finland in winter navigation “2012-2013” and selection of the generic ships operating in this region,
    - Calculation of ice performance parameters for the selected generic ships with application of the worked out models for further use them in winter navigation risk management model..

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