13th International Conference on Port and Ocean Engineering under Arctic Condition

POAC’95

August 15—18, 1995 Murmansk, Russia

VOLUME 4

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1995
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The 13th conference on **PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS** is being held in Murmansk from August 15 to 18, 1995.

The POAC-conferences have been organised since 1971, when professor Per Bruun at the Norwegian Institute of Technology in Trondheim took the initiative of organising the first conference. After Trondheim 1971, POAC has been held in Reykjavik Iceland (1973), Fairbanks Alaska (1975, 1987), St. John’s Newfoundland (1977, 1991), Trondheim (1979), Quebec Canada (1981), Helsinki Finland (1983), Narsarsuaq Greenland (1985), Luleå Sweden (1989), Hamburg Germany (1993). We are glad, that in spite of very difficult conditions in this country now, we are able to continue the history of POAC and held this conference in Murmansk.

The Russian has high achievements in the Arctic engineering activities. This is reflected also by the papers and keynote lectures at this conference.

Most of the papers presented at POAC-95 are printed in Vol. 1 and 2 of the proceedings available at the conference. However, some papers will appear in a post conference volume, Vol. 3.

The main organiser of the 13th conference POAC-95 is Murmansk Shipping Company, well known by its activities in the Arctic engineering.

The organisation of this POAC-conference was possible only through the financial support of co-sponsors Murmansk Shipping Company, Russia: Department of Maritime Transport, the Russian Federation Ministry of Transport; Russian Concern "Norilsk Nickel"; AMOCO Production Company, USA; Kverner Masa-Yards, Finland; Neste Shipping Company, Finland; Thyssen Nordseewerke GmbH, Emden, Germany; and Canadian Marine Drilling Ltd.
It is an honour for the town of Murmansk and for Murmansk Shipping Company to host 13th POAC.

The choice of Murmansk as site of POAC-95 conference outlines the attention of the world specialists to the problems of Russian Arctic Development.

We wish to thank all the keynote lecturers and all the authors of papers for their important scientific contribution as well as all participants for their interest in the conference and their contribution. We sincerely hope will have a successful conference.

Capt. **V.Mikhailichenko**

President of POAC-95

and President of National Committee
To day we open the 13-th International conference on port and ocean engineering in the Arctic conditions (POAC-95).

For the first time the conference is being held in Russia and it’s quite naturally because Russia looks into the cold waters of the Arctic by its front. These waters do not just wash its shores, but have become the transport means of communication of the people living on these shores. The Arctic transport system has been formed for centuries and the names of its creators appeared on the maps of the Arctic. The towns, settlements, icebreakers and transport vessels are named in honour of those people.

Among these names there is a good deal of the names of Murmansk Shipping Company workers. And it is easy to understand because for the last six 10 - years periods Murmansk Shipping Company was the main marine transport enterprise in the Arctic. Murmansk Shipping Company together with the scientific-research institutes of our country achieved considerable results in Arctic navigation. At present we carry out all the year round transportation In the south-west part of Kara Sea (to the port of Dudinka).

In principle all-year round transportation along the Northern Sea route may be carried out. And this Is being proved by a lot of experimental voyages of the transport vessels under the ice-breakers steering, specifically, by the passage of the motor-vessel “KANDALAKSHA” in early spring period of 1993 (in April, May) under the pilotage of the atomic ice-breaker ”RUSSIA”.

It is quite naturally that the setting in period of the USSR partition with the following economic reforms in Russia had told on the vital activity of the Arctic fleet. First of all it had an influence on the traffic volume: it was reduced from 6.7 millions of tons in 1987 to 2.8 millions of tons In 1994. It was the result of rationalization of arctic economy, reduction of the level of military and political confrontation of the East and the West.

As regards the last factor, i.e.: reducing of military and political confrontation has become the basis of our private meetings with the foreign colleagues. Is doesn’t mean that we just meet and exchange opinions on different current processes but we take part in the development of the joint projects, such as, for Instance, “INSROP” - the internationalization of the Northern sea route in the technical . economical feasibility of
exploration and equipping of oil and gas deposits in the Arctic. in solving the ecological problems in the Arctic basin.

Now, at the time of holding our conference "POAC - 95" under the "INSROP" programme, motor vessel "Kandalaksha" is going from Japan along the Northern sea route having the International expedition on board. In the area of Novosibirsk islands the German icebreaker "POLAR STERN" has been working in accordance with the ecological programme with the International expedition on board. Two cruise voyages of atomic icebreaker "YAMAL" to the North Pole with the foreign tourists aboard had been accomplished.

The Finnish and German tankers take part in transportation of oil products.

The "POAC - 95" Conference organised by Murmansk Shipping Company is one of the links of International Co-operation in the Arctic.

At present our neighbours have intensified their activity in explorations of the Russian Arctic but they cannot properly state the value of the prospects. It is of great economic importance while development to commercial level of the production capacity of the Arctic mineral deposits and long-term transport operations.

That is why the scientific material from the scientific funds of the Russian Institutes are being transferred to the foreign specialists at prices dozens and even hundreds times lower than their nominal value.

And taking into consideration the fact that the material but not the results of the analysis is being transferred, and quite often just the same principle is being observed, i.e. selling of raw material and not the product itself, the priority of the Russian science is being lost. At the same time the scientific world of Russia is obliged to accept this fact because every specialist understands perfectly well that there is no point in concealing the data that one needs today.

Elimination or reducing of these contradictions is possible only by way of integration of both scientific investigations and its realization by practical introduction provided exclusion of discrimination, including remuneration of labour.

At present a high level of marine technologies, in the study of the Arctic seas lies been reached and just this fact. I hope. will be demonstrated at the Conference by the specialists. Much of attention should be paid to the questions of ecology to the observance of the principle of human aspiration accord "to make use of the Nature
without making any harm to it". This principle must be obligatory observed when we come into contact with the Nature of the Arctic.

Let me **congratulate** the participants of the 13-th International POAC - 95 Conference with the commencement of the work. New discoveries and projects for you for the benefit of mankind and environmental protection.

**N.I. Matushenko**
President of
Murmansk Shipping Company
От имени Государственной Думы Федерального Собрания Российской Федерации приветствую участников и гостей Тринадцатой международной конференции по портовой и морской технологии в арктических условиях (РОАС'95).

Впервые Российская Федерация стала местом проведения Конференции РОАС. Выбор города-героя Мурманска в качестве места проведения Конференции свидетельствует о внимании, которое мировое сообщество уделяет проблемам освоения арктического бассейна России, месторождений углеводородного сырья шельфа арктических морей. Ведущее место на Конференции занимает проблема транспорта в Арктике, стратегия создания нового поколения судов ледового плавания и ледоколов, перспективных методов и систем мониторинга ледовых условий, а также вопросы проектирования и строительства сооружений на арктическом шельфе в условиях вечной мерзлоты.

Желаю участникам Конференции успехов в работе, дальнейшей консолидации усилий в деле освоения Арктики, большого личного счастья.
On behalf of the State Duma of the Federal Assembly of the Russian Federation I welcome the participants and guests of the 13th International POAC-95 Conference.

For the first time the Russian Federation hosts the POAC Conference. The selection of the town-hero Murmansk for this conference shows the attention which the world community pays to the problems of the exploration of the Arctic Basin of Russia and hydrocarbon deposits of the shelf of the Arctic Seas. The problems of transportation in the Arctic, strategy for creating a new generation of ice-strengthened ships and icebreakers, perspective methods and systems for monitoring ice conditions, as well as designing and constructing off-shore structures on the Arctic shelf under conditions of permafrost are key questions at the conference.

I wish to the participants of the Conference every success in their work, to further join their efforts in the Arctic exploration and personal happiness.

Deputy Chairman of
the State Duma of the RF A.N. Chilingarov

August, 1995
Уважаемый Владимир Владимирович,

Позвольте выразить признательность за приглашение принять участие в открытии 13-й Международной конференции "По портовой и морской технологии в арктических условиях" (POAC-95).

Проведение в России такого авторитетного научного форума как Рама конференция даст серьезный импульс работе по освоению арктических районов в целях продуктивного экономического развития Севера России, укреплению международных контактов ученых, организаций и деловых кругов, заинтересованных в плодотворном сотрудничестве в арктическом регионе.

Желаю участникам конференции успешной работы, новых успехов в МХ практической и научной деятельности.

А.КОЗЫРЕВ

Министерство иностранных дел Российской Федерации
121200, г. Москва, Г-200, Смоленская-Сенная площадь, дом 32/34
Телефон 244-16-06

На № _____________ от _____________

Председателю международного и национального комитетов конференции POAC-95,

Начальнику администрации Северного морского пути

В.В. МИХАЙЛИЧЕНКО
Dear Vladimir Vladimirovich,

I gratefully thank You for Your invitation to take part in the opening ceremony of the 13th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC-95).

The fact that such an authoritative scientific congress takes place in Russia, gives a considerable impulse for more effective economical development of the Northern Regions of Russia and strengthening of international contacts of scientists, institutions, and businessmen that are interested in more fruitful cooperation.

I wish all the participants successful work, new achievements in their practical and scientific activity.

Minister of Foreign Affairs of Russian Federation

A. Koziyrev
TECHNICAL AND ECONOMICAL EVALUATION OF THE "NORTHERN SEA ROUTE"

Dr. Joachim Schwarz
Hamburg Ship Model Basin (ISVA)

1. INTRODUCTION

The political changes in the former USSR have caused the Northern Sea Route (NSR) as the 40% shorter seaway connection between Europe and Far East to receive attention and interest from several countries, especially, however, from Norway, Japan and from Russia. Two years ago these countries have established the INSROP (International Northern Sea Route Project) organisation, which concentrates on research and development in connection with this seaway. Germany has established bilateral links to Russia on the topic of developing marine transportation in northern Russia. The German Ministry for Transport has ordered the Hamburg Ship Model Basin (HSVA) to prepare a study on the economical and technical feasibility of the Northern Sea Route, which is the basis for this paper.

Both, INSROP representatives and HSVA have presented results of their studies earlier this year in Brussels to the European Union (EU). This and EU-internal recherches have stimulated the EU-Minister for Transport (DG VII), Mr. Neil Kinnock to strengthen the idea of the NSR by devoting a major part of his speech in June '95 in Bremen in connection with the Annual Meeting of the European Maritime Industries Forum (MIF) on this topic. Besides selecting the NSR as one of three tasks for future sea transport developments (besides short sea shipping and safety of passenger vessels) he said:

"Recently discussions on a new international shipping corridor around the North coast of Scandinavia and Russia have been started and this "Northern Sea Route" could clearly be developed in the medium or long term.

The Northern Sea Route offers two manifest opportunities for transport transit from Europe to Asia and access to the North of Russia.

As far as the first is concerned the Northern Sea Route is the shortest distance between Europe and particular regions in Asia. The distance from Bremen to Yokohama would, for instance, be
reduced by 40% if the Northern Sea Route was used.

Considering the huge reserves of oil, gas and other minerals in Northern Siberia, the development of the Northern Russian coastline could naturally be of great interest to the EU. If the rich resources of Siberia are to be shipped out by sea, loading terminals and icebreaking tankers will be needed.

Development of the Northern Sea Route on a commercial basis will plainly require considerable investments in:

- transport infrastructure, especially relating to the ports on the North coast of Russia,
- research into ship-building technology, especially the sophisticated ice-breaking equipment needed to assure yearround navigability of the route.

Such investments are no doubt technically feasible. But they raise a number of questions, in areas as diverse as transport, energy, industry, environment and research.

The European maritime industries have already achieved a high level of technology excellence, for example in building ice-breaking ships. We, therefore, have a good potential for participating in activities relating to the Northern Sea Route. Because of its multi-sectoral nature, the MIF is a particularly good arena in which to discuss the opportunities of the Northern Sea Route and the commercial risks involved.

2. ENVIRONMENTAL CONDITIONS ON THE NORTHERN SEA ROUTE

2.1 Geographical situation

The Northern Sea Route (NSR) forms part of the North-West passage between the Atlantic and Pacific and extends from the island of Nowaya Zemlja in the West to the Bering Strait in the East. Depending upon the route taken, the Northern Sea Route is 2400 – 2900 nautical miles long and icebound for at least nine months of the year. The route leads from the Barents Sea to the Kara Sea, passing through the Laptev, East Siberian and Chukchi Seas and into the Bering Strait (Figure 1). Since these waters largely lie off the Eurasian continental shelf they are in parts shallow, such as the Zemskoy Strait and the Laptev Strait which are locally only 8 to 13 m deep. This slightly restricts the routing choice, however the waters of the East Siberian Sea are on average 58 m deep, those of the Laptev Sea 519 m and those of the Kara Sea 118 m.

The northward-flowing river system, and in particular the Ob, Yenisey and Lena rivers must be considered in conjunction with the Northern Sea Route. Those rivers are navigable up to roughly
3600 km upstream, but admittedly owing to heavy icing they are only navigable for 120 days per year in the north and 160-180 days per year in the south. The Yenisey in particular is open to sea ships up to Igarka, which is roughly 800 km upstream the mouth of the river.

Noteworthy ports along the Northern Seaway are Murmansk, Archangelsk, Novy Port, Dikson, Khatanga, Nordvik, Tiksi, Pevek and Providenya. The ports of Dudinka and Igarka are those on the Yenisey which can be reached by sea-going ships.

2.2 Ice conditions

The shipping conditions along the Northern Sea Route are much more influenced by atmospheric processes than seas of moderate latitudes. This is due not only to the low air temperatures which cause ice formation, but also to the air and sea currents which deform, drift, compact and pile-up the ice into ridges and hammocks which are difficult for ships to break through. These meteorological conditions alter throughout the length of the Northern Sea Route, and naturally also as the seasons progress. A detailed study of them, in the form of statistics and prognoses, are of great importance for efficient ship operation.

During the summer months from July to the end of September the ice from the previous winter largely thaws. This applies to the Barents, Western Kara and Chukchi Seas. In the Eastern Kara Sea, the Laptev Sea and the East Siberian Sea part of the sea ice from the previous winter remains as ice floes, but can also remain as compacted pack ice and be exposed to the new freezing process in October. This biennial ice loses most of its weakening brine during the summer thaw and then freezes into ice of higher strength during the following winter.

From October onwards a solid layer of ice freezes, which in the near-shore reach and sheltered bays remain immobile for the whole winter (see Figure 1). Further out to sea the newly frozen ice in various forms and development stages is almost constantly in motion due to tidal and sea currents. The freeze lasts until the end of May. We, therefore, find the greatest thickness of level ice (roughly 2.5 m) in the Laptev Sea in May. For natural reasons the thickness differs over the length of the Northern Sea Route (see Table 1). Where there is considerable ice movement this level ice is pushed together to form pack ice or ridges or hummocks of compacted ice which can be more than 30 in thick, it represents considerable obstacles for shipping. The ridges and hummocks consist of ice floes which are only consolidated in their upper part, 2-3 m below the
The majority of compacted ice occurs in the vicinity of obstacles such as islands, and also at the edge of large ice fields. This makes the various straights (Kara, Vilkitsky, Laptev) very difficult for ships to pass.

<table>
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<th>Region</th>
<th>Ice thickness in winter [cm]</th>
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<td>Barents Sea</td>
<td>50-100 in the south 120-150 in the north</td>
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<tr>
<td>Kara Sea, West</td>
<td>120-200</td>
</tr>
<tr>
<td>Kara Sea, East</td>
<td>120-200</td>
</tr>
<tr>
<td>Laptev Sea</td>
<td>200-250</td>
</tr>
<tr>
<td>East Siberian Sea</td>
<td>170-200</td>
</tr>
<tr>
<td>Chukchi Sea</td>
<td>130-180</td>
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Table 1

As a counterpart to these ice accumulations wide ice free channels occur, the so-called polynyas, which are highlighted in Figure 1. The polynyas are a consequence of long-duration, directionally-constant wind conditions. Thus, for example, a polynya arises off the coast of Siberia during the winter months from January to March, since during this period the winds constantly blow off the land towards the sea. Shipping is happy to use these ice free channels' where so permitted by the depth conditions.

The most difficult ice conditions are frequently to be met to the east of the Zevernaya Islands and also in the area of the Wrangel Islands in the East Siberian Sea. Central Arctic ice moves under the effect of current and wind in the form of large ice fields sometimes having a diameter of 100 nautical miles (AAR1, Polferov, 1993) against the island barriers and compresses the sea ice existing there into pack and ridge ice. That Central Arctic ice is up to 3 m thick, thus causing difficulties even for the powerful nuclear-driven Russian icebreakers. In addition, there are also numerous open leads between the ice fields. These are sought out by ships in order to navigate quickly accepting detours, rather than be hampered by solid ice on shorter routes.
The ice conditions on the Northern Sea Route have for several years been plotted by the Arctic and Antarctic Research Institute (AARI) in St. Petersburg not only by direct measurements and observations, but also by assessing satellite images. They are nowadays stored in an electronic data bank. Figure 2 shows, for example, the percentage of ice coverage in the south-eastern Barents Sea during March, while Figure 3 shows the lines of equal average ice thickness in April. Even though more extensive and detailed ice information on ice coverage, ice thickness (max, min, average) for the various months of the year and in the various areas of the NSR is available at the Arctic and Antarctic Research Institute of St. Petersburg and for internal use also at HSVA, for optimum route planning a description of ice conditions of this type is not detailed enough. Work should be done on providing ships with forecasts of ice conditions, including the location of ice free channels for the next 12-24 hours whereby account is also taken of satellite images, aerial photos, and meteorological and oceanographic influencing factors. According to HSVA's experience in expeditions with POLARSTERN helicopter reconnaissance is inadequate. Ice conditions alter too quickly by wind and tidal currents. Both can, however, be calculated and incorporated into a routing advise.

3. RUSSIAN ICEBREAKERS AND ICE-BREAKING CARGO SHIPS

Since World War Two the USSR has systematically built its Arctic icebreaker fleet and today has 24 sea ice breaker and 38 harbour and river icebreakers. Seven of them are nuclear powered and have a propulsive power of 56 MW, respectively 33 MW.

The Russians have been receptive to new developments. They demonstrated this in the 1980s by converting the bow of two relatively new icebreakers (MUVDYG and the KAPITAN SOROKIN) to the Thysseflaas icebreaking system. This icebreaking technology has proved itself on the Northern Sea Route by saving up to roughly 50% of the engine power needed (see Fig. 4) (Hellmann, 1991).

A sister ship to the KAPITAN SOROKIN, the KAPITAN NIKOLAEB, was converted in Finland and received a cone like bow. Comparative measurements of the ice-breaking capacity of both systems in the estuary of the Yenisey confirm the superiority of the Thysseflaas System (Figure 4).
The Russian icebreakers are operated on behalf of the Russian Federation by the Murmansk Shipping Company and Fair-Eastern Shipping Company, for the moment they are not fully utilized.

This is due to Russia's economic problems, as a result of which freight transport to and from Northern Russian ports has decreased. Currently there is thus adequate icebreaking capacity for the Northern Sea Route transportation i.e., icebreaker assistance to ice-strengthened freighters. According to the Murmansk Shipping Company's price list, for example, accompanying an ice-breaking freighter of the SA-15 class from Murmansk to Providencia would cost TDM 146. This price depends upon the sue and ice class of the ship to be accompanied. Short-term icebreaker...

Fig. 4
requirements are relatively expensive at TDM 72 per day. Russia now has 26 relatively new ice breaking freighters, of which 19 are of the Finnish-built Norilsk SA-15 type. These multi-purpose freighters have a carrying capacity of 15000 tonnes and are driven by 15.4 MW diesel engines. The ship dimensions are $L_{oa} = 174\text{ m}$, $B_{max} = 24.5\text{ m}$, $D_{adm} = 8.5\text{ m}$. The SA-15s can only operate without ice breaker support in ice up to about 1 in thickness. In order to improve their performance in ice it would be appropriate either to increase their power or to modernize their icebreaking bow shapes.

In the 1980s Lash Carriers were developed in Russia for the Arctic (Alexsey Kosygin-Class) and three of these have been built. Although these ships have a power of 25 MW their efficiency in ice does not meet expectations (Brigham, 1991). The most recent Arctic freighter development is the nuclear powered 30 MW Lash/Container Ship SEVMORPUT. In addition to these more recent Russian freighter types is a large number of ice-reinforced wood-transporter ships, bulk carriers and also small oil tankers, of which some have recently been built by the German Shipyard MTW Wismar.

4. CARGO POTENTIAL FOR THE "NORTHERN SEA ROUTE"

4.1 Trans-Shipments

In 1990 goods to a value of USS44.000 billion were exported to the Far East from Northern and Central Europe. In the opposite direction imports were worth USS 82 billion (Ramsland, 1991). Germany’s share in this trade is significant as Fig 5 shows. The cargo traffic from Hamburg to Far East has increased by 35% over the last two years. Even if the container transport via NSR would prove to be economical, it is not expected that the shipping companies will change quickly from their traditional seaway (Suez Route) to the NSR.

Figs. 6 and 7 show, however, that since 1989 a significant drop of the number of containers transported between Hamburg and Japan inbound and outbound occurred, which could not be compensated by the increase of transport between Hamburg and Korea. The reason for the decreasing container shipment to and from Japan is attributed to the outsourcing of the production of industrial goods from Japan to South-East Asia. This trend must be considered in any prediction of the economy of the NSR.
Extensive use was made of containers for this exchange of goods. In 1990 866500 containers were shipped from Northern and Central Europe to the Far East via the Suez Canal route and of these 317300 containers, or 36%, came from Germany. 1105287 containers were shipped from the Far East to Northern Europe.

4.2 Export via NSR

The sea transport in the Russian Arctic is essential for the development the Russian economy (Granberg, 1993).

Besides the trans-shipment of goods between Europe and the Northern Pacific the Northern Sea Route has its second major potential in the export of resources such as nickel, copper, diamonds, tin and gold, of forest products and especially of oil and LNG. While the mineral resources and forest products are already being transported via the three large rivers Ob, Yenisey and Lena to the NSR, the multi-national oil companies are planning together with their Russian partners to use the seaway to transport the mostly onshore produced oil in the north-western part of Russia.
Fig. 6 Development of container transport from Japan and Korea to Hamburg

Fig. 7 Development of container transport from Hamburg to Japan and Korea
by tankers from the Pechora Sea to western Europe. One of the problems in this concept is the tanker loading process, because of the shallow water conditions close to shore. The offshore loading terminal has to be designed in order to be operational under various drifting ice conditions. One possible solution is shown in Fig. 8, in which two prefabricated storage barges are founded at the 25 m deep sea bed. The harbor between the barges has two entrances in case one side is blocked by pack ice. The backsides of the storage barges are filled with gravel and protected against erosion by stones. Oil-spill booms at the entrances would prevent the spreading of oil in case an accident occurs during the loading process. Such type of harbor could also be used as oil production island.

The tanker transport of oil, gas condensate, and LNG could become the major driving force also for the increasing use of the Northern Sea Route for transit shipments to Far East. In this context it was very important that the Russian Parliament did sign the "Petroleum Law" this June (1995). Gas condensate and probably also LNG are intended to be shipped from the Yamal peninsula to western Europe. In this case the more severe ice conditions in the Kara Sea and especially the passage through the Kara Gate which is often blocked by compressed ice have to be managed.

5. ECONOMICAL EVALUATION

So far the Northern Sea Route has been used for cargo transit from Europe to East Asia by Russian shipping companies only to which the economy was of minor importance. If this seaway with its shorter distance between Europe and Far East is supposed to become attractive to western and nowadays also to Russian shipping companies, economical profit has to be expected.

The economical evaluation was carried out by comparing the shipping costs between Hamburg and Yokohama along the Northern Sea Route (NSR) with that through the Suez Canal (SSR) on the basis of the Required Freight Rate (RFR-value). Three types of cargo vessels have been used for the calculation, a 1500 TEU container vessel, a multi-purpose cargo vessel and a bulk carrier.
Fig. 8 Proposed concept for an Offshore Loading System in drifting ice
The RFR-value is defined as:

\[
\text{RFR} = \frac{\text{Annual overall cost}}{2 \times \text{TEU} \times \text{Number of round trips}}
\]

The annual costs include:
- operating costs
- interest and repayment costs
- passage costs
- insurance

In this paper the procedure of the calculation is shown for the container vessel only. The ship data as well as the annual costs and voyage costs are given in Table 2.

It is assumed that one 56 MW icebreaker is leading not more than two cargo-vessels through the ice; this number may change according to the ice conditions.

The price for the icebreaker assistance is taken from the price list, published in 1993 by Murmansk Shipping Company (MSCO).

Key question in the economical evaluation of the NSR is the speed of the voyage which can be maintained during the various months of the year. On the basis of published ship speeds by Ramsland (1992) and experiences of Murmansk Shipping Company with their ships of the NORILSK class and the SEVMORPUT as well as from the winter voyage in 1993 with KANDALAKSHA (Batskikh, Mikhailichenko, 1993) the following average speeds of a container ship convoy during the various months of the year seem to be possible (s. Table 3). The open water speed of each container vessel is 19 knots.

In Table 3 it is distinguished between the speed with the present status of technology and the expected speed in case more research and technological development is performed and the results implemented (with R+D-effects). The technological improvements are expected in the fields of:
- **icebreaking** technology
- prediction of optimal ship routes through the ice
- information technology
- ship operation / convoy handling
- logistics
### SHIP DATA CONCERNING A 1500 TEU CONTAINER SHIP

<table>
<thead>
<tr>
<th></th>
<th>Suez-Variant</th>
<th>NSR-Variant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>with no ice classification</td>
<td>ice class: UL</td>
</tr>
<tr>
<td>Displacement</td>
<td>t</td>
<td>28200</td>
</tr>
<tr>
<td>Weight without equipment</td>
<td>t</td>
<td>6700</td>
</tr>
<tr>
<td>tdw a t</td>
<td>t</td>
<td>21500</td>
</tr>
<tr>
<td>tdw c</td>
<td>t</td>
<td></td>
</tr>
<tr>
<td>Cargo</td>
<td>t</td>
<td></td>
</tr>
<tr>
<td>Motive power</td>
<td>kW</td>
<td>12500</td>
</tr>
<tr>
<td>Cruising speed</td>
<td>kn</td>
<td>19,0</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Per day at sea</td>
<td></td>
<td></td>
</tr>
<tr>
<td>main engine</td>
<td>U/day</td>
<td>43</td>
</tr>
<tr>
<td>auxiliary engine</td>
<td>U/day</td>
<td>3,0</td>
</tr>
<tr>
<td>Build price</td>
<td>DM x million</td>
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</table>

### ANNUAL COSTS IN DM x MILLION

<table>
<thead>
<tr>
<th></th>
<th>Suez-Variant</th>
<th>NSR-Variant</th>
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<tbody>
<tr>
<td>Depreciation</td>
<td>4,48</td>
<td>5,17</td>
</tr>
<tr>
<td>Dry dock repairs</td>
<td>0,35</td>
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<tr>
<td>Continuous maintenance</td>
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<td>0,86</td>
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<tr>
<td>Insurance incl. hull (P&amp;O)</td>
<td>0,46</td>
<td>0,66</td>
</tr>
<tr>
<td>Capital costs</td>
<td>4,08</td>
<td>4,52</td>
</tr>
<tr>
<td>Crewing costs</td>
<td>2,37</td>
<td>2,37</td>
</tr>
<tr>
<td>Other costs</td>
<td>0,22</td>
<td>0,24</td>
</tr>
<tr>
<td>Container costs</td>
<td>3,18</td>
<td>3,18</td>
</tr>
<tr>
<td>Costs per day at sea</td>
<td>TDM</td>
<td>50,9</td>
</tr>
</tbody>
</table>

### VOYAGE COSTS

<table>
<thead>
<tr>
<th></th>
<th>Suez Canal</th>
<th>NSR in convoy with two ships, per ship</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TDM</td>
<td>(summer) 94,00 (winter) 122,00</td>
</tr>
<tr>
<td>Goods value</td>
<td>TDM/t</td>
<td>7</td>
</tr>
</tbody>
</table>

### FREIGHT INSURANCE

<table>
<thead>
<tr>
<th></th>
<th>Suez Canal</th>
<th>NSR - Ice class E 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM per TDM goods value</td>
<td>0,0051</td>
<td>0,0058</td>
</tr>
</tbody>
</table>

Tab. 2
Container Vessel

<table>
<thead>
<tr>
<th></th>
<th>state of the art</th>
<th>with R+D effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>8.0</td>
<td>11.0</td>
</tr>
<tr>
<td>February</td>
<td>8.0</td>
<td>11.0</td>
</tr>
<tr>
<td>March</td>
<td>7.0</td>
<td>9.0</td>
</tr>
<tr>
<td>April</td>
<td>6.0</td>
<td>8.0</td>
</tr>
<tr>
<td>May</td>
<td>6.3</td>
<td>8.5</td>
</tr>
<tr>
<td>June</td>
<td>7.0</td>
<td>9.5</td>
</tr>
<tr>
<td>July</td>
<td>8.4</td>
<td>12.0</td>
</tr>
<tr>
<td>August</td>
<td>13.1</td>
<td>16.0</td>
</tr>
<tr>
<td>September</td>
<td>14.5</td>
<td>16.0</td>
</tr>
<tr>
<td>October</td>
<td>13.5</td>
<td>16.0</td>
</tr>
<tr>
<td>November</td>
<td>9.7</td>
<td>12.0</td>
</tr>
<tr>
<td>December</td>
<td>8.8</td>
<td>11.5</td>
</tr>
<tr>
<td>Open water</td>
<td>19.0</td>
<td>19.0</td>
</tr>
</tbody>
</table>

*Tab. 3 Average speed of the icebreaker/container vessel convoy during the various months of the year*

By using the estimated ship speeds in Tab. 3, voyage-days have been calculated for the 11340 nm long Suez-route between Hamburg and Yokohama and for the NSR-route. The distance of which is 7000 nm with 2800 nm navigating in ice.

The number of voyage-days are presented in Table 4, for the Suez-route, for the NSR at the present state of the art, and for the NSR with IUD-effects.

The RFR values have been calculated as shown in Table 5 for the container ship with a loading capacity of 1500 TEU. The same method but with other ship and voyage-speed data was applied for the bulk-carrier and multi-purpose ship. The calculation was carried out for the Suez Canal Route (year-round) and for the Northern Sea Route under the following conditions:

- 6 months NSR
- 6 months NSR plus 6 months Suez-Route (current state of the art)
- 6 months NSR plus 6 months Suez-Route (with R+D-effects)
- 12 months NSR (current state of the art)
- 12 months NSR (with R+D-effects)
The calculations were repeated for the higher ice class (ULA) container ship with DM 6 million additional investment money.

The RFR-values for the different conditions are presented in Table 6. The yearly profit (expressed in DM) when using the NSK from Hamburg to Yokohama instead of the Suez Canal Route was calculated for different conditions and for the three ship types (Table 7).

6. CONCLUSIONS

By order of the German Ministry for Transport the Hamburgische Schiffbau Versuchsanstalt GmbH (HSVA) has carried out a study to evaluate the technical and economical feasibility of the Northern Sea Route. The availability of 19 icebreakers with more than 16 MW propulsive power - five of them with 56 MW - and the experience of several years of convoy trips along the NSR have proven that navigation was during the winter season is technically possible.
<table>
<thead>
<tr>
<th></th>
<th>Variant I* yearly overview</th>
<th>Variant II** yearly overview</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suez NSR (summer)</td>
<td>Suez NSR (summer)</td>
</tr>
<tr>
<td>Number of days in operation per year</td>
<td>350</td>
<td>175</td>
</tr>
<tr>
<td>Number of days at sea per round trip (RT)</td>
<td>651</td>
<td>3.25</td>
</tr>
<tr>
<td>RT per year</td>
<td>735</td>
<td>103,40</td>
</tr>
<tr>
<td>Cost per day at sea</td>
<td>50,90</td>
<td>53,00</td>
</tr>
<tr>
<td>Insurance per RT</td>
<td>56,00</td>
<td></td>
</tr>
<tr>
<td>Passage costs for RT</td>
<td>TDM 2740,00</td>
<td>2105,00</td>
</tr>
<tr>
<td>Costs per year</td>
<td>TDM 17825,00</td>
<td>8912,00</td>
</tr>
<tr>
<td>RFR-values</td>
<td>TDM 0,91</td>
<td>0,91</td>
</tr>
<tr>
<td>Income per RT</td>
<td>TOM 3000,00</td>
<td>3000,00</td>
</tr>
<tr>
<td>Income per year</td>
<td>TDM 19530,00</td>
<td>23850,00</td>
</tr>
<tr>
<td>Profit per year</td>
<td>TDM 1705,00</td>
<td>5045,00</td>
</tr>
<tr>
<td>NSR-surplus per year</td>
<td>TDM 3340,00</td>
<td></td>
</tr>
</tbody>
</table>

*) Variant I 12 months via Suez Canal
**) Variant II 6 months via the Suez Canal and 6 months via the NSR

Tab. 5 Calculation of the RFR-values and the NSR-surplus per year for the Suez Route and for NSR (6 months) with R+D-effects
<table>
<thead>
<tr>
<th>Variant</th>
<th>RFR (DM/TEU)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At today</td>
</tr>
<tr>
<td></td>
<td>state of the art</td>
</tr>
<tr>
<td></td>
<td>with R+D</td>
</tr>
<tr>
<td>SSR (Suez-Route)</td>
<td>910</td>
</tr>
<tr>
<td>NSR 6 months (summer)</td>
<td>780</td>
</tr>
<tr>
<td>NSR 6 months plus SSR 6 months</td>
<td>840</td>
</tr>
<tr>
<td>NSR 12 months</td>
<td>890</td>
</tr>
</tbody>
</table>

Tab. 6 RFR-values for the 1500 TEU container vessel, SSR vs NSR

<table>
<thead>
<tr>
<th>Variant</th>
<th>NSR-Advantage vs. Suez-Route by DM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at today state of the art</td>
</tr>
<tr>
<td>Variant II</td>
<td>1865</td>
</tr>
<tr>
<td>Variant III</td>
<td>755</td>
</tr>
<tr>
<td>Variant II</td>
<td>180</td>
</tr>
<tr>
<td>Variant III</td>
<td>177</td>
</tr>
<tr>
<td>Variant II</td>
<td>766</td>
</tr>
<tr>
<td>Variant III</td>
<td>1038</td>
</tr>
<tr>
<td></td>
<td>CONTAINER SHIP</td>
</tr>
<tr>
<td></td>
<td>with R+D</td>
</tr>
<tr>
<td></td>
<td>3340</td>
</tr>
<tr>
<td></td>
<td>3914</td>
</tr>
<tr>
<td></td>
<td>671</td>
</tr>
<tr>
<td></td>
<td>1585</td>
</tr>
<tr>
<td></td>
<td>BULK CARRIER</td>
</tr>
<tr>
<td></td>
<td>Variant II</td>
</tr>
<tr>
<td></td>
<td>Variant III</td>
</tr>
</tbody>
</table>

Tab. 7 Yearly profit of using the NSR instead of the Suez Canal Route for three different ship types
The economical proposition of the NSR has been evaluated for three ship types (container, multipurpose, bulk) in comparison with the Suez Canal Route (SSR) by the Required Freight Rate (RFR) method. The most difficult task was the determination of the convoy speeds in the various months of the year. The experience gained in Russian convoy trips was drawn upon here. The RFR-values were calculated for the current state of technology but also for conditions when research and development (R+D) results are implemented. The R+D would have to cover the entire transport system (ship design, communication, logistics, route advise etc).

The RFR calculations show that, when conventional icebreaking technology is used, together with the assumptions made otherwise, year round shipping on the Northern Sea Route is only slightly cheaper than via the Suez Canal. If the sailing period is restricted to the summer months, the Northern Sea Route is already an attractive proposition in economic terms.

Shipping via NSR would become economically more attractive, if the transport system were to be developed further in technological terms. If this is assumed, RFR-values of 700 DM/TEU (6 months, summer) to 780 DM/TEU (entire year) can be counted upon, as opposed to 910 DM/TEU for the Suez Canal Route. Splitting of the route, i.e. 6 months NSR + 6 months SSR is not real beneficial, compared with operating the NSR year-round. When operating the 1500 TEU Container Vessel between Hamburg and Yokohama year-round on NSR the profit compared with the Suez Canal Route would be almost 4 million DM/year, if R+D-results are applied; without these developments the profit would only be marginal (755 TDM). Considering the risk involved in Arctic navigation the year-round navigation on the NSR with the present state of the art is not recommendable yet.

However, the commercial use of the Northern Sea Route could start with the 6 months (summer) operation. During this starting phase the technology could be improved by R+D which could lead to a profitable year-round use of the Northern Sea Route.

The development of the trans-shipment from Europe to Japan/Korea would gain from the development of the oil taker operation in the western part of the NSR which is supposed to start by the year 2000.
7. REFERENCES


Batsikikh, Mikhailichenko: 1993


Polferov, S.; Likhomanov, V and Browin, A: Conditions of Navigation and Possibility of Arrival to Ports Along the Northern Sea Route for Cargo Ships of SA-15 Type Navigating by Herself and with Icebreaker’s Convoy Within November-May. Arctic and Antarctic Research Institute, St. Petersburg, June 1993.

ABSTRACT

In cooperation with many Russian institutes and western consultants, Amoco engineers have been evaluating several systems for the export of hydrocarbons from the Yamal Peninsula to Europe. Some of the critical components of the export system planned for the area are an offshore terminal, pipelines, icebreakers and tankers. The major factors affecting the design and operation of these systems must be well defined. The proposed preliminary plan for the export systems includes the placement of a storage terminal in 30 m of water offshore Kharasavey and a loading system in 14 m of water in the Ob Bay offshore Mys Kenicny.

To assess the cost and feasibility of these marine systems, it was necessary to collect specific ice, environmental and other engineering data in the Kara Sea and Ob Bay. These engineering studies have focused on problems unique to the Arctic offshore. Design bases, which combine the best available Western and Russian technologies, have been developed for these export systems. This paper reviews the numerous ice engineering studies and field expeditions that were successfully accomplished over the last three years for the Yamal project.

INTRODUCTION

Amoco Eurasia Petroleum Company has funded, over the last three years, numerous technical engineering studies and field trips in order to better understand the Russian Arctic offshore and onshore [1]. These studies were done in cooperation with many Russian institutes and western consultants. To quickly gain a good understanding of the Russian Arctic, three approaches were used to collect the necessary engineering data. The first approach was based on the understanding of existing data. Amoco contracted several Russian institutes to analyze the long term statistical data that is available in the literature and institutes' data banks. This historical data was then supplemented by the data obtained from participation in several field expeditions [2]. This gave us the opportunity to compare the long term statistics with the observations made during a particular year.

Finally, we combined the best Russian and Western mathematical and computer models [3] in order to hindcast short and long term results related to the environmental conditions, loads and their combination, risks and downtime. The short term statistics were used to develop criteria for day to day operations and the long term statistics were used to estimate the magnitude of design or extreme events.

RUSSIAN CONTENT
Amoco worked in close cooperation with many Russian institutes to define the offshore environment, develop design and operational criteria, and develop and review conceptual designs for tankers and terminals. The results from these studies provide the key to a safe, economical and feasible export system. The Russian engineers and scientists were very familiar with Amoco's problems and successfully came up with cost effective solutions and sometimes alternatives to Amoco's options. Through this close cooperation, Amoco has been able to combine the best available Western and Russian technologies. Moreover, Russian and Western codes and standards were also used and compared during this exercise [4].

ENVIRONMENTAL STUDIES

The key factor to evaluate the feasibility and cost of operating in a particular area, especially the Arctic, is to have a good understanding of the environment. For transporting petroleum products by sea, the Yamburg Peninsula, this includes knowing the properties and distribution of the offshore permafrost, sea floor characteristics, coastal processes, ice, open water and meteorological conditions. Of particular importance are the ice conditions and characteristics of the seashore. This paper describes all of our activities in this area. The projects are listed in Table 1.

Table 1: Ice and Ice Scour Studies and Field Expeditions

<table>
<thead>
<tr>
<th>Topic</th>
<th>Institute</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Ice Scour Survey, Kara Sea</td>
<td>Eco-System</td>
<td>1992</td>
</tr>
<tr>
<td>2. Ice &amp; Hydrometeorological Conditions in the Kara Sea</td>
<td>CNIIMF</td>
<td>1992/1993</td>
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<tr>
<td>3. Study of Extreme Ice Features in the Kara Sea</td>
<td>AARI</td>
<td>1993</td>
</tr>
<tr>
<td>4. Global Ice Dynamics in the Kara Sea</td>
<td>AARI</td>
<td>1993</td>
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<tr>
<td>6. Ice Scour Survey, Kara Sea</td>
<td>AMIGE</td>
<td>1993</td>
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<tr>
<td>7. SA-15 Kara Sea Ice Expedition</td>
<td>AMOCO/KM</td>
<td>1993</td>
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<tr>
<td>8. Air Reconnaissance of Ice in the Kara Sea</td>
<td>KMY/AMIGE</td>
<td>1993</td>
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<tr>
<td>9. An Expedition in the Kirit-his and Pechora Seas</td>
<td>VNIP</td>
<td>1993</td>
</tr>
<tr>
<td>10. ERS-1 Image Interpretation for the Kara Sea</td>
<td>Dickins</td>
<td>1993</td>
</tr>
<tr>
<td>11. Kara Sea Ice Dynamics</td>
<td>IceCasting</td>
<td>1994</td>
</tr>
<tr>
<td>12. Ice Load Model for a Hummock field/Structure Interaction</td>
<td>SP State, Tech Univ.</td>
<td>1994</td>
</tr>
<tr>
<td>13. Coupled Ice-Ocean Dynamics Model of the Kara Sea</td>
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<td>1994</td>
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<tr>
<td>14. Kara Sea Coupled Ice-Ocean Model</td>
<td>MSUNOR</td>
<td>1994</td>
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<tr>
<td>15. Kara Sea SLAR Image Processing and Interpretation</td>
<td>Berchba</td>
<td>1994</td>
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<td>16. Ice &amp; Hydrometeorological Conditions in the Ob' Gulf</td>
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<td>1994</td>
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<tr>
<td>17. ERS-1 Image Interpretation for the Ob' Gulf</td>
<td>Dickins</td>
<td>1994</td>
</tr>
</tbody>
</table>

Ice Conditions

The Kara Sea

Much of Amoco's work on characterizing the ice conditions in the Kara Sea has been done in cooperation with members of the staff of the Arctic and Antarctic Research Institute (AARI) and the Central Marine Research and Design Institute (CNIIMF). Amoco began working with CNIIMF in 1992 and AARI in 1993. The investigations focused on the review of ice and hydrometeorological conditions and extreme ice features in the Kara Sea. This was followed by studies on the ice movement or dynamics (Table 2 to 5 in Table 1). From these studies we found the following results:

- The Kara Sea is usually covered by ice for more than nine months of the year. The median ice thickness reaches 1.2 m in the south to 1.6 in the north (Figure 1).
- It is also very dynamic, constantly in motion, resulting in the formation of large rubble fields (hummocks, Figure 2) and areas of intricately ridged ice. Most of the ice motion and deformation is due to storm winds (cyclone and anti-cyclone) moving the drifting ice in a more or less between Novaya Zemlya and the Yamburg Peninsula. As a result, the
Amoco worked in close cooperation with many Russian institutes to define the offshore environment, develop design and operational criteria, and develop and review conceptual designs for tankers and terminals. The results from these studies provide the key to a safe, economical and feasible export system. The Russian engineers and scientists were very familiar with Amoco’s problems and we successfully came up with cost effective solutions and sometimes alternatives to Amoco’s options. Through this close cooperation, Amoco has been able to combine the best available Western and Russian technologies. Moreover, Russian and Western codes and standards were also used and compared during this exercise [4].

**ENVIRONMENTAL STUDIES**

The key factor to evaluate the feasibility and cost of operating in a particular area, especially the Arctic, is to have a good understanding of the environment. For transporting petroleum products by sea from the Yamal Peninsula, this includes knowing the properties and distribution of the offshore permafrost, sea floor characteristics, coastal processes, ice, open water and meteorological conditions. Of particular importance are the ice conditions and characteristics of the seabed. This paper describes all of our activities in this area. The projects are listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Ice and Ice Scour Studies and Field Expeditions</th>
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<tr>
<td>Topic</td>
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<tr>
<td>1. Ice Scour Survey, Kara Sea</td>
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<td>2. Ice &amp; Hydrometeorological Conditions in the Kara Sea</td>
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<td>3. Study of Extreme Ice Features in the Kara Sea</td>
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<td>4. Global Ice Dynamics in the Kara Sea</td>
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<td>6. Ice Scour Survey, Kara Sea</td>
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<td>7. SA-15 Kara Sea Ice Expedition</td>
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<td>8. Air Reconnaissance of Ice in the Kara Sea</td>
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<td>10. ERS-1 Image Interpretation for the Kara Sea</td>
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<td>16. Ice &amp; Hydrometeorological Conditions in the Ob' Gulf</td>
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<td>17. ERS-1 Image Interpretation for the Ob' Gulf</td>
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<tr>
<td>19. Voyage of the Kapitan Nikolaev Icebreaker - Dec. 29 to Jan. 11</td>
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</table>

**Ice Conditions**

1. **Kara Sea**

Much of Amoco’s work on characterizing the ice conditions in the Kara Sea has been done in cooperation with members of the staff of the Arctic and Antarctic Research Institute (AARI) and the Central Marine Research and Design Institute (CNIMF). Amoco began working with CNIMF in 1992 and AARI in 1993. The investigations focused on the review of ice and hydrometeorological conditions and extreme ice features in the Kara Sea. This was followed by studies on tin* ice movement or dynamics (Topics 2 to 5 in Table 1). From those studies we found the following results:

* The Kara Sea is usually covered by ice for more than nine months of the year. The median ice thickness reaches 1.2 m in the south to 1.6 m in the north (Figure 1).
* It is also very dynamic, constantly in motion, resulting in the formation of large nibble fields (hummocks: Figure 2) and areas of intensely ridged ice. Most of the ice motion and deformation is due to storm winds (cyclone and anti-cyclone) moving the drifting ice back and forth between Novy Zemlya and the Yamal Peninsula. As a result, the
ice mass compresses itself on these two large land bodies. Depending on the wind severity and direction, this may result in zero to several degrees of compression within the ice cover (Figure 3).

- One of the critical navigational features of the Kara Sea is its narrow western entrance (Kara Gate) located between Vaygach Island and Novaya Zemlya connecting it to the Pechora Sea. Although the ice conditions in the Kara Sea may be easy to navigate during a particular period of time, the ice may bottleneck in the gate rendering the passage of ships very difficult.
- Multi-year ice and ice island or iceberg fragments are not a concern in the Kara Sea. However, small iceberg fragments (bergy bits) have been observed in the northern part of the sea along Novaya Zemlya over the 60 years of observations.
- As the fetch in the Kara Sea is limited, the ice conditions govern the design of the offshore loading terminals and tankers.

Following these studies, Amoco decided to organize or participate in several field trips and expeditions to better understand the environment of these regions and gain first hand experience (Topics 7 to 9 and 18, 19 in Table 1). Figure 4 shows the locations where Amoco representatives have worked on the ice or from an icebreaker collecting scientific and engineering data critical for the design of our export system. From these field trips we found the following results:

- The ice conditions in the Kara Sea can be difficult even during an average winter due to strong winds creating compression in the ice field. This compression can prevent the ship from moving forward which results in the ship being rescued by icebreakers.
- From our in-situ measurements, we observed several large partially consolidated hummock and nibble fields which represent the "design" ice features for our offshore terminal and icebreaking ships.
- They are several routes that can be used to navigate the Kara Sea during the winter months.
- The routing of the ships in the Kara Sea is being done by the Dickson weather and the ice monitoring station on Dickson Island. The ships are well monitored and supported by the most powerful icebreakers in the world for Kara navigation.
- The deployment of live ARGOS buoy in the Kara Sea provided us with critical data required to calibrate our ice dynamics models and help us to better define operational and design criteria (Figure 5).

- Such first hand experience was very helpful in defining the scope of work and discussing the results of our studies with our Russian contractors.

In 1994 Amoco started work with a Western firm, IceCasting, the Russian institute AARI and the Russian firm NORDECO, to develop state-of-the-art ice dynamics models which incorporate the effect of ocean currents (Topics 4, 11, 13 & 14 in Table 1). The models are unique and can predict ice movements in the Russian Arctic driven by both winds and currents (Figures 6 a & b). These models were developed in an effort to extend our database. It is planned to use the 1993 and 1995 ARGOS buoys data to calibrate these models and then use the models to generate daily and extreme ice motion statistics using historical wind and pressure data. A detailed analysis of the data has been performed by Amoco [5]

This hindcasting method has been successfully used to develop wave design criteria in different parts of the world. The results from the models will provide us with the necessary data to predict downtime, risks and loads for the terminal and tankers.

Amoco also worked with both Western (Dickins, Bercha) and Russian contractors (Eco-Systems) to characterize the ice using satellite imagery and Side Looking Airborne Radar, SLAR (Topics 8, 10 & 15 in Table 1). A map showing the position of the landfast ice edge boundary in the Kara Sea during 1993 is given in Figure 7. The position of the landfast ice edge along the Yamal Peninsula is critical for determining the location of the offshore terminal and the study of ice scour for the burial depth of submarine pipelines.

2. Ob’ Gulf

Data from the Ob Gulf was needed by Amoco in order to design the export system for the Novy Port oil. AARI was first to conduct a study on the ice conditions in the Ob’ Gulf (Topic 16 in Table 1). A map illustrating the ice conditions in the Ob’ Gulf at the end of April is given in Figure 8. In 1995 AARI accompanied Amoco on the first winter icebreaker voyage down the OW Gulf and partnered with Amoco on a sea ice characterization program for the Ob’ Gulf during both the March and April expeditions (Topics 18 & 19 in Table 1)

Without the support from AARI, it would have been impossible to adequately characterize the ice in our areas of interest and obtain permits for such work. In an effort to bring some operational experience to bear on our ice studies, Amoco also worked closely with the engineering staff at the Central Marine Research and Design Institute (CNIIMF) on ice studies in the Ob’
Gulf. Additionally, the firm of Dickins was also contracted to analyze the ERS-1 images collected over the Ob’ Gulf. From these studies and field expeditions, the following observations were made:

- In the Ob’ Gulf, the ice is even thicker than the Kara Sea. By late April, the maximum thickness is located in the middle of the Gulf. On average, it can reach a thickness of 1.8 m (Figure 8).
- The ice has a low salinity and has a high strength.
- On several occasions, large and deep ice rubble and ridges were found.
- The ice edge moves from the middle of the Bay to the north as far as Bely Island. This results in formation of shear ridges along the coast lines and across the bay depending on the amount of ridging due to winds.

### Ice Load Models

Amoco also worked with the St. Petersburg State Technical University to develop new ice load models for the Kara and Pechora Seas [3]. The models are based on finite difference method and predict ice loads for both frozen-in and impact conditions. The results of the new model [6] simulating impacts of first-year ice against a wide structure compare well with the full scale data accumulated by Amoco during operations in the Beaufort Sea [7]. The model also takes into account the effect of the ice impact velocity which was found to be important during laboratory and full scale tests.

### Ice Dynamics

The motion of the ice cover not only impacts the loads the ice can exert on a structure, but also advents the downtime that can be experienced by a tanker loading at an offshore terminal, the risk associated with approaching and leaving the tankers at the terminal and ice scour. The ice cover can also impede tankers when (raveling in areas of ice convergence. In 1994 Amoco began working with AARI on the development of a coupled ice-ocean dynamics model considering the importance of this work, a parallel study was also initiated with IceCasting, a Western firm, and NORDECO.

Numerical models have been developed to simulate the ice response to wind forcing, but in many cases, the effects of the ocean dynamics are unaccounted for. After considerable discussion with Russian scientists familiar with the current regime of the Kara Sea, it was decided that, for reliable ice drift data, a model should be developed that incorporates both ice dynamics (thickness, convergence, stress, deformation, ridges, leads, etc.) and ocean dynamics. Including both barotropic (tides and storm surges) and baroclinic (thermohaline) circulation. To accomplish this task, it was decided to couple a state-of-the-art elastic-plastic ice model with a fully three-dimensional ocean circulation model.

During model development, both AARI and the IceCasting - NORDECO team performed idealized test calculations and four Kara Sea simulations. The simulation periods were chosen to coincide with available satellite observations or drifting buoy data, thus providing a means of model validation. Both teams were quite successful at simulating the motion of the ice cover. We now possess state-of-the-art capabilities for simulating ice behavior in the Kara Sea. These models may also be easily modified for predicting the drift of the ice cover in other Arctic Seas such as the Pechora Sea.

### Ice Scour Studies

In addition to the ice conditions, we need to have a good understanding of the conditions on the sea floor. A knowledge of ice scour is needed to estimate the burial depth of offshore pipelines. Soil, permafrost, and coastal processes near the shore also need to be understood for selecting the best shoreline crossing for the pipeline.

Two offshore geophysical surveys nor Karasavey have been conducted for Amoco. One in 1992 by Eco-System and another in 1993 by AMIGE. Some of the results of these studies are presented in Figures 9. Figure 9 is a mosaic of a side scan radar survey of the sea floor. With the ERS-1 imagery and the ice scour survey data, we were able to correlate the formation of ice gouges with the formation of ridges and ice movements in the Kara Sea. However, repetitive mapping of the seabed is required for many years to come in order to identify the age of the deep gouges observed during the two years of survey.

### CONCLUSIONS

- Numerous engineering studies have been conducted onshore and offshore the Yamal Peninsula in the Kara Sea. These studies have shown that it is feasible to export hydrocarbons from the Yamal Peninsula to markets using marine systems.
- These studies have greatly improved our knowledge of the long term statistics for environmental processes and (ship operations in the Kara Sea.
- They also provide the necessary Information for setting design criteria for the different components of our export system.
- The field expeditions were key to properly understanding the Russian historical data, ship performance in ice and ice environmental and seabed conditions.
Figure 2: View of an Ice Hummock Field, 1995 Kara Sea Ice Expedition

Figure 3: Locations of Predicted Zones of Compression in the Kara Sea (AARI, 1993)
Figure 4: Areas in the Russian Arctic where Amoco personnel have worked on the ice or from an icebreaker.

Figure 5: Ice Drift Results from ARGOS Buoy Data in 1993 in the Kara Sea.
Figure 6a: Ice motion vectors from the NORDECO Ice dynamics model. 1 May 1993.

Figure 6b: Calculated ice stresses from the AARI Ice dynamics model. 1 May 1993.

Figure 7: Position of the landfast ice edge boundary in the Knra Sea during 1993.
Figure 8: Ice conditions in the Ob' Gulf at the end of April, 1992.

Figure 9: Ice scour off the west coast of Yamal, 1993.
Arctic Tanker Trafficability Studies for Yamal

Shankar Bhat - Amoco Corporation, USA
Kimmo Juurmaa - Kvaerner Masa Yards, Finland
A. I. Brovin, A. Ya. Buzuyev - AARI, Russia

ABSTRACT
Over the past three years, several Arctic tanker trafficability studies have been carried out by Amoco utilizing Western consultants and Russian Institutes. These studies were part of Amoco’s Arctic engineering studies for Yamal. Newly built ice-breaking tankers of 40,000 to 120,000 tonnes deadweight capable of operating in the Kara Sea year-round are being considered. The proposed preliminary plan for liquid export includes the placement of a storage and loading terminal for LPG in 30 m of water offshore Kharasevey and a crude oil loading terminal in about 15 m water in the Ob Gulf offshore Cape Kamenney.

Hydrocarbon liquids would be transported by the ice-breaking tankers to an openwater pod in Russia, and possibly to a major European market such as Rotterdam. Although most of the distance from Yamal to Rotterdam is in open water, ice transit issues and times have a major impact on feasibility and cost. Therefore, it becomes critical to assess the data available on ice navigation in these areas, and to consider how such data obtained from existing ships of small displacement can be extrapolated to larger ice tankers using Russian and/or Western models for Arctic ship trafficability. This is an issue which merits discussion in technical circles. It is the objective of this paper to initiate such discussions. Amoco has carried out several studies on Arctic tanker trafficability, using Western and Russian institute consultants. In order to identify and address the key issues, and to estimate the transit times. Studies done for Amoco provide a good background for a discussion of issues. It is not our objective to summarize the Amoco study results here.

INTRODUCTION
Amoco has been conducting technical and economic studies on options to transport hydrocarbon liquids from Yamal. A number of studies covering the whole spectrum of key technology and data issues have been carried out. An overview of the total study program undertaken by Amoco is given [1]. Amoco’s studies in the area of Arctic tankers are summarized in [2]. The objective of the present paper is to provide an overview of some issues related to Arctic tanker trafficability studies.

Preliminary plans are to transport hydrocarbon liquids from Yamal by ice-breaking tankers to an openwater port in Russia, and possibly to a major European market such as Rotterdam. Although most of the distance from Yamal to Rotterdam is in open water, ice transit issues and times have a major impact on feasibility and cost. Therefore, it becomes critical to assess the data available on ice navigation in these areas, and to consider the use of such data obtained from existing ships of small displacement for predicting the performance of larger, new types of ice tankers. These are issues which merit discussion, and possible further work. Such work could lead to capabilities to make more accurate predictions on Arctic tanker transit times during project planning stages for the Russian Arctic.

OBJECTIVES OF SIMULATIONS
Arctic tanker transit simulations that were carried out had the primary objective of estimating transit times during the project life, which was assumed to be 20 years. This required the calculation of transit times for every month of the year, during years with winters of different severities. These calculations allowed us to estimate the required number, size and power of tankers, and the required storage volumes. Transit routes studied are indicated in Figure 1.
Anyone who has been on an Arctic voyage will recognize the wide spectrum of parameters that can have an impact on the transit times. Ice thickness, strength properties, snow thickness, temperature, aerial extent and sizes of ridges and rubbles, the degree of consolidation of ridges and rubbles, presence of rafted ice, the frequency, duration, and the intensity of occurrence of ice compression, visibility, etc., influence the transit times. All of these factors have spatial and temporal variabilities. Another set of parameters relate to the tanker. These include the bow form, reamers, friction coefficient, mass and added mass, resistance and propulsion, backing distance during ramming, heeling system, water wash system, etc. Navigational tactics such as convoy arrangements and active ice navigation to avoid heavy ice and to make use of leads and thin ice can of course have a significant effect on transit times. Considering the large number of factors, many of which have spatial and temporal variabilities, any transit simulation to be performed can only be approximate. How best to capture the most important effects by analytical models and appropriate input data is the main question.

A number of models for Arctic ship transit simulation, which have been developed over the years, exist in Russia, Finland, Canada, USA, and elsewhere. An extensive amount of work has been done to date, by analyses, model testing, and full-scale measurements and data collection using icebreakers from USA, Canada, Finland, Sweden, Germany, and Russia. For the Yamal trafficability studies discussed in this paper, primarily two models have been used. These are the Kvaerner Masa Yards (KMY) model and the Arctic and Antarctic Institute (AARI) model. The KMY model is considered by us to be representative of the Western models, the AARI model is representative of the Russian models. One objective of this paper is to briefly describe the trafficability results from these two models, to highlight the major issues, and to briefly point to possible future steps that could be undertaken to make the best use of technology developments both in the West and Russia in this particular area.

Each of these Arctic ship transit models has its own history. For background, a very brief historical background on the KMY and AARI models is given below.

The KMY model was developed originally as early as the mid-1970s. At that time, the model was used to optimize the Finnish Icebreaker fleet and some transportation systems like the oil transportation fleet along the Finnish coast. Applications for LNG transportation in the Canadian Arctic, as well as for the cargo transportation to and from Russian Arctic, were developed in the late 1970s and early 1980s.
The KMY model has been continuously upgraded as new information has been created on ice conditions and their influence on the performance of icebreaking vessels. In the 1980s, a large amount of data was collected onboard Finnish icebreakers and cargo vessels during their regular operation in the Baltic. This data was used to verify the model and also to recognize those parameters in the ice conditions that have significant influence on the fleet performance. Later on, the data from all full-scale trials performed was used to continuously improve the equations used in the model. Thus, the model has also served as a tool to develop new designs for ice-breaking vessels and to estimate the influence of the new features in the total economic task.

The KMY model is a mechanistic model, and it requires somewhat detailed input on ice conditions, including ice thickness distribution along the route and the distribution of number and sizes of ridges. Somewhat detailed input is required on the ship parameters, including main dimensions, hull form, propulsion system performance, etc. The dynamic force balance equation applicable for ship motion in ice is then solved incrementally, from the solution for speed, distance traveled, etc. Figure 2 is a flowchart of the model, and Figures 3A and 3B show typical example outputs in graphical form, for a short segment of the route. A complete simulation along the length of the route can be carried out to get total transit time and average operating speed.

Figure 2. Flow chart of KMY transit simulation model.
Die AARI model was developed in the early 1980s as a result of generalizing multiyear special observations of the motion of icebreakers and ships in real arctic ice conditions in the Russian Arctic [3]. Based on the data, empirical dependencies of the effect of major characteristics of ice cover (concentration, thickness, age categories, amount of hummocking, fracturing, degree of ice destruction, as well as snow height and ice compacting) on the ship motion were obtained. This allowed the creation of a model for calculating technical and operating velocities of ships at any combination of indicated ice characteristics [4].

The AARI model consists of two parts. The first part is a transition from a general distribution of ice characteristics in the navigation region (which is recorded on conventional charts of airborne ice reconnaissance) to ship motion-related ice characteristics along the route. The second part of the model is the calculation of motion velocities of the icebreaker, single ship, and a convoy of ships, and this depends on the technical parameters of the vessels. At first, the technical velocity of ship motion (this is a maximum feasible velocity) in a specific ice zone is calculated, and then the expected operating velocity is estimated [5].

As a calculation example on the basis of AARI's multiyear ice conditions in the segment between Kara Gate and Kharasavey, in May 1985, shown on Figure 4, the data that is input into the AARI model is taken from the composite ice chart (Figure 4), and is shown on Table 1. The model results for calculated average operating speeds and transit times are shown on Table 2 for three cases: Artika type icebreaker traveling alone, a 120,000 dwt icebreaking tanker, and a standard convoy (Artika + UL). Results are given for both the shortest variant and the optimal variant, with and without the pressure.

APPLICATION OF TWO MODELS TO A YAMAL TANKER PROBLEM

Amoco's studies for Yamal have attempted to combine the best from the Western and Russian scientific communities. Consequently, both types of models were used. We will now briefly describe some results
Figure 4. Actual ice cover distribution in mid-May of 1985, western Kara Sea.

Table 1: Length of uniform ice zones and corresponding ice characteristics by the shortest and optimal navigation variants.

<table>
<thead>
<tr>
<th>Zone Number</th>
<th>Length of the Zone (miles)</th>
<th>Number of Ice Gradations</th>
<th>Ice Concentration, units</th>
<th>Ice Thickness, cm</th>
<th>Floe Dimensions, m</th>
<th>Amount of Hummocking, units</th>
<th>Degree of Destruction, units</th>
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<td>The Shortest Variant (B-2)</td>
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of application of the two models discussed above for one specific problem, and then discuss the issues. We will consider the problem of predicting the round-trip transit times from the Murmansk area to an offshore loading terminal near Kharasavey, on a year-round basis, during the life of a project. A 120,000 DWT icebreaking crude oil tanker capable of independent navigation is considered. Such tankers do not exist currently, and predictions made on transit times are used in making project decisions. This is why it is very important to make the best possible predictions using available technology.

The KMY study results for this case were generated during the initial screening studies for various possible transportation options. (A brief outline of the transportation options considered is given in [2].) Monthly average transit times were computed for three years representative of mild, average, and heavy ice conditions. The ice conditions input into the KMY model were based on data available to KMY, collected through several past field expeditions. The input ice data included ice concentration, thickness distribution, number of ridges per kilometer and height distribution of ridges for the different segments along the route, for every month of the year. Results for transit times tend to be sensitive to input data on ridge sizes and spacing, and also to consolidation of ridges. Admittedly, this type of analysis requires a substantial amount of data. The data available was not extensive enough, and suitable assumptions were made based on best judgment. This was considered acceptable for the screening study. Presence of ice pressure was not considered in this analysis, since not enough data was available. Also, the analysis assumed straight-line transit, without detours to make use of cracks and leads in ice, as is likely to occur in reality when the ice conditions are heavy. These two neglected effects counterbalance each other to some extent. An ice-breaking tanker with a compromise bow designed for both ice and open water performance was assumed. The following were the main particulars: Length (waterline) = 275 m, Beam = 46 m, and draft = 15 m. Conservatively assumed level ice performance curve resulted in an icebreaking capability at 2 knots of only 1.7 m. Average transit times computed using the KMY model for transit between Murmansk and a Kharasavey Offshore Terminal are given in Table 3 for a few selected months (September, April, May). The round-trip transit times given in Table 3 (and in subsequent tables) include 40 hours for loading and unloading.

In the AARI study, transit times were calculated on a monthly average basis for three representative years, with easy, medium, and heavy ice conditions. The easy, medium, and heavy classifications are qualitative, and conventional. The tanker parameters were the same as in the KMY study. Detailed input on the bow shape, friction coefficient, etc., is not needed for the AARI's empirical statistical model. For adjusting the empirical statistical model to a new type of ship, its main technical parameters (power and particulars) are required, as well as performance curve in compact level ice for a specific season of the year. (Imbedded in the level ice performance curve are the influence of bow shape, friction coefficient, etc.) For the years considered, AARI used all of the available data on navigational ice and generated the input values for the analysis. Selected results of the analysis are given below. In Table 4, the numbers in parenthesis are round-trip times when ice pressure is 0 or 1 (1 unit, 1 a Russian scale). Some useful conclusions can be drawn by a proper comparison of the results given in Tables 3 and 4, as these results represent two different approaches to the same problem. One approach has a better
Table 3: Selected monthly average round-trip transit times between a transshipment terminal near Murmansk and a Kharasavey Offshore Terminal, according to KMY's Initial screening study.

<table>
<thead>
<tr>
<th>Month</th>
<th>Years with Mild Winter (Days)</th>
<th>Year with Average Winter (Days)</th>
<th>Year with Severe Winter (Days)</th>
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<td>4.8</td>
<td>4.8</td>
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<td>9.4</td>
<td>13</td>
<td>17.1</td>
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<td>May</td>
<td>7.3</td>
<td>12.4</td>
<td>16.4</td>
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</tbody>
</table>

Table 4: Selected monthly average round-trip transit times between Murmansk and a Kharasavey Offshore Terminal, according to AARI's Initial study.

<table>
<thead>
<tr>
<th>Month</th>
<th>Years with Mild Winter (Days)</th>
<th>Year with Average Winter (Days)</th>
<th>Year with Severe Winter (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>5.5</td>
<td>5.5</td>
<td>6.5</td>
</tr>
<tr>
<td>April</td>
<td>59 (6.2)</td>
<td>6.4 (6.8)</td>
<td>12.6 (18.4)</td>
</tr>
<tr>
<td>May</td>
<td>6.4 (7.2)</td>
<td>6.6 (9.5)</td>
<td>11.4 (16.0)</td>
</tr>
</tbody>
</table>

model of the mechanics of ship motion in ice, and the need for more data than is available. The second approach is empirical statistical, and therefore, is almost completely based on transit time data collected using existing ships, which are small compared to the tanker being studied. This approach does not model the mechanics of ship motion through ice, and consequently may not properly account for any effect of ship size. But, in this case, we do have the data needed to apply this approach.

Now let us compare the results in Tables 3 and 4. First, we may note that the round-trip transit times in Tables 3 and 4 are different even for September, which is an ice-free month. This difference is due to the fact that the round-trip distances used in the two analyses were not the same. Results in Table 4 are for travel to and from Murmansk, not to a possible transshipment terminal location. The difference in round-trip travel distances accounts for about 0.6 day of transit time difference between the two Tables. This correction could be applied to either Table 3 or Table 4. If we apply this to Table 4, the following table is generated.

Table 5: Selected monthly average round-trip transit times between a transshipment terminal near Murmansk and a Kharasavey Offshore Terminal, according to AARI's Initial study.

<table>
<thead>
<tr>
<th>Month</th>
<th>Years with Mild Winter (Days)</th>
<th>Year with Average Winter (Days)</th>
<th>Year with Severe Winter (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>April</td>
<td>53 (5.8)</td>
<td>5.8 (6.2)</td>
<td>12.0 (17.8)</td>
</tr>
<tr>
<td>May</td>
<td>5.8 (6.6)</td>
<td>6.0 (8.9)</td>
<td>10.8 (15.4)</td>
</tr>
</tbody>
</table>

Table 3 and Table 5 can now be compared, for no ice pressure, since this was the assumption in generating Table 3. It can be seen that the AARI results for round-trip times in April and May are significantly less for all cases without ice pressure. This is attributed to the fact that the AARI analysis is based on real voyage.
data collected over the years. In real voyages, ice navigation plays an extremely important role. Heavy ice is avoided to the extent possible. Polynyas, offshore leads, thin ice stretches, or cracks are used to the extent possible. On the other hand, KMY's analysis results were conservative, and this is consistent with the fact that conservative assumptions were made with regard to the ice conditions, as requested by Amoco.

A few comments can now be made on the advantages and limitations of these models. AARI's empirical-statistical model can use AARI's extensive navigational ice database. This is its most important advantage. It was pointed out in the previous paragraph that the model includes the effect of ice navigation. Which is also an advantage. A definite disadvantage of this model is the empirical nature of the dependencies of the calculated operating characteristics. The mechanics of ship motion in ice are not modeled. Therefore, to get accurate predictions for new types of ships, it is desirable to have tests in full scale conditions. Data from such full-scale tests can be used as input into the AARI model. Also, some difficulty for the Western user is the fact that the bases for the empirical correlations used in the model are not explained in the Western literature, making it difficult to judge the validity of results produced for new types of ships or new traffic situation with independently operating tankers or where the relative size of icebreakers compared to the assisted tankers is completely different from that in the statistics. The first description of the correlations and dependencies of the model will appear this year in a INSROP Working Paper 155. Planning and Risk Assessment (4:5).

KMY's model includes the mechanics of ship ice interaction adequately, and consequently is better able to model effects such as the size effect of a large tanker on ramming performance. A large icebreaking tanker such as this does not exist today. At the time these analyses were done, there was not even a fully developed concept design. KMY's model is such that it can be used to perform sensitivity analyses to design changes, changes in dimensions or other key parameters, etc. For this type of application, it is most important that the ice conditions are described in detail so that the performance of the proposed design can be evaluated also in other ice conditions than level ice. The use of equivalent ice thickness to describe ridges, etc., could lead to wrong conclusions when estimating the influence, for instance, of rearrangements or similar features. During the concept design stage, simulations carried out using this model with laser profiler-based ice data helped us to make a decision on the required power for the independent navigation. Such a model is extremely useful. This is why there are a number of such models in the Western world with similar, but not necessarily equal, capabilities. Various aspects of these models, such as the modeling of the level ice resistance and the ridge resistance, have been verified to various degrees by full-scale measurements. In consultation with Amoco, conservative assumptions were made by KMY with regard to the ice conditions to be used in the analyses. Thus the results generated were conservative, as is appropriate in a very preliminary study.

AARI analyses showed the effect of ice pressure. With one ball pressure, small-to-moderate increases in round-trip times can be expected in mild-to-average years, and large increases in round-trip transit times in the work months can be expected in the severe years. A probabilistic analysis of how round-trip times will be affected by ice pressure has not yet been done.

To avoid possible misunderstanding on theuse of the above numbers in the Yamal project, the following should be noted. Subsequent to the initial trafficability studies mentioned above, conceptual designs were developed for a 120,000 DWT icebreaking crude oil tanker and a 110,000 cubic meter icebreaking LPG carrier. Both these ships have significantly better ice-going capabilities than the 120,000 DWT tanker used in the initial trafficability studies. Round-trip times corresponding to the conceptual designs that have been developed are lower than that in any of the tables above.

In the course of Amoco's study program, three Arctic tanker trafficability studies have been carried out on 40,000 DWT ice-breaking tankers transiting from Cape Kamenny to Murmansk area. These studies were carried out by KMY, CNIMF, and AARI. Some results for 40,000 DWT tankers from one of these studies are presented in [6]. All of these studies used that it is feasible to transport tankers from Cape Kamenny to Murmansk, and a number of issues remained to be examined in future stages of the project.
POSSIBLE FUTURE STEPS

We consider it desirable to go a little deeper into the comparison between the two models, for a better understanding of the differences in approach and the consequences on predicted results. This may help us make better predictions using ice data existing in Russia. One approach that we could take is to make a rigorous comparison for one test case. This could be done by calculating transit times for a voyage along a route for which we have good, quantitative ice data, such as the laser profiler data. Russian model(s) would do the calculation using the archived ice data available in Russia, not using the laser profiler data, since the detailed quantitative ice data obtainable from laser profiler is not needed to use the empirical-statistical models. Western model(s) would do the same transit calculation using the ice ridge profiles obtained using the laser profiler, since these models do require such detailed ice data. These calculations could be done for an existing ship, such as the Arktika class icebreaker, and a new type of ship, such as a large ice-breaking tanker. Then, a comparison of the predicted results could be done. Conclusions drawn from such a comparison would help us make better predictions for new types of ships using existing ice data.

Another future step that Amoco is actively considering is to develop a total transportation system simulation model. Other companies are also pursuing this objective. Such a model will be capable of making Monte Carlo type simulations of the behavior of the transportation system over the life of a project. Such a model will have multiple components, including the ice and openwater voyages, multiple tankers, modeling of loading and unloading, impact on performance of Icebreaker support, etc. The simulation model will need to be able to use the existing ice data. The model should, of course, be able to simulate the performance of new ship types. The model comparison work discussed above may provide useful insights on the proper usage of existing ice data in a total system simulation tool.

CONCLUSION

A number of Arctic tanker trafficability studies have been carried out for Amoco, using both Western-type models and Russian institute models.

A comparison of results for one case is given in this paper. In order to discuss the issues. A step to move forward in this technology area is proposed.

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Ice Loads on Multi-Legged Structures in Cook Inlet

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ABSTRACT
Three multi-legged offshore oil platforms in Cook Inlet were instrumented from 1966 to 1976. The results of this effort have produced a long-term ice data set spanning a period of ten years. A brief summary of the peak ice load data recorded from these platforms is provided, along with probabilistic estimations of extreme ice loads based on this data set. A deterministic analysis of extreme ice load on Cook Inlet platforms is also presented. The analysis considers the ice properties, leg diameter and spacing, and ice movement velocity. Results of the probabilistic and deterministic analyses for extreme loads are compared with original design loads.

INTRODUCTION
Multi-legged structures have been used successfully in Cook Inlet for 30 years. In Cook Inlet, there is over 400 platform years of experience without a major failure. Despite our long operating history in the area, there is very little published information on the ice loads on these structures. In a widely read landmark paper by Blenkarn (1970) written a quarter century ago, some ice force measurements made in Cook Inlet before 1970 were presented, along with correlations and interpretations. To our knowledge, there has not been any additional full scale data from Cook Inlet published in the past 25 years. A few recent publications have discussed this subject (Ut and Turner (1992), Visser (1992, 1993, 1995) and newly revised API recommended practice on Ice design criteria, RP2N). These recent publications speculate that design ice loads used for some early platforms could be too low, based on latest calculations. The purpose of this paper is to shed some new light on this issue by reporting a summary of additional full scale data and analyses.

DESCRIPTION OF ICE FORCE DATA
Strain (convertible to total ice load) and acceleration data from three Cook Inlet platforms were recorded on strip charts during several ice seasons between the years 1965 and 1976. The three platforms were Anna, Bruce and Dillon, all installed in 1966. Their location in Cook Inlet is shown in Figure 1. Figure 2 gives the main dimensions and leg spacings of the platforms. A review and analysis of the extensive data collected from the three platforms is reported in Knapp and Bhat (1989). Most of the available data was recorded on strip charts at a slow chart speed of 6 in/hr. On the average, 720 ft of strain charts and an equal length of acceleration charts were obtained for each platform each season. A short sample of strain data is shown in Figure 3. Since the fundamental natural frequencies of the platforms are around 1 Hertz, much higher chart speeds are needed to get information on platform dynamics. The resolution is such that spectral analysis techniques of random signal analysis cannot be used to analyze the data. Therefore, ice failure pressures could not be derived from the force magnitudes. However, information on peak loads and accelerations can be extracted. Data quality was judged to be good, based on visual examination of the charts for trends, reversals etc. and an examination of the correlation between strain and acceleration. An example of the correlation observed in this data is shown in Figure 4. A similar examination of other platforms over many years showed that the data to be of unacceptable quality. This is probably because platform Baker was installed in 1965, before Amoco's strain measurement instrumentation and techniques had sufficiently evolved. As indicated in Blenkarn's (1970) study, unfortunately, the data were recorded by field personnel, and no accompanying ice observations were made.
Figure 1. Location map of Cook Inlet platforms (from Visser, 1992).

Figure 2. A typical Cook Inlet platform (Anna).
Figure 3. Sample of strain gauge data.

Figure 4. Correlation between ice force and platform acceleration.
DATA ANALYSES

In Cook Inlet, ice moves in and out of the Inlet with tidal currents. There are two tide cycles (two ebbs and two floods) in a day. Lists of the maximum force for each tide cycle were generated from the strip charts. The daily maximum ice loads were then tabulated from these lists, and plotted on lognormal probability paper for each of the years for which data was available. There was some year to year variation in ice forces, as expected. It was also observed that the variation from year to year was generally consistent with the variation in the 30-day accumulations of freezing degree days, as anticipated in Blankarn (1970). Generally, there were more peaks with higher ice loads in years with more severe winters. However, because of the random nature of ice loads, a good correlation between maximum yearly values of 30-day accumulations of freezing degree days and the recorded annual maximum force was not obtained.

Figure 5 and 6 show all of the daily maximum ice load data for platform Anna and Dillon, for all years for which data was collected, displayed on lognormal probability plots. Data from platform Bruce also shows a similar trend, with force values close to (and somewhat less than) those for Platform Anna.

![Graph showing lognormal probability plots for daily maximum ice forces on Platform Anna, 1966-1976.](image)

Figure 5. Daily maximum ice forces recorded from Platform Anna, 1966-1976 (plotted on lognormal chart).

Figure 7 shows the lognormal probability density functions for daily maximum forces for the three platforms, based on the straight line fits to all available data from these platforms, as in Figures 5 and 6. The distributions are generally consistent. Some variability is expected in any real full scale data set of natural forces, such as these. Figure 8 shows calculated probability functions for annual maximum ice loads on the three platforms. The equation used for this calculation is given in Appendix 1. The calculated probability density functions of annual maximum forces for the three platforms are similar. The mean values are in general agreement with the mean values of annual peak forces in the measured data. The standard deviations are different, reflecting the fact that the amount of data that was available was not the same. The platform
Time and Freezing (1980).

The average duration of the ice shelf is calculated given the ice thickness, the ice surface temperature, and the ice shelf thickness. This information is used to calculate the ice load on a fixed, vertical, or horizontal platform. Assuming that the study is

**DETERMINISTIC ANALYSIS OF DESIGN ICE LOAD**

Based on measured data, the 100 year ice load and the extreme ice load are calculated. The 100 year load is calculated from the annual ice thickness and the ice surface temperature. The extreme ice load is calculated from the maximum ice thickness and the ice surface temperature.

![Graph showing daily maximum ice loads recorded from platform, 1960-1979.](image)
Figure 7. Probability density functions for daily maximum forces on three Cook Inlet platforms.

Figure 8. Probability density functions for annual maximum ice load.
manner at tower loads. Sufficient amount of data is given in Blenkarn (1970) to confirm this statement, and no contrary data is known to the authors. Consequently, we will assume that the ice is warm (-3°C surface temperature) and that it has a peak strength characteristic of ductile to brittle transition.

The temperature profile is given by

\[ T_j = T_{surface} - (2j-1)\left(\frac{T_{surface} - T_{bottom}}{20}\right) \]  

(1)

where \( T_{surface} \) is -3°C, \( j \) is an index varying from 1 to 10, and \( T_j \) is the layer temperature. \( T_{bottom} \) is the bottom surface temperature, taken to be -1.8°C. The mean temperature turns out to be -2.4°C.

Given the temperature of each layer, the brine volume profile is now calculated using the equations given by Cox and Weeks (1983).

Pure Ice density as a function of temperature is given by (metric tons/cubic meter):

\[ \rho_i = 0.917 - 1.403 \times 10^{-4} T_j \]  

(2)

The estimated bulk density \( \rho_{bulk} \) is 0.89 tonnes/m³.

Average Ice salinity (parts per thousand, ppt) of sea ice as a function of ice thickness for \( h \geq 0.4 \) m is given by

\[ S = 7.88 - 1.59 h \]  

(3)

For ice thickness less than 0.4 m, a different equation should be used (see Cox and Weeks, 1974).

Equation 3 gives an average salinity of 6.8 ppt for a sheet ice thickness of 0.65 m. According to Blenkarn (1970), the average salinity of Cook Inlet Ice is 4 to 6 ppt. Therefore, we assume an average salinity of 6 ppt.

The total porosity of each layer can now be calculated as

\[ (\psi_j) = \frac{1}{\rho_j} \left( \rho_{bulk} \frac{S}{\rho_i} \right) (1 + F2_j) \]  

(4)

where

\[ F1_j = -4.732 - 22.45T_j - 0.6397 (T_j)^2 - 0.01074 (T_j)^3 \]

\[ F2_j = 8.903 \cdot 10^{-2} T_j - 1.763 \cdot 10^{-4} T_j - 6.33 \cdot 10^{-4} (T_j)^2 - 8.801 \cdot 10^{-4} (T_j)^3 \]

Total porosity varies from 0.12 to 0.173 for the various layers.

The strain rate corresponds to ductile to brittle transition, \( 10^{-3} \) (1/s). The strength profile can now be computed as follows:
with $\varepsilon = 10^{-3} (1/s)$. The resulting strength profile is given in Figure 9. The mean ice strength is calculated to be 2.224 MPa. Having determined the mean ice strength, the ice load on a single isolated leg is calculated applying the methodology similar to that given in Timco (1986).

\[ \sigma_I = 37 \left( \varepsilon \right)^{0.22} \left( 1 - \frac{(\rho I)}{0.27} \right) \]  \hspace{1cm} (5)

The leg diameter of a typical Cook Inlet structure is 4.27 m. This results in an aspect ratio (diameter/ice thickness) of 6.6. Indentation coefficient can be computed according to Afanasev (1973) for aspect ratios greater than 1, using the following expression (Timco, 1986):

\[ I = \left( \frac{5D}{D + 1} \right) \]  \hspace{1cm} (6)

The Indentation coefficient is comes out to be 1.327. Now, the total force on one leg is calculated by the Korzhavin equation:

\[ F = m k D \sigma_{mean} \]  \hspace{1cm} (7)

where $m$, the shape coefficient, is 0.9 for circular shape of the leg cross-section, and $k$, the contact factor is 0.5 for the poor contact associated with rapidly moving Cook Inlet ice. $\sigma_{mean} = 2.224$ MPa, as calculated from equation (5).

The product $m k D$ has a value of 0.697. API RP 2N, based on Blenkarn (1970) recommends a lower value of 0.55 for Cook Inlet ice. If we use an Indentation ratio of 1.2 as applicable for granular ice, the product comes out to be 0.54. We will use the more conservative value of 0.597 as computed above.

From equation (7), the total force per leg is calculated to be 3.7 MN. This results in an effective pressure on a single leg of $F/kD = 13$ MPa. This is in agreement with Blenkarn’s (1970) measurements of the ice loads on Cook Inlet platforms. Maximum measured ice pressures were of the order of 1 MPa, considering both variations in ice thickness and temperature. For similar conditions (velocity, temperature, thickness, etc.)
and aspect ratio), comparable results were found by Lipsett and Gerard (1980) on Hondo River Bridge in Alberta. They recorded a maximum pressure of 1 MPa.

Based on the results from model basin tests (Evers and Wessels, 1986) and field obsewallons (Blenkam, 1970), the maximum load on a four-legged jacket platform is twice the load on a single isolated leg, regardless of ice movement direction. This is applicable to situations where the ratio of the leg spacing to leg diameter is about 5, as in the case for Cook Inlet structures (Timco, 1986 and Evers and Wessels, 1986). In addition, model tests have also clearly shown that the loads on individual legs are not simultaneous. Therefore, the total load on a platform is $2 \times 3.7 = 7.4$ MN.

The above calculations are for smooth undeformed ice. However, in Cook Inlet we have to deal with rafted ice, ridges and stamukhas, and dynamic loading. This issue is discussed in Blenkam (1970). The peak loads due to these effects can be as much as 1.5 to 3 times the level ice loads. When the level ice loads are high, the ratio tends to be low and vice versa. The current design practice, initiated by Blenkam (1970), is to increase the maximum level ice load by a factor of 2 to account for these ice features and dynamic loading. This is justifiable from a variety of considerations, such as the consideration of rafted ice thickness (a maximum thickness of twice the maximum level ice thickness) or ridge consolidation (a maximum consolidated thickness of twice the maximum level ice thickness). If we use 2, then the design ice load for the structure becomes $2 \times 7.4 = 14.8$ MN = 3300 kips. This is close to the 100 year value reported earlier in this paper (14.2 MN or 3200 kips), based on analysis of measured data.

There are two major differences between the above deterministic analysis and those in current practice for Cook Inlet platforms, as in Visser (1992). These are: (1) the temperature of the ice to be used for the extreme ice load calculation and (2) the assumed ratio of the total load on the platform to the load on a single leg. There is sufficient evidence in Blenkam (1970) to indicate that the maximum loads on Cook Inlet platforms occur when the ice is warm. With regard to the multiple to be used for the total load on the platform, we used the available information which comes from the ice model tests reported in the literature (Evers and Wessels, 1986), deviating from a value of 2.83 assumed by Blenkam in 1965.

**COMPARISON OF CALCULATED DESIGN LEVEL ICE LOADS**

The two extreme load values, one calculated deterministically from physical properties of ice and the second (100 year load) computed using a probabilistic analysis of the full scale data from platforms, are in agreement with each other. Both these extreme loads are much less than the original design ice loads for the structures. The three platforms were designed for an ice load of 21.2 MN (4760 kips), which is about 40% higher than the estimates given in this paper.

The maximum measured ice load during the approximately 10-year period of monitoring was 7.5 MN (1680 kips).

**GENERAL COMMENTS AND OTHER DESIGN CONSIDERATIONS**

The measured data and analysis suggest that design ice loads could even be lowered from the values assumed in the original designs for these platforms. Other Cook Inlet platforms were designed with even higher ice loads, as noted by Visser (1992) and Utter and Turner (1992).

Structure design requires an examination of various possible failure modes, including those due to extreme load, fatigue, corrosion, and appropriate combinations of these factors. Early designers of Cook Inlet platforms did not have adequate data to set fatigue design criteria, and the designs were based on extreme loads, assuming that such designs would also be satisfactory for fatigue. New data reported in this paper can be used to lower the extreme design loads, but care must be taken to ensure that the designs have adequate fatigue strength. This is explained further in the paragraphs below.
During the examination of the data, it became obvious that conditions necessary for design criteria to be based on a rare extreme occurrence are not present in the loading from Cook Inlet ice. To understand why, one must understand what a rare event criteria means, and how it is applied when designing. The concept of 100 year criteria has its basis in hydrology. Its primary purpose was to calculate runoff to size flood channels, bridge openings, retention dams, etc. It worked only because of the very large difference in a runoff volume from an annual rainfall compared to a 20 or 100 year occurrence. The 100 year concept was also applied to the design of tall buildings for wind and to Gulf of Mexico petroleum producing platforms for wind and waves. It worked reasonably well as hurricane affects a Gulf site approximately once in 15 years. The difference in magnitude between hurricane winds or waves and normal extra tropical storm winds or waves is large and, besides, the force is dominated by the drag term (proportional to the square of wind and wave magnitudes). Thus, the condition for a very large difference between an annual force event and a rare extreme event is fulfilled.

Extreme occurrence criteria did not work well for the North Sea. Here, extremes are generated by the same type of storm and the difference between annual and 50 or 100 year extremes was not as great as in the Gulf of Mexico (although the drag domination of force tends to amplify the differences). Early designers that used the extremes for design found that in a short time, metal fatigue problems developed. Evaluating the design structure for metal fatigue from forecast load cycle histograms solved this difficulty, as it showed the need to increase the member strengths in certain platform areas.

The above discussion is included here only to point out the need to take a broader view of design, including extreme events and fatigue. The extreme ice loads in Cook Inlet are well within the original design loads for the three platforms. With regard to fatigue, it is reported in Visser (1993) that the platforms show no evidence of fatigue cracking or other significant underwater damage, even after serving through the original design life.

CONCLUSION

This paper provides a brief summary of full scale ice load data collected from three multi-legged platforms in Cook Inlet during ten years between 1966 and 1976. A summary of the peak ice load data recorded from these platforms is provided, along with probabilistic estimations of extreme ice loads based on this data set. A deterministic analysis of extreme ice load on Cook Inlet platforms is also presented. The analysis considers the ice properties, leg diameter and spacing, and ice movement velocity.

Results of the probabilistic and deterministic analyses for extreme loads are compared with original design loads.

ACKNOWLEDGEMENT

The authors acknowledge the leadership and contribution of A. E. Knapp in carrying out the work reported in this paper.

REFERENCES


APPENDIX A

Let $X$ be a random variable denoting the daily maximum ice force in a winter season, with $x$ being one of the realizations of this random variable. Consider a sample consisting of $n$ values of $X$. Let $Z$ denote the largest of $n$ values (n day maximum). Then $Z$ will also be a random variable, and it can be shown that the probability density function of $Z$ will be

$$ f_z(z) = n f_x(z) \left( F_x(z) \right)^{n-1} $$

(A1)

where $f_x$ and $F_x$ denote the pdf and cdf of $X$. In the present case, these are lognormal, and derived from the data for daily maximum ice forces. The probability density function for yearly maximum ice force can be computed from equation (A1) using $n = 60$ days, since there are about 60 days of significant ice loading in a normal year.
NEW ICE BREAKING TANKER CONCEPT FOR THE ARCTIC (DAT)

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ABSTRACT

The paper gives some background information on the philosophy behind the DAT (Double Acting Tanker) concept and describes the development work done by the Arctic Research and Development group of Kvaerner Masa-Yards in Helsinki, Finland. The DAT concept combines the historical development of the icebreakers with bow propellers and modern technology with propulsion systems. With the new concept it is possible to solve the problem that arises when a cargo vessel must be able to proceed through heavy ice conditions and still be able to operate safely and efficiently on a relative long open water voyage.

The basic philosophy has been known for almost as long as there has been engine powered traffic in ice bound waters. But it was only the development of new azimuthing propulsion systems that made it possible to take full advantage of the fact that best icebreaking performance is achieved with 100% power at the bow.

The DAT concept was first tested in full scale with two smaller icebreaking vessels and with a 16,000 tdw icebreaking tanker. The experiences with these vessels are described in the paper with some results from the full scale ice trials. Based on these experiences a DAT was developed for the Pechora Sea conditions in the Russian Arctic. The paper describes the general requirements that were set for the tanker and gives also some results of the ice model testing done with alternative solutions in Masa-Yards Arctic Research Centre (MARC).

The DAT concept that was developed for the Pechora Sea is a potential alternative to be used within many of the oil and gas projects in that area. It also gives possibilities to utilize the marine transportation solution even in more severe conditions further East.
1. HISTORICAL BACKGROUND

The idea of using bow propellers on icebreakers is very old, the first "American type" icebreakers were built as early as 1880's. The idea was based on the experience of captains operating in icebound waters, who had learned that in some cases it was easier to proceed through difficult ice conditions running their vessel astern. This experience has been verified by several captains since those days. The problems were how to steer the ship when operating in that mode, low efficiency of the bow propellers and of course in the Arctic how to protect your propellers against damage. The solution used was to divide the propulsion power partly to the stern and partly to the bow. This concept was very popular in icebreakers designed for the Baltic and for the Great Lakes. When the modern development of ice breaking ships was started in the late 60's and early 70's with model testing in ice, the model tests were utilized to optimize the power distribution between the bow and the stern and also to find the form and location for the bow propeller bossings (fig. 1).

Since there was a great need for icebreakers operating in the Arctic areas, where the bow propellers were not accepted due to the risk of their damage, a number of alternative ways to improve the performance of icebreakers were developed. As a result of this development these new solutions (airbubbling system, low friction coating, new hull forms etc.) were adopted also in the modern Baltic icebreakers and, although not all the icebreaker captains do agree, their performance could be improved.

2. FIRST APPLICATIONS AND THEIR OPERATIONAL EXPERIENCE

The development of the so called Azipod drive was started to take full advantage of the diesel electric power transmission widely used on icebreakers and also to improve the manoeuvring characteristics of icebreakers without bow propellers. Already with first installation onboard buoy tender Seili (fig. 2) it was clearly shown that the vessel could perform in astern mode better in heavy ice conditions than her sistership operating ahead and even though her sistership utilized the extra thrust created by the nozzle. The experience with Seili also showed, that the vessel could easily be steered when operating astern in ice.
2.1. MV Seili

The vessel before modification had the ice breaking capability of c. 45 cm of level ice when running forward with a power of 1.6 MW. Because of the rudder arrangement the vessel was not able to brake any ice backwards. After the controllable pitch propeller and the rudder was replaced with an 1.5 MW Azipod unit, the performance was enhanced in every respect:

- Ice breaking level ice ahead from 45 cm -> 55 cm, due to better efficiency
- Ice breaking level ice astern from 0 cm -> 60 cm,
- Crossing old channels no problems

The arrangement of MV Seili is in figure 3.

2.2. MT Uikku

The second vessel to get an Azipod was MT Uikku, a 16000 DWT ice breaking tanker, figure 4, owned by NEMARC (Neste and Kvaerner Masa-Yards) and operated by ARCTIC SHIPPING SERVICES, Murmansk in the Northern Sea Route. The vessel was originally designed by Wärtsilä (now Kvaerner Masa-Yards) and built in Germany for Neste Shipping. Today the vessel is operated in the winter primarily in the Baltic and during the summer season in the Northern Sea Route. Occasionally the vessel is also operating in the Arctic during the winter months. This vessel due to the conversion did get before all better maneuvering behaviour. Also ice breaking performance especially when running astern was improved. The ice resistance in level ice in astern mode was 40 % of that when running ahead, figure 5.
2.3. IB Röthelstein

The third vessel, IB Röthelstein, a river icebreaker (Danube river) was delivered from Kvaerner Masa-Yards Helsinki New Shipyards in April 1995, is designed to utilize Azipod propulsion in full. The vessel is designed to break level ice of 70 cm in thickness when running ahead and to break apart/loose 2.5 m thick ice jams. Figure 6 illustrates IB Röthelstein penetrating a ridge (running astern) deeper than the draught of the vessel. The vessel is in operation in figure 7.
Based on these results a comparison was made with the last vessel series with bow propellers, the Urho-Class (Urho, Atle Frey, Sisu and Ymer). In the design of these vessels the experience from the previous vessels as well as model tests was utilized. Special consideration was paid to the shape of the forward bossings. The vessel also was equipped with two rudders. All this gave the vessel excellent icebreaking and maneuvering capability. The effectiveness of bow propellers was tested in several occasions. In the comparison the third vessel is IB Otso, which is one of the latest stages of vessels having two propellers and two rudders in the stem. Figure 8 shows the speed in 0.8 m thick level ice with different propulsion arrangements:

- IB Otso, no bow propellers
- IB Urho, 40% of the power at the bow
- Azipod Icebreaker, 100% power at the end of the vessel going first

The results show the superiority of the Azipod vessel by 1.5 m/s (3kn) to the Otso-class and 2.5 m/s (5 kn) to the Urho-class.

The fact that icebreakers have been usually able to proceed in level ice sometimes backwards as well as forwards and even better is well known fact. Also vessels with two enough powerful (>50% of total power) bow propellers have shown advantage in ice breaking capability. However in today's requirement for economics there is very little justification not to use the most compact and centralized solutions.
Typical ice breaking vessel today has an ice breaking bow and all the propellers are in the stern.

The new vessel concepts offer unique solutions based on existing ideas.

3. DEVELOPMENT OF THE NEW CONCEPT

3.1. Operation philosophy

The mission for instance could be to transport oil and gas condensate from the Pechora Sea area to Murmansk and on to Rotterdam. The possible operation route variants are in figure 9. Of these routes most of the distance can be travelled in open water year-round.

![Route map](image)

On this leg the vessel is sailing bow first utilizing the good open water characteristics. In light ice conditions the vessel can still proceed in bow first mode and depending on the actual traffic and ice condition it can change the running mode to stern first operation. During the wintertime in the Pechora Sea the vessel is operating mostly stern first.

The stern first operation is most effective in the most severe conditions. The vessel in question having the main characteristics shown below is able to proceed through, for example, a 12 m thick ridge without ramming with close to double speed and the dependency on icebreaker assistance is reduced.

<table>
<thead>
<tr>
<th>Length</th>
<th>= 235 m</th>
<th>Breadth</th>
<th>= 38 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draught</td>
<td>= 13 m</td>
<td>Power</td>
<td>= 16 MW</td>
</tr>
<tr>
<td>No of propellers</td>
<td>= 1</td>
<td>Deadweight</td>
<td>= 90000 tonnes</td>
</tr>
</tbody>
</table>

An example of the hull forms tested (two propellers) is in figure 10.
This new concept offers several advantages:

- Open water efficiency like open water vessel
- Superior manoeuvrability
- Icebreaking capability is not in conflict with open water behaviour
- Increased icebreaking capability
- Better overall economy

3.2 Hull form/propulsion arrangement

The hull form of the vessel will have new requirements due to the new operational philosophy. The vessel is designed to operate in heavy ice conditions running astern. In this case the bow can be designed like an open water bow with moderate ice breaking capability. The shape of the ice breaking stern is dependent on ice conditions and the size of the vessel. The power requirement will determine the number of propellers needed to fulfil the operational demands. The stern can be designed for different types of propeller arrangements. However, the recent experience in azimuthing propulsion units has shown their superiority when the vessel is operated in astern mode in ice. Today the largest Azimuth unit built, installed and tested is the 11.4 MW Azipod units onboard MT Uikku and MT Lunni, see figure 11.

The original shape of the stern in these vessels was quite conventional. When one Azipod unit was installed the stern became more spacious and ice could be broken better.
In case of bigger vessels, of course, due to higher power requirements, the number of propulsion units must be increased. The most powerful Azipod unit on design board can absorb c. 20 MW. The number of propellers has certainly affect on the hull form. The increasing number of propellers creates a very flat area in the hull above the propellers. Each operational area has special features, which influence the design. The shape of the Azipod has to be optimized of course to give the maximum performance in the most critical condition. A typical twin Azipod arrangement is presented in figure 12.

As an example the following performance can be achieved with different concepts:

- Conventional tanker/one propeller/ice breaking bow:
  - Open water speed 16 knots with 50% power
  - Ice breaking capability 1.2-1.8 m
  - Efficiency 80% of ordinary open water vessel

- Azipod tanker/one propeller/open water bow/ice breaking stern
  - Open water speed 16 knots with 40% power
  - Ice breaking capability, astern 1.6 - 2.2 m, ahead 0.5-0.7 m
  - Efficiency 100% of ordinary open water vessel

The performance of an Azipod unit is dependent on the possibility/restriction in turning it. In case the unit can be rotated 360°, the maximum propeller thrust is the same both running astern and ahead. In some cases the Azipod cannot be rotated 360°, then the available thrust in the other direction can be 70-80% of the maximum.

The overall performance of the vessel is a combination/compromise of the selected propulsion system and hull form. Model tests in ice have had a significant role in understanding the problematic in running a large scale vessel through heavy ice conditions.
4. MODEL TEST VERIFICATION

First time the idea of breaking ice running the vessel astern came into serious consideration in the early nineties and the results from the preliminary tests were encouraging. The ships tested were capable to proceed through medium thick ridges with continuous motion instead of ramming and the level ice breaking capability required was achieved with considerably smaller power.

In a test series conducted in 1994 four different aft ship versions of an ice breaking tanker were tested. Two of the aft ships were equipped with one Azipod (a conventional and a vertical flow type of stern) and two were equipped with twin Azipods (a twin skeg and vertical flow type of stem). The overall performance of the versions was very similar. However the variants had differences in individual conditions. The model ships were tested in the following conditions:

- level Ice
- own channel
- old channel
- ridges of three different quality
- maneuvering

The results in addition to the comparison between the versions were referred also to the tests done with conventional mode of operation. Figure 13 illustrates the results of tests performed in 0.8 m thick level ice. Compared to conventional ice breaking bow, the modified ice strengthened bulbous bow develops almost 100% higher resistance and on the other hand the vessel running astern gives on average 40-50% reduction in resistance.

The main obstacles the vessel normally meets are the ice ridges. The traditional way of penetrating through the ridges is by ramming. In case the vessel is entering the ridge propellers first (astern) it has a greater chance to go through with less ramming and in some cases even proceeding with continuous motion. The achieved average speed in a 12 m thick ridge can increase by 50-100%.

The efficiency of this new concept is primarily based on the following:

- propellers are allowed to mill/distract ice
- more open stern (less appendages)
- efficient operation of Azipod units (water flow can be directed)
- keeps up the dynamics
- water lubrication (minimizes static conditions)

![Figure 13, Ice resistance](image)
6. FUTURE TRENDS

The development of the DAT concept has concentrated on the performance of the vessel in both heavy ice conditions and open water. The concept solves the problem of compromising between these two conditions. It can be clearly seen that the DAT concept also helps solve many of the problems related to offshore loading in moving ice. One can say that for the first time there is a tanker concept, which makes the development of marine transportation of Arctic oil a really attractive alternative.

Pechora Sea is a relatively moderate area as the ice conditions are concerned. In areas further East, where ice features grow bigger, the marine transportation of oil and condensates has been considered unfeasible. In May 1995 the Russian-Finnish joint venture company Arctic Shipping Services organised the first commercial transportation of condensate from the Ob Bay area in the winter time. The vessel used was the tanker Uliku which is equipped with new Azipod drive. The experience of that voyage was, that even in the heavy ice conditions of Ob Bay it is possible with the new technology perform year round shipping operations. The development of a larger vessel for independent navigation in those shallow water areas is underway and when completed it will solve many of the problems that the oil and gas producers in that area have today.

With the DAT concept it is possible to create tankers that can operate in the shallow water areas of the Russian Arctic coast. For many of the potential onshore oil and gas fields this may be the key to feasibility. The long pipelines to be built and maintained on tundra and permafrost are expensive to construct and operate. The marine transportation alternative will be much cheaper in many cases.

The development of the mainly independently operating tankers are only partial solution for marine transportation system. It is quite obvious that a number of icebreakers is also needed to guarantee the regularity of the service required by the oil and gas projects. The need for reliable icebreaker assistance will increase with line increasing commercial traffic.
ICE FORCES ON A DOWNWARD-BREAKING CONICAL STRUCTURE
FROM PARTIALLY CONSOLIDATED RUBBLE ICE

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ABSTRACT

Model tests were conducted to determine the forces that are generated during interaction between partially consolidated rubble ice and a downward-breaking conical structure. The model structure broke ice in flexure when the ice contacted the structure at a sloping surface. Other failure modes were observed when the ice contacted vertical surfaces, resulting in high ice forces. The ice forces measured during model tests are presented. These forces compare well with those predicted by theoretical models. No ice jamming was observed during the model tests.

INTRODUCTION

Offshore structures placed in an ice environment such as the Kara Sea must withstand the forces generated by the moving ice fields around them. A conical structure offers advantages in reducing ice forces by failing the ice sheet in flexure. Among the two types of conical structures, a downward-breaking structure is able to clear broken ice pieces by submerging and moving them past the structure, and may also reduce the interaction forces.

The type of structure considered in this study is shown in Figure 1. It may be used as a loading terminal in 28-30 m of water. Tankers and vessels can be moored close to the structure on the leeward side, while it offers protection to the vessels by resisting ice action from all directions. The structure is octagonal in shape rather than circular, and its exterior is composed of flat surfaces to facilitate its fabrication. The downward-sloping surfaces at the waterline will push an ice sheet down to break it in flexure. Bic its hour-glass shape will allow the broken ice blocks to move past the structure. Because completely submerged ice has about nine times less buoyancy force compared to its weight above water, it is anticipated that the resistance face encountered by the broken ice pieces will be much less than if the same ice pieces were to move above water. As would be the case in an upward-breaking conical structure. Further, the hour-glass slope will offer less frontal area to the moving ice blocks, resulting in less jamming of broken ice forces.

In designing a structure of this type, it is necessary to estimate the forces that will be generated during its interaction under all ice conditions and to verify that there will be no jamming of ice blocks during the icebreaking process. Because partially consolidated rubble ice is often found in the Russian offshore area, it will be necessary to determine the forces arising from its interactions with the structure. To achieve this objective, we conducted a model study at a length scale of 50:1 to determine horizontal forces generated during the interactions Bic to observe the clearing or jamming of broken ice pieces.

MODEL STUDY

Because gravitational Bic icebreaking forces are dominant during this type of ice-structure interaction, we conducted the model tests by adopting Froude scaling (Ashion 1986). According to this similarity principle, the lengths are reduced by the length scale factor adopted for a particular study, and the elastic and strength properties of model ice are also reduced by the same factor. The velocity is reduced by
square-root of the length scaling factor. whereas the forces are reduced by the cube of the length scaling factor.

We constructed a model structure similar to that shown in Figure 1, but 50 times smaller. Figure 2 shows a sketch of the model structure and its supporting system. We constructed a welded steel frame to support the model structure underneath the carriage, which spans the test basin at the Laboratory. We built the model structure with plywood around an octagonal-shaped steel cylinder made of 12-mm-thick steel plate. Underneath the cylinder, we attached a steel frame to support a plywood surface which represented the sea floor. We mounted the assembly of the model structure under the carriage in such a way as to enable measurement of horizontal and vertical forces during a test. The model sea floor was also instrumented to measure the horizontal and vertical forces acting on it. The surface of the model structure was painted to obtain a smooth finish, but it was damaged at the waterline during the course of experiments. In retrospect, we should have taken measures to prevent this damage either by constructing the model with steel plates or by covering the wooden model with thin steel sheets.

We mounted an underwater video camera with a lighting system to observe and record the movements of broken ice pieces. The video recordings were useful in determining the extent of ice jamming close to the model structure. In a few instances, the view in front of the camera was obstructed by broken ice pieces during tests in heavy rubble ice, making it difficult for us to observe ice jamming. We did not observe any persistent ice jamming during all tests.

We conducted four trial tests to develop a procedure for making partially consolidated ice. In the first two tests, we accumulated the nibble across the width of the basin (Figure 3). This nibble field was not long in the direction of model travel, resulting in a short-duration interaction between the structure and the rubble ice. To increase the duration of interaction with limited supply of broken ice, we decided to accumulate the broken ice in the middle of the basin (Figure 4). The intact ice sheet, which was fixed to the basin walls, surrounded the rubble ice and held it together during a test. We conducted two more trial tests to verify that this procedure of making rubble ice worked well, and to observe that the model rubble field did not split apart during a test.

The final procedure of making partially consolidated nibble ice is given in the following. We first grew an ice sheet in the basin to a thickness of about 35 mm, broke a portion of this sheet on one end of the basin into small pieces, accumulated the broken ice pieces in the center of the basin to the required thickness of rubble ice, and refroze the top portion of the rubble ice to the required thickness of consolidation. At the end of these operations, there were three types of ice in the basin (Figure 4): (a) thick ice which grew initially to a thickness of about 35 mm and later to a thickness between 50 and 70 mm, (b) partially consolidated nibble ice in the middle, and (c) thin ice which grew during the refreezing of rubble ice. After the ice growth procedure, we allowed the model ice sheet to temper for a certain time to decrease its strength. However, we did not temper the ice to any target strength value. We measured the flexural strength of the consolidated portion of the rubble ice after each test and also measured the flexural strength and the characteristic length of thick and thin ice sheets before conducting a test.

We conducted tests to measure the static and the dynamic coefficients of friction between the model ice sheet and the structure. These tests were conducted using a painted board of plywood of the type used to make the model structure. We determined the static coefficient of friction by placing a piece of ice on the board and tilting the board until the ice started to slide. We measured the dynamic coefficient of friction in a specially designed apparatus. We loaded a piece of model ice by dead weights and measured the tangential force on the holder when the board underneath was moved horizontally back and forth. We found the static and dynamic coefficients of friction to be about 0.23 and 0.1, respectively. As mentioned,
earlier, the wooden model structure was damaged during the tests. We expect the actual coefficients for the damaged surfaces to be higher than the values reported above.

We conducted tests at two speeds \((5 \text{ and } 28.5 \text{ cm s}^{-1})\), two water depths \((57 \text{ and } 48 \text{ cm})\), two thicknesses of consolidated rubble ice \((5 \text{ and } 8 \text{ cm})\), and two full-scale water depths \((28.5 \text{ and } 24 \text{ m})\). We also conducted two tests at the same two speeds with unconsolidated rubble ice, which we made in the same manner described above, omitting the refreezing procedure.

RESULTS

As mentioned earlier, we conducted six tests at a water depth of \(57 \text{ cm} \) \((28.5 \text{ m} \) full scale\) and four tests at a water depth of \(48 \text{ cm} \) \((24 \text{ m} \) full scale\). We did not observe any ice jamming during the tests. Because of the shape of the structure, the ice contacted the model structure near the vertical section (Figure 1 and 2) during tests conducted at the lower water depth. This caused very high interaction forces during the model tests. In two tests, the interaction forces were so high that the surrounding ice sheet attached to the basin walls started to move with the structure, ending the tests after that. In the remaining tests at low water depth, the interaction forces were high because the structure did not fail the ice in bending. Though we are not able to analyze the results of these tests, the high forces measured during the tests constitute a strong warning that care must be taken to avoid ice interaction at lower water levels. In the following, we report the results of the tests conducted at the greater water depth, in which the structure failed the ice in bending.

We present the horizontal force measured during the tests at high water levels with consolidated layer thicknesses and no consolidation of rubble ice in Figure 5, 6, and 7. In each figure, the forces presented are for low and high speeds. The parameters measured or set for each test are given in Table 2. The force levels differ greatly according to the type of ice and the thickness and strength of ice. The force levels are very low during tests with unconsolidated rubble ice in comparison to those measured during the tests with consolidated rubble ice.

DISCUSSION

We compared the measured forces with those predicted by formulations in existing literature. Because the forces depend on many factors, we computed the ice forces for the parameters and variables in individual portions of force records of each test. In estimating the ice forces, we used Croasdale’s (1980) model to compute the forces required to break an ice sheet in bending and to push the broken ice pieces down to the sea floor. We used Mellor’s (1980) model to compute the force required to deform unconsolidated rubble ice and the frictional force encountered while the ice sheet moved on top of the accumulated rubble ice in front of the structure. An estimate of the last two components is about 6.5 kN, which is also the level of force measured during tests with unconsolidated ice. Because of damage caused by ice to the structural surface, we assumed a value of 0.5 for the coefficient of friction between the model and the structure. We arrived at this value of the coefficient of friction was by comparing experimental and theoretical force in one test and then using it for all tests. In Figure 8, we present a comparison of the theoretically estimated forces with those measured during the tests in deeper water level to the structure passed through uniform thin ice, partially consolidated rubble ice and uniform thick ice.
The data shown in Figure 8 depict the range of peak forces measured during a test. Though the comparison shewn in Figure 8 looks good, the predicted forces, in general, are slightly lower than those measured during the tests.

In Froude sealing, the forces measured in model tests are multiplied by $A^2$ where $A$ is the length scaling factor, to scale up to full scale values. Because $λ=50$ in our model tests, we get a value of $125,000$ for the force scaling factor. If the forces in a model test are dominated by flexural failure of ice, we can arrive at the scaling factor by considering the force to be proportional to the product of flexural strength and the square of ice thickness. In other words, the force scaling factor can be taken as the $λ^2λ_s$, where $λ_s$ is the ratio of full scale flexural strength to that in model tests. So far, we are not aware of any measurement of the flexural strength of consolidated nibble ice in the field. If we assume the flexural strength of consolidated nibble ice in the field to be $700$ kPa, the strength of model ice should have been reduced to $14$ kPa. However, the flexural strength during the test program ranged between $50$ and $80$ kPa. On average, the flexural strength was about four to five times higher than what it should have been. Because of this, the scaling factor that should be used to scale the model ice forces to full-scale values needs to be $λ^2λ_s$, which is less than $A$. If we assume that the ratio of flexural strength in full scale to that in model tests is about 10, we get a scaling ratio $(λ^2λ_s)$ of force to be about $25,000$, instead of $125,000$. Therefore, a force of about $10$ kN during tests with $8$-cm-thick consolidated nibble ice and about $16$ cm of unconsolidated ice will scale up to a force of about $250$ MN for $4$-m-thick consolidated nibble ice with $8$ m of unconsolidated ice. Theoretical estimates of loads from models proposed by Croasdale (1980) and Mellor (1980) are also of the same order of magnitude. Hence, their models can be used to estimate the ice force using an appropriate value of the coefficient of friction. The force estimates are lower for lower values of the coefficient of friction between the ice and the structure.

This force estimate does not imply that this will be the design load to be used for a structure because there may be other mechanisms or failure modes by which the design force may result in smaller force than those determined by the present model tests. It is beyond the scope of this paper to discuss this issue any further. Only the forces generated as a result of flexural failure of partially consolidated nibble has been determined in this model study.

CONCLUSION

After a few trial tests, we were able to conduct model tests with partially consolidated nibble ice and an octagonal-shaped conical structure. We did not observe ice jamming during the model tests. The measured horizontal forces depend on the thickness and the strength of consolidated nibble ice and compares well with that estimated from theoretical formulations in existing literature. The structure breaks consolidated nibble ice in flexure when the ice contacts a sloping surface of the structure at a higher elevation. When the ice contacts the structure on vertical surfaces, very large forces develop. In designing such structures, care should take that the ice does not interact with the structure on vertical surfaces.

ACKNOWLEDGMENT

The author is grateful to Exxon and Mobil for the funding for this project under a Cooperative Research and Development Agreement. This project was accomplished by a team effort at CRREL. Peter Stark did the welding and made the model structure. Jesse Stanley conducted the tests in the test basin. The author thanks them and all others at CRREL who helped to make this study a success. Reviews provided by Mark Hopkins, Kathy Forland and Steve Bowen are gratefully acknowledged.
Table I. List of variables and parameters used in full scale situation along with their values for the model study.

<table>
<thead>
<tr>
<th>Variable or Parameter</th>
<th>Prototype values</th>
<th>Model values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice drift velocities</td>
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<td>0.05</td>
</tr>
<tr>
<td>(m/s)</td>
<td>2.00</td>
<td>0.28</td>
</tr>
<tr>
<td>Consolidated rubble thickness</td>
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<td>0.05</td>
</tr>
<tr>
<td>(m)</td>
<td>4.0</td>
<td>-0.28 -0.08</td>
</tr>
<tr>
<td>Water depth</td>
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<tr>
<td>(m)</td>
<td>28.5</td>
<td>0.89 -0.57</td>
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<tr>
<td>Friction coefficient</td>
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</table>

Table 2. List of variable either set or measured during the model study.

<table>
<thead>
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<th>Water depth Spec</th>
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<th>Rubble ice</th>
<th>Thick ice</th>
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<td></td>
<td>m</td>
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<td>6</td>
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<td>7&amp;8</td>
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Figure 1. Sketch of an octagonal-shaped, conical structure.
Figure 2. Sketch of experiment set up for model tests.
Figure 3. Sketch showing accumulation of broken ice across the buin width.

Figure 4. Sketch showing accumulation of broken ice in the middle of the buin.
Figure 5. Horizontal force measured during model tests with higher consolidation thickness at (a) 5 cm s\(^{-1}\) and (b) 28 cm s\(^{-1}\) speeds. The values of other parameters during each particular test are given in Table 2.
Figure 6. Horizontal force measured during model test with lower consolidation thickness at (a) 5 cm s⁻¹ and (b) 28 cm s⁻¹. The values of other parameters during a particular test are given in Table 2.
Figure 7. Horizontal force measured during model test with no consolidation at (a) 5 cm s$^{-1}$ and (b) 28 cm s$^{-1}$ speeds. The values of other parameters during a particular test are given in Table 2.
Figure 8. Comparison of horizontal ice forces measured during model tests with those obtained from theoretical estimates.
APPLICATION OF RESULTS FROM THE RESEARCH PROJECT 'A SHIP IN COMPRESSIVE ICE' TO SHIP OPERABILITY

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Lecture given in POAC '95, Murmansk, August 15-18, 1995

ABSTRACT

A joint research project between the Institute for Problems in Mechanics, Russian Academy of Sciences and the Ship Laboratory at Helsinki University of Technology about the mechanics concerning ships in compressive ice field was started in 1989. The project concentrated on clarifying the factors influencing the ice loads on ships which navigate in converging ice fields. The research clarified the additional ice resistance due to ice pressure and could thus shed some light on the susceptibility of ships to get stuck in ice. The research also clarified the physical processes present when the ice is pressing at ship sides in the situation when the ship is stopped in compressive ice. A calculation routine to estimate the forces on ship sides was produced.

The present paper summarises the work carried out in the joint research project and highlights the results that can be used in predicting ice loads on the parallel midbody of ships. The other factor which is highlighted is the application of the generated knowledge in ship transit simulations through Arctic seas. Also the application of the knowledge to the ship operational procedures in ice is commented on. The paper will finally point out the present deficiencies in the knowledge about ships in compressive ice and identify future research tasks.

1. INTRODUCTION

A joint research project entitled 'A Ship in Compressive Ice' was started by Helsinki University of Technology, Ship Laboratory and the Russian Academy of Sciences, Institute for Problems in Mechanics in 1989. The object of the project was originally to clarify factors influencing ice loads of ships which are caught in an ice field which is converging. These converging ice fields are called pressurized or compressive ice. The scope of the project has become larger as it encompassed also factors influencing ice resistance to ship motion in these ice fields. The approach selected in the project was to find physical processes influencing the
loads and resistance.

The project included theoretical and empirical work. The empirical work consisted mainly of model tests in the ice basin at Helsinki University of Technology. Model tests were carried out to clarify the ice resistance and loading of the parallel midbody in closing channels and also to clarify the failure process of an ice sheet against a vertical structure, in this case, the ship side. Apart from the model tests some full scale observations of ships in compressive ice were carried out. These served the purpose of identifying the factors leading to the situation where a ship gets stuck in a closing channel.

The other part of the project involved interpretation of the model test results and identification of physical processes in the test situation. These were then modelled theoretically in order to produce a more general theory for ice loading or ice resistance in a compressive ice field. The theoretical modelling identified the main parameters influencing these processes. The division of work between the Finnish and Russian sides is that the empirical work, modelling of the failure process of ice edge and the transit simulations has been done in Finland. The interpretation and analysis of model tests and the theoretical modelling of the added resistance was carried out in Russia.

The results from the project are published in laboratory reports and congress papers (Goldstein & Osipenko 1994, Kujala & al. 1991, Kujala & Kuuskoski 1992, Kujala & al. 1993, Kujala & al. 1993, Kujala & Ralph 1994). This paper will highlight the application of the results from the project to practical ship problems like predicting ice loads on the parallel midbody of ships or transit simulation in cases where the converging ice must be accounted for. These applications represent an intermediate stage of the cooperation as it continues with somewhat modified work contents.

2. A SHIP IN COMPRESSIVE ICE

Wind and current drag cause stresses in an ice field which results in ice cover motion if no obstacles prevents the motion. If the ice motion is restricted by a shoreline, stresses increase in ice cover and can eventually result in ice ridging. When the leads in ice cover are closing and thus ice coverage is increasing or ice ridges start to form, the ice cover is said to converge. In a diverging ice field leads are opening and the average thickness of ice is decreasing. The basic factors controlling the dynamics
of ice cover are the floe-floe interaction and ice ridge formation. The basic quantity in ice dynamics modelling is the ice thickness distribution. The stresses in the ice cover are described in ice dynamics modelling by line loads $q$ and the limit stress when ridges start to form is of order of $q_r=100$ kN/m.

When a ship proceeds in a level ice field where there is compression, the compression can be clearly detected because the channel opened by the ship is closing behind the ship. The wind and current caused stresses in the ice cover are low compared to those caused by breaking the ice by the ship bow. The loads and the breaking pattern of ice is thus not influenced by the compression in the ice cover. The main question relevant to ship navigation in compressed ice is whether the channel edges touch the sides of the ship due to ice motion. Fig. 1 presents a sketch of the situation. The quantities controlling the situation are the speed of the ice cover (i.e., the closing speed of the channel) $v_i$, the speed of the vessel $v_s$, length of the parallel midbody of the ship $L_{par}$, and the transverse dimension of the last ice cusp broken at the shoulder of the ship $d$. The ice edge does not touch the parallel midbody if

$$\frac{d}{v_i} \geq \frac{L_{par}}{v_s}$$

This relationship shows that the quantity

$$\kappa = \frac{d}{L_{par}} \cdot \frac{v_s}{v_i} \quad \cdots \quad (2)$$

can be considered as an ice compression index. When $\kappa \geq 1$, ice does not touch the parallel midbody.

Fig. 1. Description of parameters influencing the ship motion in compressive level ice field.
The ice compression index can be applied also to the situation where a merchant vessel follows an icebreaker. The ice compression index should be modified to

$$\kappa = \frac{0.5 (B_{\text{eff}} - B)}{D} \frac{v_s}{v_I}$$

where $B_{\text{eff}}$ is the width of the channel the icebreaker has broken, $B$ the breadth of the merchant vessel and $D$ the distance between the ships.

If the ice cover touches the ship's parallel midbody the ice resistance increases and usually becomes larger than the thrust of the ship. The ship is stopped in the ice and cannot move astern. When the ship is stuck in compressive ice this way, the ice cover starts to break against the parallel midbody of the ship. The ice loads are very large, especially if the ship sides are vertical. The magnitude of these loads in the Baltic is of order of 1 MN/m, much higher than the stresses in a compressive ice cover. The reason for this is that when the channel closes and the ship is obstructing the ice motion, the driving forces for ice motion are transmitted through the ship. The force on the ship decrease only when the channel has closed completely.

The situation in pack ice where there is also open water and many different sizes of ice pieces like multi-year ice floes is somewhat different. If the ship gets stuck in this kind of compressive ice field, the interaction between ice floes close to the ship becomes the dominating factor in determining the loads on the ship. The reason for this is that when the ship channel starts to close, ice cover is compressed close to the ship by closing the leads and failing or rafting some weaker i.e. thinner floes in the pack ice. This gives some time for loads to increase. While this is taking place the channel closes and the loads are redistributed.

3. THE FAILURE PROCESS OF ICE AGAINST THE SHIP

The case of level ice failing against the ship side when the channel closes was analyzed using the flaking ice failure model developed by Daley (1991). The flaking model assumes that ice fails under the contact forces in a brittle manner along straight lines and thus triangular shaped ice pieces are formed. Fig. 2 depicts the geometry analyzed. This flaking model was extended to cases where the structure is inclined and the failure process is allowed to include bending failure.
The bending failure of ice cover was modelled, as shown in Fig. 2, by treating the ice as a beam on an elastic foundation under vertical and horizontal forces and a bending moment, all these concentrated on the neutral axis of the beam. The essence of the failure process model is that the moment is

$$ M_0 = -F_h(e + w) $$

where $w$ is deflection of the ice cover and the vertical force is

$$ F_v = p_c h_c (\mu \cos \beta - \sin \beta) + (p_v - p_i) g A_e - p_i g A_e $$

where $p_c$ is ice crushing pressure, $h_c$ contact height, $\beta$ is the inclination of the structure towards vertical, $\mu$ coefficient of friction, $g$ acceleration of gravity and $A_e$ and $A_i$ are the cross-sectional areas of failed ice forced below and on top of the ice cover. The eccentricity $e$ is a result of the asymmetric flaking process.

The flaking pattern, horizontal force and bending moment in one simulation run are shown in Fig. 3. The development of the bending moment shows very clearly the process where the ice cover deflection starts to increase due to accumulated ice fragments on top of the ice resulting in rapidly increasing bending moment. When the ship side is inclined the process is qualitatively similar, see Fig. 4, but the bending failure occurs earlier.
Fig. 3a. Typical flaking process in contact with vertical structure.

Fig. 3b. The horizontal contact force during the flaking process.

Fig. 3c. The variation of the bending moment $M_b$ during the contact.
The process model makes it possible to estimate the maximum horizontal force caused by level ice cover failing against a ship's side. When the side is vertical the maximum horizontal force is highest; even small inclinations reduce the load level. The maximum horizontal forces are shown in Fig. 5 from where it is also clear that the frictional force becomes important when the side is inclined. The high load level is caused by failing the full depth of ice and the lower force level corresponds to bending failure. Ice should be broken by bending and this reduces loads by about 85%. This study shows for example that ships intended for independent navigation in ice covered waters should have inclined frames in the parallel midbody area as there is always a possibility to get stuck while navigating independently.

Fig. 4. The flaking process when the structure is inclined by 5°.

Fig. 5. Maximum horizontal force during the contact as a function of the inclination angle with the coefficient of friction as a parameter.
4. THE INCREASE OF ICE RESISTANCE DUE TO COMPRESSION

The research project included model tests where the ice resistance of ships proceeding in a closing channel was investigated (Kujala & al. 1991). The tests were done by towing a vessel in a previously made channel and pushing the ice on one side of the channel to close it. The resistance to motion (i.e. towing force) and the force applied on the parallel midbody of the vessel were measured. A sketch of the test arrangement is shown in Fig. 6. Four test series, A,...,D, using two thicknesses of ice, were carried out.

![Fig 6. The arrangement of model tests and the instrumentation of the ship model.](image)

The results of the tests show a marked increase in the ice resistance of a ship proceeding in a closing channel. The relative increase decreases, however, with increasing ship speed, see Fig. 7. In the same situation the ice forces applied on the parallel midbody decrease markedly with increasing ship speed, see Fig. 6. These test results form the basis for the modelling of the added resistance in compressive ice.
Fig. 7. The ice resistance measured in the model tests where the scale was 1:33.5.

Fig. 8. The measured horizontal forces on the parallel midbody.

Above it was indicated that the main parameter controlling the forces due to compression is $\chi$. Thus the test results may be interpreted to yield a first order estimate for the horizontal force on the parallel midbody of the ship as

$$F_h = F_{h,s}(1-C_1\chi)$$  \hspace{1cm} (6)

where $F_{h,s}$ refers to the horizontal force on a stationary ship and $C_1$ is a constant to be determined (all quantities $C_i$ will subsequently be empirical constants). This expression contains one unknown parameter, $d$, which must be estimated. An estimate for
this is given in (Goldstein & Osipenko 1994) as

\[ d = C_i h_i \left( \frac{S_t}{V_p \rho} \sqrt{\frac{E}{\rho}} \right)^{\frac{3}{2}} \]  

(7)

where \( E \) is Young's modulus of ice, \( \rho \) is the density of ice, \( h_i \) is the thickness of ice, and \( S_t \) is the tensile strength of ice. These estimates give finally an estimate for the compression force as

\[ F_h = F_{h,0} [1 - C_i \left( \frac{h_i}{L_{par}} \right)^{\frac{1}{3}}] \left( \frac{S_t}{P_e} \sqrt{\frac{E}{\rho}} \right)^{\frac{3}{2}} \]  

(8)

A fit gives the value of the constant \( C_i \) as about 0.65. The result of this formulation is shown in Fig. 9. The comparison between the values given by eq. (8) and the model test results is good. The added resistance due to this force component is frictional and thus

\[ \Delta R_1 = \mu F_h. \]  

(9)

The other component of the added resistance of ships moving in a closing channel arises from the fact that ship turns slightly while proceeding in the channel due to the uneven breaking sequence on port and starboard sides. The longitudinal component of this force may be estimated as

\[ \Delta R_2 = C_s F_h \sin \arctan V_s \]  

(10)

and the total addition to the ice resistance due to a closing channel is

\[ \Delta R = \Delta R_1 + \Delta R_2 \]  

\[ = F_{h,0} [1 - C_i \left( \frac{h_i}{L_{par}} \right)^{\frac{1}{3}}] \left( \frac{S_t}{P_e} \sqrt{\frac{E}{\rho}} \right)^{\frac{3}{2}} (\mu C_s \sin \arctan \frac{V_s}{V_i}). \]  

(11)

The values given by eq. (11) are compared with the measured values in Fig. 10 and the correspondence is seen to be fair. Eq. (11) contains the force \( F_{h,0} \) which is the maximum compressive force on the sides of a stationary force. This must be determined in order to determine the added resistance. The direct approach should be to use the ice cover stress where the force would then be proportional to the stress and the length of the parallel midbody as
Another approach is to use the eq. (11) as a proportionality factor for level ice resistance. This is described in the next chapter.

![Graph showing comparison between measured and calculated forces on parallel midbody.](image1)

**Fig. 9.** Comparison between the measured and calculated forces on the parallel midbody.

![Graph showing comparison between measured and calculated added ice resistance.](image2)

**Fig. 10.** Comparison between the measured and calculated added ice resistance.
5. APPLICATION OF THE ADDED RESISTANCE

The above formulation contains the horizontal force which must be determined separately for each vessel and each ice field having e.g. different thicknesses. A first estimate for applications may be obtained if the multiplicative factor to $F_{b,e}$ in eq. (11) is assumed to represent the addition to the level ice resistance in noncompressive ice. According to the analysis presented earlier, the resistance stemming from the parallel midbody should be increased only. The level ice resistance formulations are not that refined as to account for from which hull area resistance stems. This gives a preliminary resistance formula for ships in compressive ice

$$R_t = R_{t0} + \Delta R_t$$

$$= R_{t0}[1 + K(\beta) \left(1 - C_3 \frac{h_i}{L_{pm}} \left(\frac{S_t}{E_{p}}\right) \left(\frac{\rho}{\rho} \right)^{\frac{1}{3}} \left(\mu + C_6 \sin \arctg \frac{V^*}{V_t}\right)\right)]$$

where $R_{t0}$ is the ice resistance in level, noncompressive ice and $R_t$ the added resistance given in eq. (13) may be used in conjunction with logistic analyses where certain ship routes are investigated in order to evaluate the economics and risks related to different fleet solutions. One of the modules in the logistic analyses is the transit simulation where the ship navigation through a set of ice conditions is investigated. The results of transit simulations usually include the instantaneous speed of the ship along the track chosen. To reach this the ice resistance in level ice, ridges and other ice conditions should be known. This kind of simulation routine has been developed by Riska, La Prairie & Wilhelmson (1995). This is now modified to account for the compressive ice fields.

The first thing which must be evaluated before a general transit simulation may be conducted is that some quantitative measurable unit for compression must be found. The closing speed of the channel is not general enough because it is very much influenced by the local conditions close to the ship. The Russian practice is to measure the ice compression in the units of ball. This is a measure of stress in ice and 1 ball $= 30$ kN/m. In the model tests
where ice thickness was 0.5 m the maximum loads on the ship were about 75 kN/m when the closing speed of the channel was 0.3 m/s (these figures are naturally the extrapolated full scale values). This result gives an indication of the relationship between the ice cover stresses and velocities.

The Norilsk-type (SA-15 type) ship is used in this example transit simulation. The calculation is made in a ridge field where the level ice thickness is 0.5 m between the ridges and the ridges are assumed to be similar with a ridge spacing of 100 m and ridge thickness of 5 m. The ice compression is applied to the level ice between the ridges. A result from the calculation where the channel closing speed was 0.3 m/s is shown in Fig. 11. The average transit speeds through this ridge field are shown in Fig. 12 versus the closing speed of the channel and ridge thickness. At the ridge thickness of about 4 m, the ship has to start ramming and the average transit speed decreases much.

![Graph of transit analysis in a ridge field where there is compression.](image)

Fig. 11. An example of transit analysis in a ridge field where there is compression.
6. CONCLUSIONS

The aim of the present paper is to describe some applications of the results from the research project 'A Ship in compressive Ice'. Two applications were selected. One concentrated on the load level on the parallel midbody of ships encountered when an ice cover moves against the ship side. The frame angle and coefficient of friction were shown to influence the load level dramatically. These results may be used in designing the strength of the midbody of vessels when there is a risk that the ship gets stuck in ice.

The other application was the determination of the added resistance due to compression in the ice cover. Based on the model tests carried out a preliminary equation for the added resistance was derived and it was applied to a transit simulation calculation. This application may be considered as a research plan for future work—because many assumptions are not validated properly.

This paper presents two applications of the research conducted jointly. These applications were selected as much interest in these matters exists at present. There is much discussion about
the influence of different operational modes on the required strength level of the ship hull. The results presented here may be used in conjunction with evaluating how much the deployment of icebreakers to assist merchant vessels influences the ice loading on the midbody of the merchant vessels. The application of the resistance due to compression in transit simulation may be used in evaluating the feasibility of new transit routes in ice covered sea areas.

Especially the resistance equation must be viewed as a very preliminary result. More research to validate and improve it should be conducted. The application of this equation also highlighted the need to develop a more general measure for ice compression, a measure which can be determined by remote sensing methods and which can be used in conjunction of ice forecasting methods based on meso-scale modelling of dynamics of ice cover.

ACKNOWLEDGEMENTS

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REFERENCES


COMPARATIVE ANALYSIS OF THE OUTLINES OF CLASSIFICATION AND REQUIREMENTS OF VARIOUS CLASSIFICATION SOCIETIES FOR THE ARCTIC VESSELS

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CNIIMF  
Russia

Y.V. Glëbko  
CNIIMF  
Russia

INTRODUCTION

The national Rules for the classification and construction of ships intended to operate in the Arctic differ essentially from one another. Differences exist in the ship classification systems, machinery requirements, extents to which environmental safety is secured, sizes of ice strengthening as well as principles of ice load calculations.

To assess comparability of classification requirements of the Maritime Register of Shipping (MRS) and foreign Classification Societies comparative calculations of main scantlings (framing and hull) for representative ships have been performed. Their dimensions and hull forms have essentially encompassed the whole range of standard sizes of ice ships used to transport goods along the Northern Sea Route and in the North American zone of the Arctic.

COMPARISON OF ICE CLASS REQUIREMENTS

A number of common points and approaches as well as differences exist between the MRS and some foreign Classification Societies.

The Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR), for example, to provide environmental protection of the Canadian Arctic in case of accidental damages strict requirements for arrangement of bottom and side fuel oil tanks have been set forth. The basis for the current Rules of the MRS (1990) is the provision of safety of a ship when navigating in ice. At the same time, sizes of the ice strengthening are not of relevance to requirements for environmental protection of the water area.

The Rules of the MRS cover the entire variety of ice-going ships ranging from vessels sailing under light conditions in the non-Arctic seas (L4, L3) up to liner icebreakers of classes (LL2, LL1), capable to operate all-the-year-round in heavy ice of the Central Arctic. Lack of an unified classification range makes establishment of correspondence between the domestic and foreign classes rather difficult. Icebreaking capability could serve as a key parameter for this purpose but the classification of domestic icebreakers is only of indirect relevance to it. In plying simultaneous regulation of propulsive output.

In recent years the Rules of CASPPR'89 (draft), Lloyd's Register (LR) and Germanischer Lloyd (GL) show tendency to extend the classification ranges combining icebreaking transport ships and purely icebreaking ships.

List of the ice classes of some Classification Societies with corresponding working ice thickness data is given in Table 1.
Intensity of ice loads and distribution thereof over the underwater hull are determined in the draft CASPPR Rules according to the inclination angles of frames and lines tangent to the waterlines in various areas of the hull; in the Det Norske Veritas (DNV) Rules classification for icebreakers is taken separate from the transport ships. Icebreakers in this case are classified by navigation area rather than by their purpose. In the latter case, for Arctic icebreakers the class notation is affixed by an abbreviation icebreaker. Ships are subdivided into subclasses according to the thicknesses of ice which can be broken through by the icebreaker and for each class of icebreaker* ramming speed is regulated.

Attention may be attracted by similarity of the coefficients of design ice load distribution over ship’s surface in different Rules [1]. Thus, longitudinal distribution coefficients for zones A, B, C are equal to:

<table>
<thead>
<tr>
<th></th>
<th>MRS</th>
<th>CASPPR</th>
<th>DNV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.5-0.6</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>B</td>
<td>0.7-0.75</td>
<td>0.8</td>
<td>0.7-0.75</td>
</tr>
<tr>
<td>C</td>
<td>0.6</td>
<td>0.8</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Relationships of the loads between the ice belt and bottom:

<table>
<thead>
<tr>
<th></th>
<th>MRS</th>
<th>CASPPR</th>
<th>DNV</th>
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</thead>
<tbody>
<tr>
<td>In MRS</td>
<td>0.25-0.35</td>
<td>0.3</td>
<td>0.25</td>
</tr>
<tr>
<td>In CASPPR</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>In DNV</td>
<td>0.25</td>
<td></td>
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</table>

Similarity degree of relationships between the design ice loads on hulls of various ship types is shown in Table 2.

### Table 1

<table>
<thead>
<tr>
<th>Classification Society</th>
<th>Ice Class</th>
<th>Ice Thickness (m)</th>
<th>Ice Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASPPR’89</td>
<td>CAC4</td>
<td>1.2 - 1.8</td>
<td>Thick first-year</td>
</tr>
<tr>
<td></td>
<td>CAC3</td>
<td>2</td>
<td>Thick first-year. second-year</td>
</tr>
<tr>
<td></td>
<td>CAC2</td>
<td>2.4</td>
<td>Multi-year</td>
</tr>
<tr>
<td></td>
<td>CAC1</td>
<td>3</td>
<td>Multi-year</td>
</tr>
<tr>
<td>Lloyd’s Register</td>
<td>AC1</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>AC1.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AC3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Germanischer Lloyd</td>
<td>Arc1</td>
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<td></td>
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<tr>
<td></td>
<td>Arc2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Arc3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Arc4</td>
<td>3</td>
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### Table 2

<table>
<thead>
<tr>
<th></th>
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<tr>
<td>LL1</td>
<td>1</td>
<td>Arc1</td>
<td>Polar30</td>
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<tr>
<td>LL2</td>
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<td>Polar10</td>
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<td>Ice15</td>
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<tr>
<td></td>
<td></td>
<td>Arc4</td>
<td>Ice10</td>
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<tr>
<td></td>
<td></td>
<td></td>
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</table>
DEVELOPMENT OF COMPARISON TABLES

Purpose of the comparison of the requirements imposed by national Rules to ice class ships is the development of the classification table specifying the degree of correspondence to each other of the ice classes compared.

For the correct solution of the problem of the development of identification tables for the establishment of compliance between ice classes of various Classification Societies it is necessary for the ships to be compared to provide for fairly close values of the following characteristics:

- purpose 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.

Individual salient features of the national Rules make it difficult to directly use the results of calculations for the comparison of classes.

In comparison of the Rules requirements of leading Classification Societies there are following main obstacles:

- Differences in the composition of classification criteria: which include, along with requirements to the strength of ice belt structures, various combinations of the following parameters:
  - thickness of ice broken through in continuous motion,
  - thickness of ice in which a ship is able to operate.
  - shaft power.
  - speed,
  - mode of operation in ice.
  - area of navigation in the Arctic,
  - season.
- Different structure of the design relationships. Formulas for the determination of design loads and contact zone sizes contain various combinations of:
  - shaft power.
  - displacement.
  - ice thickness.
  - frame inclination angles.
- Non-uniformity of normalized parameters.
- Differences in calculation processes.
- Different y of the Rules classification net.
- Different account of ship operating conditions.

The common approach to the description and comparison of ice classes is based on the following principal provisions:

- Purpose of ship:
  - for transport ships it is admissible to disregard differences in requirements to the hull afterbody.
  - sign of identity for icebreakers is the conformity of requirements in all ice belt areas.
- Real shaft power ranges within which the comparison of classes is to be made. In the present work, for running Rules it is suggested to dike as a range of icebreaker powers regulated by the MRS Rules has been taken.
- Similarity of ship's form while comparing icebreaker classes in particular of the frame inclination angles according to the recommendations of MRS Rules.
- Restriction of the compared parameters only by ice belt members.
Exclusion from the consideration of the wall section areas of ordinary frames (f) bearing in mind that in a number of Rules of leading Classification Societies (ABS, GI) there is no regulation of this parameter. Only requirements to plating

For the comparison the following Classification Societies were selected: MRS, ABS, CASPPR, L.R., DNV and GI.

the results of calculations for the selected representative ship of 25,000 t in displacement (SA-15 type, U.L.A class, displacement = 25,000 t, length = 159.6 m, breadth = 24.5 m, draft - 9 m) are presented as relative values summarized in tables. One of the typical form of result derivation is given in Table 3. Selection of the representative ship derives from the fact that its operating experience including the degree to which it is consistent with the operating conditions in the Arctic has been well investigated.

Comparability of the results has been assured by common source information: spacing 4110 mm, yield limit of steel - 320 MPa and design frame span 2 m (4 m for ABS, proceeding from the structure of formulas).

Calculations for the icebreaking classes of the Russian Register have been performed on the assumption that the propulsive output is not lower than the minimum design output specified in the Rules 12,000 kW (L.I.4), 22,000 kW (L.L.3), 47,500 kW (L.L.2).

To bring the hull form parameters in line with the above power limitations, angles of frame inclination and stem take have been corrected in accordance with recommendations of the Rules in this respect.

In the comparison of classes L.I.3, L.I.2, L.L.1 with foreign classes of the close purpose, the shaft power and frame inclination angles (up to 50°) were taken equal to values specified by the MRS.

Certain results of the analysis are presented in dimensionless form in comparative Tables 3 and Figure 1. In the assessment of results the comparison is assumed to be made within sub-groups divided by shaft power.

Such a division has created more favourable conditions for the comparison of results.

In each group there is a satisfactory agreement just between the classes in the requirements to which the experience of operation in ice of real representative ships was well reflected.

Dimensionless values contained in the tables have been obtained by dividing the absolute values of design pressures and scantlings by corresponding values determined for an icebreaking transport ship of U.L.A category. The analysis shows that absolute correspondence of all the ice strengthening parameters between the classes of the M.R.S and foreign rules is unfeasible [1, 2] primarily due to difference in the requirements imposed to the after end strengthening. Besides, running Rules of such major Classification Societies as ABS, GI, and CASPPR72 do not regulate in an explicit form section area of the web of main and intermediate frames which makes it impossible to consider this parameter when a common criterion of comparability of the requirements to ice strengthening in various national Rules is chosen. Therefore, the degree of correspondence of the Rules, as applied to ice strengthening of the hull, is established here based only on the requirements to section modulus of the frames and shell plating.
Table 3

<table>
<thead>
<tr>
<th>Societies</th>
<th>Hull area</th>
<th>Shaft power, kW</th>
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</thead>
<tbody>
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<td></td>
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<td></td>
</tr>
<tr>
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In spite of some differences in the individual requirements it turned out to be possible to establish with an accuracy sufficient for practice (on the average up to 10 - 15%), the degree of correspondence between the ice classes of different Rules (Tables 4 and 5). Identification of ice classes was made in the forebody by the requirements to shell plating and in the middle body by relative sizes of framing ice strengthening.

While using Tables for the identification of ice classes it was assumed that stability of the framing and diaphragm walls may be ensured by structural measures.
Fig. 1. Comparison of the requirements of the Rules for ice belt framing for icebreakers with a displacement of 25,000 t (for classes L L 4, CAC4, A4 - power of 12,000 kW; for classes L L 3, CAC3, A3 - 22,000 kW; for all other classes - 47,500 kW)
### Table 4

<table>
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( ) - correspondence of classes by the shell plating

### Table 5

<table>
<thead>
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</tr>
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</table>

( ) - correspondence of classes by the side framing

### CONCLUSION

The analysis made shows that it is necessary to make the comparison of the classification requirements within groups of ships with similar purposes: cargo vessels independently sailing in ice, ships escorted by icebreaker, port and linear icebreakers, as well as within subgroups of similar shaft power.

The level of requirements for bow framing of the ships of high ice classes and high power in foreign Rules (classes CAC1, Arc.3, A4, A5, Polar 30) is considerably higher in comparison with that of the MRS.

Substantial increase of framing requirements in new foreign Rules may be considered as an aspiration for the development of a classification niche for new types of future ships - transports-icebreakers. Displacement of such ships may reach 100,000 t and shaft power 40,000-50,000 kW and over.
As there is no experience of ice operation of ships with a displacement of 50,000-100,000 t and shaft power exceeding 50,000 kW it is necessary in the development of a new classification range for these ships to ensure its close relation with the classification drawn up for ships now in operation.

The comparability of results is significantly influenced by the density of classification nets (inter-classes range).

The requirements of certain ice classes (for example LL.1, LL.2) are very close between them, therefore it is not seldom that there is some compliance of two neighbouring Russian classes with a foreign one, and vice versa.

It seems advisable in the new Rules of ABS, GL and CASPPR to increase density of the classification net (part of which should be consistent with modern fleet).

The gap in GL, ABS and draft of CASPPR between highest classes as well as the level of their requirements and the strength of the most powerful arctic icebreakers seems to be too great. In the higher class group it is apparently advisable to have more closely spaced net well adapted (for the lightest classes of this group) to the operating ships.

Bearing in mind the fact that in a number of Rules of leading Classification Societies (ABS, GL, CASPPR'72) there is no regulation of the section areas of ordinary frames, it is advisable to exclude this parameter from the consideration at this stage of work.

The closest as to the level of MRS requirements to Arctic ships are Rules of ABS, CASPPR'72, LR and to a lesser degree of DNV.

REFERENCES


ATMOSPHERIC AND HYDROLOGICAL PROCESSES LED TO THE EXTREME THERMOHALINE ANOMALY IN THE SOUTH WESTERN KARA SEA IN SEPTEMBER 1994

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ABSTRACT

The big positive anomalies of temperature (up to +6°C) and salinity (up to +40/00) in Baydaranskaya Bay in the middle of September 1994 are described. The possible formation mechanisms are discussed. The hydro meteorologic parameters (air pressure fields, winds, air and water temperatures) for 1.5-month period before times of anomaly arc analyzed. It was shown, what local thermal and salt fluxes through water surface can't create this anomaly. Its most probable cause is convergent advection of relatively more warm and saline Barents Sea water into south-western part of the Kara Sea. The air pressure field in all summer month of 1994 year was favorable to this process.

1. INTRODUCTION

Only large scale space and time features of the Arctic Ocean thermohaline structure are studied exactly now [4, 9]. Hitherto, the main attention in this area is paid to large scale interannual variability [3, 6, 8].

At the same time thermohaline structure synoptic scale variability observations give the clear evidence of its high intensity, variability of its space and time scales and generation mechanisms. For
example, [1] showed considerable thermohaline indignation in underice pycnocline, caused with 15-20 km diameter sinoptic eddy, and [3] showed 10 km/day velocity of salinity front moving in the Kara Sea, induced with storm wind. In both cases time scale of temperature indignations were about two weeks in spite of their different genesis. As shown by [2] in the shelf zone the main range of the sinoptic variability is from several days to two to three weeks.

Sinoptic scale thermohaline anomaly amplitudes are of several degree, psu and kg/m$^3$, which considerably impacts processes of atmosphere-sea-shore interaction.

Hitherto research of sinoptic scale indignations in the Arctic Ocean are extremely rare. The presented article cover just this question.

2. SITE SURVEY DATA

According to 36 oceanographic station site survey in the Kara Sea to the South of 73°N including 16 oceanographic stations in the Baydarataya Bay the 100 km wide shelf stripe from the Kara Straight to the Cope of Kharaevaya was occupied with 5-6°C extremely hot and 31-32%o salt water in the layer from surface to 30-40 m depth.

The most considerable thermohaline anomalies were observed in the Baydarataya Bay. Temperature field in the surface and bottom layer* of the Baydarataya Bay and its deviation from 1988-1993 September field are shown in the Fig.1. The same for salinity is shown in the Fig.2. Analysis of these distributions showed that the better part of the aquatory with depths up to 30 m was occupied with homogenous water from surface to bottom, bottom temperature anomaly (Fig.1d) and surface salinity anomaly (Fig.2b) being extreme.

Anomaly distribution showed that the mod probabk mechanism of anomaly genesis is convective mixing in site and advection of anomaly from outside.

Combination of the temperature and salinity anomaly in the surface layer (-1.5°C and +3.0‰) and in the bottom layer (+3.0°C and -0.5‰) rejected local thermic convection as a cause. Calculations showed that +2.7°C difference between water and air temperature during two week period was not abk to break stable stratification due to heat losses.

Advection alone could cause inch anomaly, but usually in this region to September it is limited with the 5-10 m depth, i.e. the top boundary of season pycnocline. Advective water penetration into the bottom layer is possible only due to inter convergency in the Baydarataya Bay and corresponding downwelling. This process was promoted with advective water higher salinity and
mentioned above heat from the surface. However, the main cause of the anomaly should be convergent thermohaline advection into the Baydarskaya Bay.

To identify possible source* and trajectories of advective water the atmospheric processes since July beginning and satellite data on sea surface temperature since August beginning were analysed.

3. RESULTS

Usual air pressure distribution over Eurasian sector of Arctic in July - September first half is a High over polar regions and a drough over North Europe which is connected with Siberian Low. This drough separates Polar High from the ridge over Southern Europe. Such distribution came* prevailing North East winds over South Eastern Barents Sea and South Western Kara Sea.

In July - September 1994 air pressure distribution in Arctic was anomalous, the whole pressure system being shifted into the Western Hemispheric. Polar High was shifted to Canada, in the Eurasian sector Polar regions were occupied with Low highly intensive in August. Its centre with pressure about 996 mb was near 80°N and 90°E. The monthly mean pressure anomaly in the Low centre was -8 mb in July, -14 mb in August, mid -6 mb in September. The ridge from the Southern Europe was shifted to the North. Air pressure anomalies over Northern Europe being up to +8 mb in July and about +2 mb in August and September. Such pressure distribution led to prevailing of South West winds over the investigated area.

In particular, according to daily data from the August beginning to September 23 such winds were observed during 32 days including 19 days in August and 13 days in September, i.e. their probability exceeded 60% meanwhile their c t i i probability is less than 40%.

Daily atmospheric processes were separated into two types: 1. Favourable for drift penetration of warm Barents water into the South Western Kara Sea; 2. Unfavourable when according to South Western Kara Sea average cyclonic circulation the cold Northern Kara Sea water penetrated into the investigated region along Novaya Zemlya Isles Eastern shores [6].

Each of two main types was separated into three groups corresponding to wind velocity in the vicinity of Kara Straight: 1 ("+" for favourable and "-" for unfavourable type) which is for wind velocities not exceeded 5 m/s; +2 for up to 10 m/s; +3 for wind velocities exceeded 10 m/s. So these groups* represent pressure field sign and its intensity.

These index* along with air pressure, water temperature and its anomaly vs. 1977-1993 mean and difference between air and water temperature in the Anderena HMS are shown in the Fig.3.
Analysis of the presented time series showed the high synoptic variability of the conditions which impact on water drift moving in the investigated region.

There was no tie between pressure field sign and pressure value. Conversely, there was a close correlation between water temperature changes and the index of pressure field sign and intensity. During favourable days integral water temperature increase was $+7.8^\circ C$, integral water temperature decrease during unfavourable days was $12.2^\circ C$. A much during period from August 1 to September 23 integral water temperature decrease at the Amdemra H M S was $4.4^\circ C$ while 1977-1993 mean decrease was $2.5^\circ C$. Such considerable decrease is a feature of warm water years because of more considerable heat low. Particularly, the water was $20^\circ C$ warmer than the air while average value is about $1^\circ C$.

The cause of considerable synoptic scale water temperature increase along with higher heat low could only be the warm drift advection from Barents Sea through the Kara Straight. During warm water years in the Arctic seas the Westerlies in the atmosphere over them prevail [4,5,7] and 1994 was just of that type, so that by the August beginning the positive water temperature anomaly at the Amdemra H M S exceeded $4^\circ C$.

Satellite data (NOAA 11) showed that in the South Eastern Barents Sea the water temperature was $12.5^\circ C$ in the July end - August beginning, 9-10 $^\circ C$ warm water areas with horizontal scale of 100-200 km synoptically occur to the East of Kara Straight and the Vaigach Island. Two strips of relatively warm water of 5-6 $^\circ C$ extended from that area: one extended the North East along the Yamsib Current [7] another extended to the South East to the Baydaratskaya Bay. There were about 100 km diameter 8-9 $^\circ C$ warm cores in both strips. In the inner part of the Baydaratskaya Bay from mid July to mid August surface water temperature was 9 to 11 $^\circ C$.

So, satellite data confirmed the conclusion on the role of warm Barents Sea water advection in the South Western Kara Sea water temperature increase, the Baydaratskaya Bay being likely to be a trap for relatively warmer Barents Sea water. Along with summer insolation that led to considerable water temperature increase till the values peculiar in South Western Barents Sea.

Since mid August the stable cloud cover which might be caused by anomalous warm water made it impossible to obtain satellite data. However, the Amdemra H M S surface data showed the continuation of the synoptic scale advection variability till the very site survey. In the conditions of the integral water temperature decrease with small solar absorption more saline water is warmer because of more effective heat flux from underlaying water. Just that water filled the Baydaratskaya Bay from the surface to the bottom in mid September 1994.
4. CONCLUSIONS

1. More than 30 m thick anomalous warm and saline water layer formation in the Baydaratskaya Bay and South Western Kara Sea in September 1994 was caused with convergent advection of South Eastern Barents Sea water.

2. Buoyance deficit cured with higher salinity and surface cooling were favourable for penetration of warmer water into the bottom layer and pushing out from there overage cold water.

3. That synoptic condition in the sea was caused with favourable anomalous atmospheric circulation over Eurasian sector of Arctic with inversive air pressure field and prevailed westerlies.

4. On the mentioned large scale anomaly background the close tie between synoptic scale processes in the atmosphere and the water were identified. This information could be the base for the hydrometeorologic processes forecast scheme of investigated region development.

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Fig. 1. The temperature fields, °C, (a, c) and temperature anomaly fields (b, d) in the surface (a, b) and the bottom (c, d) layers of Baydaratskaya Bay from vessel observations 19-23 September 1994.
Fig. 2. The salinity fields, o/oo (a, c) and salinity anomaly fields (b, d) in the surface (a, b) and the bottom (c, d) layers of Baydaratskaya Bay from vessel observations 19-23 September 1994.
Fig. 3. Temporal variability of: the pressure field types upon South Western Kara Sea (a), the air pressure (mb, b), the water temperature (°C, c), their anomaly related climatic mean values (d) and the difference between air and water temperatures (e) from observations on HMS Amderna in August-September 1994.
NEW DEVELOPMENT IN MODELLING TECHNOLOGY OF FIRST-YEAR RIDGES

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Research Engineer  Arctic Research Centre.

ABSTRACT

Normally tests in a model basin start with making a smooth ice sheet for tests in level ice, channels and maybe for manoeuvring. In a typical programme after these tests follows a test in an ice ridge. The preparation of a ridge has many customs and to get as result a ridge, which is of geometry and physical properties comparable to ridges met in the field is a very complex task. This paper discusses the recent work at the Kvaerner Masa-Yards Arctic Research Centre (MARC) in the development of better simulation of ice ridges, their properties and practical usage.

1. INTRODUCTION

In the nature ridges are of different types depending for instance on the water depth and the activity (wind etc.) of the area. First-year ridges can be described for instance the following way:

- Hummock
- Individual ridge
- Ridge field
- Rubble field
- Rubble pile
- Grounded ridge (stamukha)
- Ice jam

In different laboratories the method to prepare a ridge vary. First of all you choose the type of ridge could best be modelled. Then comes the preparation method. Ridges are very complicated to simulate properly. Some of the methods used are:

- Build a ridge by piling on top of each other ice plate
- Cut the ice sheet to two halves mid push the ends against each other and hope to build on individual ridge
- Break ice into small pieces and form a uniform thick wide rubble
In the simulation of the ridges in the Baltic the last of the three methods has worked quite well and has been correlated at MARC to full scale measurements. However when traffic end operations are stretched to areas with more severe conditions, the parameters of the ridges also change, especially the degree of consolidation must be taken into consideration. Ridges are harder and thus more difficult obstacle to the traffic.

2. RIDGE MODELLING PROJECT AT MARC

2.1. Properties to be modelled

The properties of the ridges in model scale base on the properties of the "natural" ridges. During the full-scale expeditions following properties of the ridges are usually determined:

- main dimensions of the ridges (sail height and profile, keel depth, width of the ridge)
- the age and type of the ridges (first-year, mutliyear; floating, grounded)
- the size of the ice blocks in ridges
- porosity of ridges
- the thickness of the consolidated layer of ridges
- the mechanical properties of the ice in ridges (sail, keel, consolidated layer)
- the physical properties of the ice in ridges (salinity, temperature)
- inner properties of the ridge (cohesion, inner friction)
- ridge intensity, orientation and size distribution.

The most essential difference between the ridges in different sea areas is the thickness of the consolidated layer of the ridge. It depends mainly on the age — the cumulative temperature history of the ridge. The maximum freezing time of the Baltic Sea ridge is about 4 months while the freezing time of the Barents Sea ridge can be even 8 months. Typical thicknesses of the consolidated layers in ridges are:

- the Baltic Sea ridge 0.5 m
- the Gulf of Bothnia ridge 0.5 - 1.5 m
- the Pechora Sea ridge 2 - 3 m
- the northern Barents Sea ridge up to 5 m

The total thickness of the ridges concerning the floating ridges in different sea areas is found to be the same order, but the porosity is varying. The porosity of the Baltic Sea ridges is about 30%. The porosity of the Pechora and Barents Sea ridges varies a lot being 10 - 40%.

The width and the length of the ice blocks in ridges is found to be 5 times the level ice thickness.

The compressive strength of the ice in ridges is measured a lot (mainly the strength of the ice in the sail part and in the consolidated layer). For the compressive strength of the ice in the consolidated layer values 0.5 - 1 times the strength of the surrounding level ice are measured. There is no significant difference between compressive strength values measured in different sea areas; the uniaxial vertical compressive strength varies 0.5 - 9 MPa (typically
2 - 6 MPa) with high deviation. The uniaxial horizontal compressive strength is usually 10 - 30 % lower than the vertical one.

The inner properties of the ridges - cohesion, inner friction - are not systematically determined during expeditions. Values 0 - 4 kPa for cohesion are suggested.

22 Modelling of the ridges

When developing the new modelling technology of floating first-year ridges at the Kvaerner Masa-Yards Arctic Research Centre (MARC) the two comparatively large test phases were carried out in 1993 - 1994. In the tests the four different types of the floating first year ridges (in scale 1:20) were simulated:

- the Baltic Sea ridge
- the Gulf of Bothnia ridge
- the Pechora Sea ridge
- the northern Barents Sea ridge

In the tests the thickness of the consolidated layer was varied while the main dimensions of the ridges, the block size in ridges and the porosity of the ridges were kept constant.

In the second test phase, in addition, the influence of the isolation of the surface layer of the ridge was studied. The reason for isolation was the excessive freezing of the surface layer of the ridges in the first phase tests.

23 Manufacturing of ridges in ice model basin

The ridges were manufactured from the FGX model ice developed in the Kvaerner Masa-Yards Arctic Research Centre. The scale was 1:20. Thus, the level ice thickness was 40 mm (corresponding 0.8 m in full-scale) and the flexural strength of the ice 25 kPa (corresponding 500 kPa in full-scale). The consolidated layer of the ridge was simulated by level ice layers piled one upon another. The rest of level ice field was cut into regular pieces (5 times ice thickness) with a special ice piece cutter. The keel pieces were pushed under the simulated consolidated layer with the push-bar of the carriage. One test ridge was manufactured without the separate consolidated layer.

24 Methods and results of testing ridges

The properties of the ice material (level ice sheet) from which the ridges were built were measured (the ice thickness, the flexural strength of the ice in cantilever beam test, the Young's modulus in bending by the infinite plate testing).

The main emphasize for measurements in each ridge was the definition of the thickness of the consolidated layer and its mechanical properties:

The crushing strength and the vertical pressure distribution of the ridge were determined by indentation test. The ridge indenter (figure 1) was equipped with the force transducer for the total load measurement and with 8
pressure transducers (diameter of 14 mm) for determining the pressure distribution. Four pressure transducers were installed at the supposed consolidated layer. In tests the ridge indenter was pushed through the ridge with constant 20 mm/s speed. Also a test series with speeds 1, 10.20 and 40 mm/s was conducted in the second phase.

In figure 2 examples of the vertical pressure distributions of the Baltic Sea ridge and the Pechora Sea ridge are presented. The difference in the thickness of the consolidated layers and in their properties can be seen.

Examples of crushing strengths (phase 1 tests) calculated from the total force of the ridge indenter are presented in figure 3. The isolation used in phase 2 seemed not to have any influence on the crushing strength values.
The shear strength of the ridges was studied by push-through test; the consolidated layer was removed from the loading area (d = 200 mm) and the keel was loaded vertically until failure with weights (figure 4). Results of the shear strength measurements are presented in Tables 1 (phase 1 tests) and in Table 2 (phase 2 tests).

The shearing strength values were slightly higher in tests of second phase. In the case of the Baltic Sea ridge the values received in the second phase tests were, however, remarkably higher. In some tests the isolation was noticed to reduce the shear strength even 40 %, but generally examining the isolation had no effect on the shearing strength. If the results of the push-through tests in model scale are compared with cohesion values measured and estimated in full-scale, the model scale values are in the upper limit.
Table 1. Shear strength of ridge keels (phase 1).

<table>
<thead>
<tr>
<th>Ridge type</th>
<th>Shearing strength (KPa)</th>
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<tbody>
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<tr>
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<tr>
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<td>0.17</td>
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<tr>
<td>Barents</td>
<td>0.21</td>
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</tbody>
</table>

In the second phase the influence of the indentation speed on the crushing strength and the vertical pressure distribution was also studied. The both values show remarkable signs of increasing in lower speeds. The crushing strength vs. indentation speed is presented in figure 5 and the vertical pressure distribution vs. indentation speed in figure 6. When examining the pressure distributions should be noted that the upper pressure transducers have been in the air over the consolidated layer because of the too low water level in the basin during the test day.

![Crushing strength vs. indentation speed in model scale](image)

Figure 5. Crushing strength vs. indentation speed.
3. TESTS WITH SHIP MODEL

The tests with ship models were conducted in conjunction with the development of the new tanker concept. The ship tested is a 90000 t\text{dwt} tanker with the following dimensions (varying by version):

- Length 224-236 m
- Breadth 38 m
- Draught 13 m
- Power 16 MW
- No of propellers=2

In these tests the ridges were of three different type:

- Rubble field in the Baltic Sea
- Gulf of Bothnia ridge
- Pechora Sea ridge
The ridges were built according to the method described above and in the target values the most followed parameter was the thickness of the consolidated layer in the ridge. Summary of the parameters of the ridges are presented below, table 3.

Table 3, Ridge parameters in ship tests

<table>
<thead>
<tr>
<th></th>
<th>Rubble field</th>
<th>Gulf of Bothnia</th>
<th>Pechora ridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total thickness</td>
<td>8-12 m</td>
<td>8-12</td>
<td>12.5-23</td>
</tr>
<tr>
<td>Thickness of the</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>consolidated layer</td>
<td>0.5 m</td>
<td>1.1 m</td>
<td>25</td>
</tr>
<tr>
<td>Flexural strength of:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ø level tee</td>
<td>600 kPa</td>
<td>600 kPa</td>
<td>600 kPa</td>
</tr>
<tr>
<td>ø consolidated layer</td>
<td>400 kPa</td>
<td>400 kPa</td>
<td>400 kPa</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>3 MPa</td>
<td>3 MPa</td>
<td>4 MPa</td>
</tr>
<tr>
<td>Porosity</td>
<td>35 %</td>
<td>30 %</td>
<td>20 %</td>
</tr>
</tbody>
</table>

The tests were done with the model ramming into the ridge by self propulsion. Thickness profiles of the Pechora Sea ridges are in figure 7. In figures 8 and 9 there are samples photographs from the tests.
The main results from the tests when looking at the preparation of the ridges was that the ridges were extremely difficult to build but after all the method worked. The ridges built followed well the specification.

On the ship point of view the main result was that the different types of ridges really resulted significant differences in resistance, see figure 10. A comparison in figure 10 shows that the resistance of a vessel with traditional icebreaking bow form (SA 15 TYPE) increases more than the resistance of the tanker models tested. This favours also the new thinking of running the vessel stem first in heavy ice conditions.

![Figure 10, Ice resistance in ridges](image)

4. FUTURE TRENDS

The modelling techniques today allow to simulate the real ice conditions more realistically. However this development is in full dependent on the information collected in the field. The results discussed in this paper are encouraging. The following list shows the view point of the present and the desired future:

- the properties of model ice ridges can be controlled
- differences in ridge qualities can be noticed in model tests
- tests with ship models have given good results
- development to test marine operations (ships and structures together) has started
- more information on site specific ice conditions must be collected
Arctic Shipping Services - three years of successful tanker operations on the Northern Sea Route

BACKGROUND

At the end of 1992 the management of the Murrnansk Shipping Company and the representatives of the Finnish shipping company Neste Shipping, with experience from Arctic navigation from Canada and Greenland, and Kvaerner Masa-Yards, the builder of more than 60 per cent of the world's icebreakers created the idea of joining forces for tanker operations along the Northern Sea Route. Due to the remarkable changes caused by the collapse of the U.S.S.R., this was considered especially necessary to secure the continuation of the fuel supplies to Eastern Siberia.

The idea was developed further and in July a new joint venture company, Arctic Shipping Services, was registered in Murmansk. Primary task for the company was stipulated to be oil product movements in the Northern Russian waters, including fuel supplies to Northern bases as well as export of oil products from Northern Russia.

Secondary, the company was planned to take care of other oil transports to and from Russian ports.

It was also thought that in the future the company could look at transportation of project cargoes and modules to Northern Russian sites in co-operation with Murmansk Shipping Co.

SHAREHOLDERS

Established in early 1993, A/O Arctic Shipping Services is owned 49 per cent by Russia's Murmansk Shipping Co. and 34 per cent by Nemarc, a joint venture between Finnish Neste Shipping and Kvaerner Masa-Yards Inc. The remaining 17 per
cent is held by other Russian interests, representing the Department of Merchant Marine in Moscow and interests of the former Sovfracht.

The board is today headed by Yu. F. Gluchko of Murmansk Shipping Co and other members have been appointed by the Department of Merchant Marine, Moscow, the Northern Sea Route Administration, Neftehimservice Ltd, Kvaerner Masayards Inc., and Neste Oy Shipping, Finland.

Managing Director of the company is today Mr. Igor Kazakov in the company's office in Murmansk.

ASS FLEET

The company focuses on both import and export of oil products from the regions along the Northern Sea Route. Its highly ice-strengthened double hull ships come from Finnish and Latvian Shipping Company fleets. M/T Kiisla is already managed by Arctic Shipping Services itself and operates under Russian flag.

<table>
<thead>
<tr>
<th>Name</th>
<th>tdw</th>
<th>Flag</th>
<th>BIB</th>
</tr>
</thead>
<tbody>
<tr>
<td>M/T Kiisla</td>
<td>7,000</td>
<td>Russian</td>
<td>B/B</td>
</tr>
<tr>
<td>M/T Uikku</td>
<td>16,000</td>
<td>Finnish</td>
<td>TIC</td>
</tr>
<tr>
<td>M/T Lunni</td>
<td>16,000</td>
<td>Finnish</td>
<td>TIC</td>
</tr>
<tr>
<td>M/T Samburga</td>
<td>14,000</td>
<td>Latvian</td>
<td>TIC</td>
</tr>
<tr>
<td>M/T Rundale</td>
<td>14,000</td>
<td>Latvian</td>
<td>TIC</td>
</tr>
<tr>
<td>M/T Kashira</td>
<td>5,000</td>
<td>Latvian</td>
<td>TIC</td>
</tr>
</tbody>
</table>

Table 1. The double hull ships used by Arctic Shipping Services Ltd in the Arctic trade.
EXPERIENCE

During the first season in 1993 Arctic Shipping Services chartered a total of nine vessels and carried close to 200,000 tonnes of fuel to destinations along the Northern Sea Route. Nemarc's M/T Lunni made three voyages from Arkhangelsk to the Yana River on the Laptev Sea.

Arctic Shipping Services saw a big expansion in traffic during last season (1994) on the Northern Sea Route. During the brief Arctic sailing season, lasting about four months from early July to late October, the vessels reached from the West almost as far as the Bering Strait separating Siberia and Alaska. For the first time, too, refined oil products for export were loaded from the shores of the Northern Sea Route.

The Lunni was joined by M/T Uikku and M/T Kiisla as well as four Latvian tankers, shipping almost 300,000 tonnes of oil products.

For their part, Kiisla and Uikku made several voyages during last season with oil products to the Yenisey and Yana rivers. Uikku also carried an export cargo back from Dudinka, while Kiisla took out another export cargo from Yenisey.

During the winter the Kiisla was mainly carrying export cargoes for LUKOil through the Baltic ports. Currently she is working with fuel loads to military bases in the Novaya Zemlya area.

Icebreaker assistance has been successfully provided by the nuclear fleet of Murmansk Shipping Co. There has been no major problems and the ice pilots onboard the foreign flag vessels have managed to co-operate well with the icebreakers.

TOWARDS YEAR-ROUND TRADE

The volumes of the fuel supplies through the Northern Sea Route tend to have a slightly decreasing trend because of the
lower economic activities in the regions. However, a growth potential has been identified in fuel supplies to the Chukotka area in the Far East, and currently preparations are being made for cargoes from the Murmansk/Archangelsk area to the most Eastern areas of Russia, eventually up to the Pacific Ocean.

The largest growth potential, however, is in the export trades. For this reason A.S.S. has initiated a number of experimental trips.

Picture 1. The Nemarc Shipping Company of Finland has invested 40 Million USD in the modernisation of the 16,000 tdw sister vessels M/T Uikku and M/T Lunni for the Arctic trades. Both ships are currently furnished with an diesel-electric 11.4 MW Azipod rudder propeller propulsion system.

Last April the Uikku headed to the Eastern coast of the Yamal peninsula through a virgin 1.5 metres ice cover in the River Ob estuary in order to pick a 11,529 ton cargo of gas condensate from the Tambey gas field. The actual loading took place through a temporary 4 km pipeline built on the river ice.
Operationally this experimental trip was a success, it clearly demonstrated that a year-round exports from these areas is technically possible. New technology was also tested for this trip; a Finnish aeroplane was able to fly over the region with its electromagnetic measuring system and the size and location of the ice ridges could be reported via a satellite onboard to *Uikku*’s master.

Economically this trip appeared to be less successful. Due to the temporary loading arrangement the vessel had to stay much longer on the site than normally in a standard terminal. In addition, the vessel had to pay the normal Northern Sea Route tariff fees for the assistance of the nuclear icebreakers. A surprise, however, were the amounts of the MSCO charges for a stand-by icebreaker and its mobilisation from and back to Murnansk.

If the icebreaker tariffs will be tripled, as has been forecasted, this promising export trade will fade out before it actually has emerged.

![Image](image_url)

*Picture 2. The 11.4 MW electric Azipod drive on the tanker 8M/T Lunni was installed in June 1995.*

The *Uikku* is currently unloading in Western Europe a similar export cargo which she has picked from *Yamburg*, higher up on the Ob river. There are expectations that a similar export
of 70,000 tons of oil products from the Yenisei area (Dudinka) could be handled during the current open water sailing season.

**FUTURE PLANS**

The experience from last season on the Northern Sea Route and the Tambey experiment convinced that oil cargoes can be safely transported along Russia's Arctic shores.

The experience of Neste Shipping in ship to ship cargo transfer was successfully utilised in the Arctic.

The Arctic Shipping Services joint venture is looking for the possibility to increase its Russian flag fleet of heavily ice-strengthened tankers. As soon as the company shows necessary financial solidity, suitable newbuildings will be constructed. Such newbuildings could be successfully utilized in the Arctic fuel supplies during the Arctic summer season and in the ice-covered Baltic or Russian products exports during the winter period.

One of the most important prerequisites for any technological development in the Arctic trade is a healthy freight rate level. The current rates are reflected by the old, often substandard ships which are currently still operating in the area. They are inherited from the former U.S.S.R. and do not have the burden of any capital cost.

The authorities should understand the sensitivity of the Arctic environment and prohibit commercial operations of such vessels in these waters, which do not fulfil sufficient environmental standards.

A great challenge will be the start-up of the crude production in the Timan-Pechora area. Volumes which could amount up to several 100,000 tdw vessels every week will require heavily ice-strengthened special tonnage and a new generation of icebreakers. A/O Arctic Shipping Services with its shareholders are prepared to initiate discussions on long term transportation contracts for operations in the Northern Russia.
ABSTRACT

For ridge sail height two distribution hypotheses have been suggested. The first, of the form $a \exp(-ch^2)$, was proposed by Hibler et al. (1972) and the other, of the form $a \exp(-ch)$, by Wadhams (1980). In laser profilometer surveys the latter has been in most cases found the fit the data excellently. However, the profilometer data refers to two-dimensional ridge cross-sections while in the derivation of the Hibler distribution the reference was to ridge segments or links. The height variation of ridge links has been measured in the Baltic. The results strongly suggest that correctly interpreted the two hypotheses imply each other.

1. INTRODUCTION

Ridge sails form horizontally a complex two-dimensional geometry. As no generally accepted two-dimensional statistics exists ridging is usually quantified by linear transsects across the ridge field. The two basic components of the linear statistics are the ridge sail height and ridge spacing distributions. There are two commonly used models for sail height (or keel depth). The first was proposed by Hibler et al. (1972) and according to it the sail heights distribute as

$$f_1(h) = \frac{2}{\pi \mu} \exp\left\{-\frac{1}{\mu} \left(\frac{h}{\mu}\right)^2\right\}$$

(1)

The expectation of (1) is $\mu$. As ridge data sets normally have a cutoff $h_0$ for sail height the tail of (1) above this value is applied. This changes the expectation in a nonlinear fashion.
Another distribution hypothesis is the negative exponential proposed by Wadhams (1980),

\[ f_2(h) = \frac{1}{\mu} \exp\left(-\frac{h}{\mu}\right) \] (2)

The expectation of is likewise p. Separating the tail above the cutoff simply shifts the distribution and changes the expectation to \( \mu + h_0 \).

These distributions have been fitted to data in a routine fashion and variable results have been found. The virtue of the exponential distribution is its analytical simplicity and easy fitting to the data. The results are not bothered by the cutoff. For the Hibler distribution the choice of cutoff and reference level is crucial; if these are adjusted, the properties of the distribution change. Thus the Hibler distribution has two independent parameters although the zero level of the data set is usually applied, wherever it refers.

On the other hand, the Hibler distribution can be derived by an argument borrowed from statistical physics. In the 1972 paper Hibler et al. decomposed the ridge field into ridge segments or links and derived (1) by assuming that all arrangements of ridge links constrained by a constant total volume of deformed ice are equally likely. To obtain (1) one must assume also that the cross-sectional area of a link has a quadratic dependence on ridge height. It is clear that cross-sectional area and height are to be defined as averages over the link length. For (2) no explanation has thus far presented.

In most papers following Hibler (1972) it is left undiscussed what is the reference of 'ridge height'. Ridges are can be several km long and a sail segment has a certain maximum, minimum and mean height. The sail height variation can be large and even massive ridges can contain gaps. As ridges are classified visually the reference is either to the maximum height or to general massivity, related to the mean height of a certain segment. On the other hand, as the sail height is measured along a linear track the reference is to a narrow sail cross section which for laser profilometers is two-dimensional. The recorded height value is a random sail height sample and has certain relations to the mean or maximum height of the corresponding segment.

In the following the statistical relations of cross-sectional height to the mean height of ridge sail segments, called ridge links, is examined. As segment statistics exists for sails only, ridge keels are not considered.
2. STATISTICAL DESCRIPTION OF RIDGED ICE FIELDS

In a heavily ridged ice field the ridges join to a complex network. From above this is observed as the totality of ridge sails. Also in rubble fields, where the ice underside is an unstructured ice mass, sails can often be discerned.

Following Hibler (1972) the complex horizontal geometry of ridge sails is decomposed to a large number of ridge segments or links. These are assumed to be units the geometry of which is constrained by the local deformation history of the ice field. Two adjacent short segments of a pressure ridge can be assumed to have formed in a compressive event the direction and magnitude of which are the same for both segments. The segments are expected to have about the same volume which sets a constraint to the variation of sail height and keel depth. On the other hand, two segments from ridges far away from each other have independent local deformation histories and their properties are correlated through the large scale dynamics and ice thickness only.

If one observes ridge formation in the field it constitutes a local deformation event where the sail has well defined end points. It is thus meaningful to say that the ridge field consists of individual ridges where the statistics of each ridge is constrained by the characteristics of the corresponding deformation event. If ridge links are identified with individual ridges the link length $L$ is a random variable. However, this is not possible in practice. Therefore all links are assumed to have the same length $L$ which is of the same order as the shortest individual ridges.

As the ridge field is decomposed into links, three distributions are associated to it. Given a cutoff value $h_0$ for the ridge sail height, then if per unit area

$$F(h) = \frac{\text{length of ridge sail exceeding } h}{\text{length of ridge sail exceeding } h_0}$$

define the ridge sail height distribution as

$$f(h) = \frac{\partial F(h)}{\partial h}.$$  

Within each ridge link sail height variation exists. The size of the link is measured by the mean sail height $s$ of the link. Define, per unit area, the ridge link size distribution $g(s)$ by

$$g(s) = \frac{\text{number of ridge links exceeding } s \text{ in size}}{\text{total number of ridge links}}, \quad g(s) = \frac{\partial G(s)}{\partial s}$$
and for each ridge link size the distribution of height variation within the link, \(k(h,s)\), as

\[
k(h,s) = \frac{\text{length of link sail exceeding } h}{L}, \quad k(h,s) = -\frac{\partial K(h,s)}{\partial h}
\]

These distributions are related to each other as

\[
f(h) = \int g(s) \frac{k(h,s)}{K(h_0,s)} \quad s = \int h k(h,s) \quad (3)
\]

If \(h_0=0\) the expectations of \(g(s)\) and \(f(h)\) are equal. If the distributions \(f(h)\) and \(k(h,s)\) are known, (3) is an integral equation for the unknown \(g(s)\).

### 3. Profiling Measurements of a Ridge Field

Consider a measurement of a ridge field along a linear track (Figure 1). The device can observe the surface or underside only, like laser profilometers and sonars. Sound through the ice, like AEM (airborne electromagnetic) systems and Impulse radars, and it has a certain physical footprint and measuring frequency. How a ridge link is observed depends on the footprint and the measurement method. An AEM system footprint is tens of meters and the calculated ice thickness can be interpreted as a weighted average within the footprint (Multala et al., 1995). Therefore, the result is likely to be correlated with the ridge link size. A sonar beam width is typically from 20 to 100, corresponding to footprint diameter increase of 3.5 to 17.5 m per 100 m distance increase. The measurement system may record the first returning signal, like many sonars do, and refer to the maximum within the footprint, or it may calculate the output from several signals. All these things matter when the data is interpreted.

A typical footprint diameter increase for a laser profilometer is 0.3 m per 100 m, and it resolves the ridge structure to the scale of block thickness. It produces two-dimensional cross sections from the ridge. As a laser profilometer is flown across a ridge link sail, the cross-sectional maximum is a random sample from the height distribution \(k(h,s)\) of the link. If the ridge field has homogeneous statistics over a large region, the sail height distribution obtained from it is \(f(h)\). This cannot be assumed to be equal to the link size distribution \(g(s)\).
4. SAIL HEIGHT DISTRIBUTION

In the Baltic negative exponential sail height distributions have been found in laser profilometer surveys (Leppäranta 1981, Lewis et al 1993, Lensu 1993, 1995). The surveys have restricted to the most heavily ridged sea area, the Bay of Bothnia, and the exponentiality has been confirmed almost beyond doubt. This may be associated to the fact that the Bay of Bothnia constitutes more or less a single sea regime with little variation in level ice thickness. The mean ridge height (0.5 m cutoff) is almost constant 0.7 m (that does not vary much interannually.

In Arctic and Antarctic areas there is room for dispute between the negative exponential and Hübner distributions (Table). Several explanations can be suggested. The Arctic and Antarctic surveys cover often large regions. It is conceivable that the exponentiality holds regionally but the regional distributions, having different mean values, do not superpose in a way that would enhance this property. The superposing of exponential distributions result to distributions that have some similarity with the Hübner distribution. The tall of the Hübner distribution has qualitative similarities to the
negative exponential. It has been suggested that the ridge search procedure effects (Wadhams 1980) or simply that both distributions are approximate models (Clerking 1995).

It is, however, noted that exponential distribution applies to all data sets obtained by a profilometer. Devices with larger footprint produce distributions that are usually well fitted by the Hibler distribution. The same applies to the quantification of ridge heights from stereo pairs. Visual classification is bound to refer to some sail segment or its maximum. It is remarkable that the keel draft distribution in Wadhams (1980), obtained by a wide beam sonar, was found to obey Hibler distribution while the sail heights measured by a profilometer along the same track obeyed exponential distribution. On the other hand, keel draft measured by a narrow-beam sonar is excellently modelled by the exponential distribution (Wadhams and Davy 1986).

Table: Ridge sail height measurements in the Arctic and Antarctic. The footprint diameter is included when reported.

<table>
<thead>
<tr>
<th>Source</th>
<th>Region</th>
<th>Method /lp</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hibler et al 1972</td>
<td>Arctic</td>
<td>Visual observations</td>
<td>Good fit with Hibler, exponential not considered</td>
</tr>
<tr>
<td>Hibler et al 1974</td>
<td>Western Arctic</td>
<td>Laser profilometer</td>
<td>Hibler acceptable, exponential not considered</td>
</tr>
<tr>
<td>Tucker et al 1979</td>
<td>Chukchi and Beaufort Seas</td>
<td>Laser profilometer</td>
<td>Exponential better than Hibler, both acceptable</td>
</tr>
<tr>
<td>Wadhams 1980</td>
<td>Central Arctic</td>
<td>Laser profilometer</td>
<td>Good fit with exponential; keel depths along the same track fitted Hibler</td>
</tr>
<tr>
<td>Kreider and Tho 1981</td>
<td>Beaufort Sea</td>
<td>Stereographic photography</td>
<td>Exponential slightly better than Hibler, both acceptable</td>
</tr>
<tr>
<td>Sayed and Frederking 1991</td>
<td>Canadian Arctic shear zone</td>
<td>Stereographic photography</td>
<td>Lognormal at the shear zone edge, Hibler in the interior pack, exponential not considered</td>
</tr>
<tr>
<td>Weeks et al 1989</td>
<td>Ross Sea</td>
<td>Laser profilometer</td>
<td>Good fit with negative exponential, Hibler not considered</td>
</tr>
<tr>
<td>Granberg and Leppäranta 1990, 1993</td>
<td>Weddell Sea</td>
<td>Laser profilometer 0.2</td>
<td>Good fit with negative exponential, Hibler not considered</td>
</tr>
<tr>
<td>Lytle and Ackley 1991</td>
<td>Eastern Weddell Sea</td>
<td>Acoustical Sounder 1 / 3</td>
<td>Hibler better than exponential in all cases</td>
</tr>
<tr>
<td>Dierking 1995</td>
<td>Weddell Sea</td>
<td>Laser profilometer 0.06</td>
<td>Exponential better for low ridging intensity, Hibler for high ridging intensity</td>
</tr>
</tbody>
</table>
5. THE DISTRIBUTION $k(h,s)$: LONGITUDINAL RIDGE PROFILES

The measurements of longitudinal profiles of ridge segments are few. These would be available, for example, from stereographic pairs but the ridge height has been measured from these along linear tracks only (Table). Hibler and Ackley (1975) measured longitudinal profiles from ridge shadows in the Beaufort Sea in order to model the probability for a vehicle to find a gap enabling it to cross the sail. The height was quantified from images in 5 m intervals and with the accuracy of $0.25$ m. No specific effort to find the best possible model for the height distribution was made. It was assumed to be multivariate normal distribution and the covariance matrix was calculated from the data. The mean height was $1.9$ m, the standard deviation $0.7$ m, and a large variation over short distances can be seen in the profiles.

In Lensu (1994a) a longitudinal profiling of a 1460 m long Baltic ridge in 44 m average interval is reported. The measurements were made with a laser theodolite and the accuracy was $0.01$ m. The results are shown in Figure 2. Mean height was $0.8$ m and maximum $25$ m. The normal distribution was acceptable (Figure 2 b) while the negative exponential distribution was not (Figure 2 c). However, the best fit was obtained with the squared exponential distribution (Weibull distribution with Index 2, Figure 2 d). In Lensu (1994b) six longitudinal profiles are reported. The measurements were made with a laser levelling device in 1 or 1.5 m constant intervals and $0.01$ m accuracy. The profile lengths varied from 99 m to 191 m. In chi-square analysis the Weibull hypothesis was valid for 4 ridges and rejected for one and the indices of best fit varied from 18 to 28. Squared exponential (Index 2) was valid for three ridges and rejected for one. The negative exponential was rejected in all cases.

Since each measurement referred to an identifiable singular ridge they can be assumed to be samples from the ridge height distribution $k(h,s)$. The results suggest that the cross-sectional area is distributed exponentially along the link which for the quadratic dependence on ridge height gives squared exponential height distribution.

$$k(h,s) = \frac{\pi}{2s} h \exp\left\{-\frac{\pi}{4s} h^2\right\}. \tag{4}$$

In the measurements it was also found that the ridges contained gaps where the sail completely disappeared and that the distribution $k(h,s)$ was defined for all nonnegative values of $h$. 

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Figure 2. Site height distribution of a 1460 m long belt (a) Histogram of site height

Cumulation

(a) Cumulation

(b) Cumulation

(c) Cumulation

(d) Normal Cumulation

(e) Number of Instances

(f) Number of Instances
6. RIDGE LINK SIZE

For given \( f(h) \) and \( k(h,s) \) the link size distribution \( g(s) \) can be solved from (3). Since the distributions \( k(h,s) \) were observed to be defined for all nonnegative \( h \) the same is assumed on the ridge height distribution \( f(h) \). The negative exponential \( f(h) \) is assumed to be extrapolated down to zero. However, it is not known whether this applies or not. For generality a form of \( k(h,s) \) comprising a larger family of distribution hypotheses \( \text{is assumed} \), namely a powered gamma distribution with mean value \( a \),

\[
k(h,s) = \frac{\alpha h^{a-1}}{\Gamma(a/p)} \exp \left\{ -\left( \frac{h^{(1+a)/p}}{s^{(1+a)/p}} \right)^{b} \right\} \left( \frac{\Gamma((1+a)/p)}{s^{(1+a)/p}} \right)^{a}.
\]

The Mellin transform of \( k(h,s) \) with respect to \( h \) is

\[
M(h, s) = \int_{0}^{\infty} dh h^{z-1} k(h, s) = \frac{\Gamma((a+z-1)/p)}{\Gamma(a/p)} \left( \frac{\Gamma((1+a)/p)}{\Gamma((1+a)/p)} \right)^{z-1} s^{z-1}.
\]

As these are applied to the integral equation (3) for the link size distribution, the Mellin transform of \( g(s) \) can be solved as

\[
M(g(s)) = \frac{\Gamma(z)}{\Gamma((a+z-1)/p)} \left( \frac{\Gamma((1+a)/p)}{\Gamma(a/p)} \right)^{z-1} s^{z-1}
\]

For Weibull distributions \( a = p = 2 \) in which case

\[
M(g(s)) = \frac{\Gamma(z)}{\Gamma((z+1)/2)} (\Gamma(3/2))^{z-1} s^{z-1} = \Gamma(z/2)(\Gamma(1/2))^{z-2} \mu^{z-1}
\]

Comparing (6) and (7) (change stop) reveals that the link size is distributed as

\[
g(s) = \frac{2}{\pi \mu} \exp \left\{ -\frac{1}{\pi} \left( \frac{s}{\mu} \right)^{3} \right\}.
\]
It is thus found that if the ridge height distribution \( f(h) \) is exponential and the link height distribution \( k(h,s) \) squared exponential then the link size distribution follows Hibler distribution (1).

7. DISCUSSION

The results suggest that the two distribution hypothesis are not rivals but rather two sides of a coin that moreover imply each other when correctly interpreted. The Hibler distribution is to be considered as more fundamental one since it can be derived with some general arguments. It also refers to entities that correspond to what is understood by a 'ridge' in the field. The applicability of negative exponential distribution appears as a secondary feature. It follows also that devices with large footprint sample values more closely following the Hibler distribution. The burden of explanation is transferred from \( f(h) \) to the distributions \( k(h,s) \). In a simple configuration this would mean the derivation of \( k(h,s) \) in a process where a rectangular ice sheet is used up to produce a pressure ridge link.

The main problem in the application of Hibler distribution is the adjustment of reference level and cutoff. The distributions \( k(h,s) \) are defined down to zaro elevation which implies that \( f(h) \) is, too. On the other hand, ridge link size can be assumed to have a certain physical minimum value \( s_0 \) which is probably related to the parent ice thickness. This means that the system of the three distributions can be expected to start to collapse near \( s_0 \). This implies further that the exponentiality of \( f(h) \) is not expected to hold for small values of \( h \). This is supported by the observation that the exponentiality of \( f(h) \) can to some extent extrapolated downward to produce estimates of ridge density but the extrapolation to zaro raises the ridge density to unrealistic values.

More extensive measurements of longitudinal ridge sail elevation would be needed to clarify these matters. Resolving stereographically the topography of a say, 1 sq. km of ridge ice field would provide all three distributions and their Interrelations. This would also give the distribution \( f(h) \) below the cutoff value necessary in profilometer data analysis and make possible the calculation of ridge densities that would correspond to those observed in the field or measured from aerial photography.

It should be remembered that \( f(h) \) refers to the relative length of ridge sail in a certain area and that the height distribution obtained with a profilometer can be identified with it only if the ridge field is homogenous over the area of survey. In the Baltic heights exceeding 2 m are seldom observed in profilometer surveys but...
commonly in the field. This is in accordance with the interpretation of \( f(h) \) since the tail probability of finding them is of the order of 0.001. For typical Baltic ridge densities (3-5 ridges/km) this means that few meters of ridge sail exceeding 2 m is found within easy reach (500 m) in the field. Extrapolation upwards implies that typically one ridge exceeding 3 m is found per 100 sq. km and one exceeding 4 m per 30 000 sq. km. This is also in accordance with observations (Lensu 1995).

If the ridge field is homogenous w.r.t. height, as appears to be in the Bay of Bothnia, then the stereographic measurement of 1 sq. km would correspond to a profilometer survey of several hundred km. This indicates that an effective ridge survey would consist of stereographic mapping for the distributions \( f(h) \), \( g(s) \) and \( k(h,s) \) together with a laser profilometer flight for ridge spacing distributions. This could be completed by a search of maximal ridge heights which cannot be expected to be found by either method.

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ABSTRACT

New coupled ice-ocean model with prognostic temperature and salinity fields and realistic bottom topography for ice and water dynamic's simulation in the Kara Sea area is represented. A sea ice model with elastic-plastic rheology was chosen to describe the ice failure under high internal stresses and was realized with the help of quasi-Lagrangian numerical technique in area with free boundaries. The threedimensional ocean circulation model was used to describe tidal and drift circulation, sea level evolution, momentum, heat, and salt exchanges at ice-water and water-air interfaces, and fresh water discharge. The onedimensional upper-ocean and sea ice growth model enables to calculate upper ocean thermal conditions, sea ice growth and melting. The model yields realistic mean currents, upper ocean thermal conditions, tidal motions and ice behavior in idealistic tests. Model behavior in realistic situations was compared with the observations data and, on the whole, results of modelling was in good agreement with observations.

INTRODUCTION

Insufficient detail information about the hydrometeorological regime in some sea regions of Russian North, including sea ice characteristics, and necessity to forecast the main ecological and technical problems set thinking specialists to obtain new data for some practical applications. In some cases new informations may be obtained by means of mathematical modelling. To forecast typical and extreme situations which may be critical for oil industry (for example) on Russian continental shelf zone and evaluate the
potential damage risk due to possible accidents it is necessary to create coupled sea ice-ocean dynamic model. When developing the model authors was encountered with the following problems specific for Kara Sea - extended open boundaries, intense tidal motions, high ice conditions variability, influence of river discharge on hydrological regime of area. Poor hydrological data set allows to reconstruct only monthly (in the best case) averaged field of temperature and salinity. Ice observations are limited by periods when atmospheric conditions enable to use remote sensing data. When observation data are insufficient the minimum empirical parametrizations use is the only way in model developing.

MODEL DESCRIPTION, BASIC EQUATIONS AND MATHEMATICAL FORMALIZATION

The elastic-plastic ice model \cite{Pritchard1990}, 3D baroclinic circulation model and 1D upper-ocean model \cite{Nechvolodov1988} were determined as a basis of the coupled model.

1. Ice model

Ice conditions are represented by thickness distribution $G(r,h,t)$ \cite{Thorndike1975}. Compactness $A(r,t)$ is $A(r,t) = 1 - G(r,0,t)$.

Changes in thickness distribution arise from both thermal and mechanical factors

$$\frac{DG}{dt} + \frac{\partial G}{\partial h} = \psi - C \nabla \psi$$

(1.1)

where $\frac{DG}{dt}$ is the substantial derivative, $h_t(r,h,t)$ is the growth or ablation rate of ice which is derived from thermal energy balance equation, $h$ - ice thickness. $\psi$ is a redistribution function that describes mechanical conversion of ice between categories when rafting and ridging occur. The redistribution function $\psi$ depends on $G$ and the plastic stretching $D_p$, following the concepts introduced by Thorndike et al. (1975). It is a linear function of stretching magnitude.

Forces acting on the ice cover include air stress, water stress, internal ice stress divergence, sea surface tilt, Coriolis and inertial accelerations:

$$m\frac{Du_{\text{III}}}{dt} + f \times u + g \nabla \eta = A(\tau_x - \tau_y) + \nabla \sigma$$

(1.2)
where \( m = \rho_i H \), \( H = \int hK_i \), where \( f \) is the Coriolis parameter, \( g \) is gravitational constant, \( h \) is sea surface elevation, \( \tau_s \) and \( \tau_w \) is air and water stress respectively, \( \sigma \) is internal ice stress integrated through ice thickness, \( \rho_i \) is ice density.

The internal stresses are described by an elastic-plastic constitutive law [Pritchard, 1975, 1981] and are determined by four elements: yield surface, flow rule, elastic response, and kinematic relationship. The isotropic yield constraint is

\[
\phi(\sigma, \sigma_n, p^*) \preceq 0
\]

(1.3)

where \( \sigma = \frac{1}{2} \text{tr} \sigma \) (negative pressure), \( \sigma_H = (\frac{1}{2} \text{tr} \sigma^* \sigma^*)^{1/2} \) (maximum shear), \( \sigma^* = \sigma - \sigma I \), and \( p^* \) is the isotropic compressive strength. A triangular shape surface is used. Strength is described according to Rolhrock (1975) and Pritchard (1981) as

\[
p^* = c^* \frac{h}{h} a(h) dh
\]

(1.4)

where \( a(h) \) is fraction of ice participating in the redistribution process, and \( c^* \) depends on density and ice friction coefficient. All material constants are taken from Pritchard (1981).

An associated flow rule describes plastic stretching \( D = \lambda \frac{\partial \phi}{\partial \sigma} \), where \( \lambda \) is non-negative scalar multiplier that keeps stress within or on the yield surface.

The stress satisfies an isotropic linear elastic response

\[
\sigma = (M_1 - M_2) \text{tr} e + 2M_2 e
\]

(1.5)

where \( M_1 \) and \( M_2 \) are bulk and shear moduli, and \( e \) is elastic strain.

The elastic strain satisfies the kinematic relation

\[
\text{div} \omega + \text{e} \text{W} = D - D,
\]

where \( D = \frac{1}{2} (L + L^T) \) is stretching, \( \omega = \frac{1}{2} (L - L^T) \) is spin, and \( L = \nabla u \) is velocity gradient.

The governing equations of the dynamics are solved in a 2D area \( \Omega(r, t) \) with boundary \( L(r, i) = I_i(r, t) \cup L_2(r, t) \cup L_3(r, t) \) where \( I_i \) is a free boundary (ice edge), \( L_2 \) is a constant (solid) boundary, and \( L_3 \) is an open boundary. The boundary \( \Omega(r, t) \) is unknown (because of \( L_4 \)). The governing equations must be appended by kinematic boundary conditions.

\[
L_1 : \ R_i + \nabla R - f_t(0^+) \frac{\partial \chi(0^+)}{\partial h} \frac{\nabla R}{\nabla \chi \cdot \nabla R} = 0
\]

(1.6)

where \( R(t, x, y) = 0 \) is the equation of free boundary, \( f_t(0^+) \) is the rate of melting for the most thin ice, \( \frac{\partial \chi(0^+)}{\partial h} \) is part of area covered by the most thin ice, and dynamic condition

\[
L_1 : \ (\sigma . n) = 0
\]

(1.7)

Along the fixed (contact) boundary \( L_2 \) (if any) we require that

\[
L_2 : \ u_n = 0 \quad \text{if} \ (\sigma . n) = 0
\]

(1.8)
\[ L_1: \quad (a \cdot n) = 0 \]

where \( n \) is external normal to boundary \( L_1 \).

The first two terms of equation (1.6) are traditional and describe movement of the free boundary due to movement of boundary particles. The last term describes movement of the free boundary due to thermodynamic processes:

\[ L_2: \quad U_n = 0 \quad \text{if} \quad (\sigma \cdot n) > 0 \quad (1.9) \]

where \( U_n \) is normal to \( L_2 \) component of \( U \), and

\[ L_3: \quad u = u_L; \quad \text{if} \quad (u_L \cdot n) > 0 \]

\[ u = n_L \cdot G(h) = G(h)_L; \quad \text{if} \quad (n_L \cdot n) < 0 \quad (1.10) \]

where \( u_L, G(h) \) must be determined from observational data or from other model, \( n \) is external normal to \( L_3 \).

The system (1.1) - (1.2) must include initial conditions:

\[ \Omega(r,0) = \Omega_o(r), G(r,h,0) = G_o(r,h) , U(r,0) = 0 \quad (1.16) \]

2. Circulation model

\[ \frac{\partial u}{\partial t} + Lu - f v = - \frac{1}{\rho_o R \sin \theta} \frac{\partial P}{\partial \lambda} + Du \quad (2.1) \]

\[ \frac{\partial v}{\partial t} + Lv + f u = - \frac{1}{\rho_o R \sin \theta} \frac{\partial P}{\partial \theta} + Dv \quad (2.2) \]

\[ \frac{\partial P}{\partial \zeta} = g \rho_0 \quad (2.3) \]

\[ \frac{\partial w}{\partial t} + \frac{1}{R \sin \theta} \left( \frac{\partial u}{\partial \lambda} + \frac{\partial}{\partial \theta} (v \sin \theta) \right) = 0 \quad (2.4) \]

\[ \frac{\partial T}{\partial t} + L_T T = D_T T \quad (2.5) \]

\[ \frac{\partial S}{\partial t} + L_S S = D_S S \quad (2.6) \]

where \( D_T, D_T, L_T \) are diffusive and advective operators. \( f \) is Coriolis parameter.

Equations (2.1) - (2.6) assume the usual Boussinesq, hydrostatic, and incompressibility assumptions. The following notations are assumed:

\( u, v, w \) are velocity vector component on axes \( \lambda, \theta, \zeta \) respectively, \( f \) is Coriolis parameter, \( f = -2 \omega_E \cos \theta \sim \frac{u \cos \theta}{R \sin \theta} \), where \( \omega_E \) is angle speed of Earth rotation, \( \rho_o \) is a constant, an average water density, \( \rho \) is the density anomaly with respect to \( \rho_o \), \( P \) is a pressure anomaly, \( q \) is a gravitational acceleration, \( T, S \) are the temperature and salinity of water, \( v, v_f \) are coefficients of vertical turbulent diffusion of momentum and heat/salt.
respectively, $\mu_t, \mu_T$ are coefficients of horizontal turbulent diffusion of momentum and heat/salt respectively, $R$ is average radius of Earth, and $t$ is time.

The system of equations is accompanied by system of boundary conditions. Let us specify on the upper undisturbed boundary $\partial_\Omega$ at $z=0$ the linearized kinematic condition

$$w = -\frac{\zeta}{\partial t},$$

(2.7)

where $\zeta(\lambda, \theta, t) = \frac{1}{\rho \theta} P|_{z=0}$ is a level elevation.

End momentum fluxes

$$\rho_0 v \frac{\partial u}{\partial z} = -\tau_\lambda, \rho_0 v \frac{\partial v}{\partial z} = -\tau_0;$$

(2.8)

where $\tau_\lambda, \tau_0$ are wind stress components on axes $\lambda$ and 0 respectively.

For temperature and salinity at upper boundary either fluxes

$$v_\tau \frac{\partial (T, S)}{\partial z} = (Q_T, Q_S)$$

(2.9)

or temperature/salinity itself

$$T = T_0(\lambda, \theta, t), S = S_0(\lambda, \theta, t)$$

(2.10)

are specified.

At the bottom $z = H(\lambda, \theta)$ assume motionless condition

$$u = v = w = 0$$

(2.11)

and heat/salt isolation

$$\frac{\partial T}{\partial N_T} = \frac{\partial S}{\partial N_T} = 0,$$

(2.12)

where

$$\frac{\partial^*}{\partial N_T} = v_\tau \frac{\partial^*}{\partial z} \cos(n, z) + \frac{\mu_T \cos(n, z)}{R^2 \sin^2 0} \frac{\partial^*}{\partial \lambda} + \frac{\mu_T \cos(n, \theta)}{R^2} \frac{\partial^*}{\partial \theta},$$

$n$ is the outward normal, $\cos(n, \lambda), \cos(n, \theta), \cos(n, z)$ are cosines of angles between vector $n$ and axes $0, \lambda, 0$ respectively.

On the side boundary $\sigma$ we may pose

$$u = v = 0,$$

$$\frac{\partial T}{\partial N_T} = \frac{\partial S}{\partial N_T} = 0,$$

(2.13)

(2.14)

if the side boundary is "dry", i.e. represents solid land. and

$$u = u^*(\lambda, \theta, z, t), v = v^*(\lambda, \theta, z, t),$$

$$T = T^*(\lambda, \theta, z, t), S = S^*(\lambda, \theta, z, t).$$

(2.15)

(2.16)

if the side boundary is "liquid" (or we may call it "open").

System (1) - (16) are accompanied by initial conditions

$$(u, v, T, S)|_{t=0} = (u^0, v^0, T^0, S^0).$$

(2.17)

The state equation is defined by an empirical correlation.

When the sea surface is only partially covered by ice, the fluxes of heat and salt, and the water stress are linear combinations (weighted by compactness) of the
corresponding terms from air and the ice.

One of the most delicate problems in the case of extended "open" boundaries is the problem of the boundary conditions. Generally speaking, we should take them from observations or from some other model.

In the model presented here, we assume that quasistationary velocities \( u_0, v_0 \) are specified by quasigeostrophical formulas \cite{Sarkisyan, 1977}.

\[
\begin{align*}
  u_s &= -\frac{g}{f} \left( \frac{1}{R} \frac{\partial Z}{\partial \vartheta} + \frac{1}{\rho_s R_s} \frac{\partial p}{\partial \vartheta} \right) + \frac{\kappa}{2 \rho_s c_{pv}} \left( (r_s - r_a) \cos(\alpha \varphi) - (r_a + r_s) \sin(\alpha \varphi) \right), \\
  v_s &= -\frac{g}{f} \left( \frac{1}{R \sin \vartheta} \frac{\partial Z}{\partial \lambda} + \frac{1}{\rho_s R_s \sin \vartheta} \frac{\partial p}{\partial \lambda} \right) + \frac{\kappa}{2 \rho_s c_{pv}} \left( (r_s + r_a) \cos(\alpha \varphi) + (r_a - r_s) \sin(\alpha \varphi) \right), \\
  \alpha &= \frac{\sqrt{1 + \kappa}}{2 v_s} \zeta_s = -\frac{1}{\rho_s} \int \rho d \xi + \frac{1}{\rho_s} \int \cos \theta.
\end{align*}
\]

To prevent mass leakage, these quasigeostrophic velocities were balanced over the whole liquid boundary. Some parts of the boundary are treated as river discharge boundaries. At these boundaries, mean velocities derived from the known values of river discharge are specified. The river water assumed to leave the model area through the southern boundary and velocities at the last one are correspondingly corrected.

For tide oscillations, we specify velocities \( u_t, v_t \) derived from the radiation condition for gravity waves at the open boundary.

\[
  u_t = \frac{g}{\sqrt{H}},
\]

which assumes that tidal velocity \( u_t \) is directed approximately tangential to sea level isophases (i.e., geostrophic approximation is valid) and from the results of numerical modeling of the Arctic ocean tide circulation.

3. **One-dimensional** upper ocean and sea-ice growth model.

For the sea-ice growth, the equation based on the Stephan problem (1889) is used

\[
\frac{\partial H}{\partial t} = q_a - q_{H},
\]

where \( H \) is ice thickness, \( q_a \) and \( q_{H} \) are heat fluxes at the ice surface and at the ice bottom, respectively. \( p = 0.9 g \times cm^{-3}, \rho = 1.025 g \times cm^{-3} \) is density of ice and \( \text{water}, c_{pm} = 80 \text{ (cal g)} \) is latent heat of fusion. \( c_p = 0.97 \text{ (cal g K)} \) is specific heat of sea water. Heat fluxes at the ice boundaries are presented as

\[
\begin{align*}
  q_a &= A(T_s - T_a) / H \quad (3.2) \\
  q_{H} &= C_c \rho U' \times (T_s - T_{H}), \quad (3.3)
\end{align*}
\]
where $T_m$ is frozen point of sea water that depends, in common case, on water salinity, $T_e$ is air temperature at the ice surface, $T_{bb}$ is water temperature near the ice bottom, $U'_m = \frac{r_m}{\rho}^{0.5}$ is friction velocity in the boundary layer under ice, $\tau_{bb}$ is shear stress under ice that depends on currents velocity or on velocity of ice moving. $A = 5 \times 10^{-4} \text{cal}/(\text{K cm s})$ is thermal conductivity of ice [Oberhuber, 1990], $C_1 = 3.8 \times 10^{-5}$ is empirical coefficient.

Temperature time evolution in the mixed layer is described with traditional thermodynamic energy equation integrated vertically through the mixed layer

$$\frac{\partial T_{mm}}{\partial t} = \frac{q_m - q_h}{Ah} \quad (3.4)$$

where $Ah = h - H$; $h$ is mixed layer thickness, $q_h$ is turbulent heat flux at the bottom of mixed layer.

Note, that in case of ice absence, i.e. free sea surface, $Ah = h$, $T_m = T_e$, $T_e$ is sea surface temperature, $q_m = q_h$ is heat flux at the sea surface, which is determined with the use of traditional bulk-formulae.

For the $q_h$ parameterization, the diffusion approach developed in [Nechvolodov, 1988] is used.

$$q_h = -k_h \frac{\partial T}{\partial z} |_h$$ \quad (3.5),

where $\frac{\partial T}{\partial z} |_h$ is vertical temperature gradient in the seasonal thermocline. $k_h = k_w + k_c$, $k_h$ is coefficient of turbulent heat exchange at the bottom of mixed layer, indexes $w$ and $c$ note the turbulent processes due to wind mixing and convective mixing, respectively.

Turbulent coefficients for dynamic and convective mixing are determined [Nechvolodov, 1988] with the use of similarity theory conclusions for the scale and energy of turbulence (Monin, Yaglom, 1965),

$$k_w = C_2(U'_w)^{0.5} \frac{\partial T}{\partial z} |_h \quad (3.7)$$

$$k_c = C_1 \Delta h (\alpha_f \Delta h |q_h|)^{0.5} \quad (3.8)$$

where $U'_w = \frac{r_w}{\rho}^{0.5}$ is friction velocity at the jump layer, $\tau_w = f(\alpha_f \sqrt{w})$ is shear stress at the bottom of mixed layer, $w$ is wind velocity; $\alpha_f$ is buoyancy parameter, $C_2 = 0.8 \times 10^{-1}$, $C_1 = 10^{-2}$ are proportionality coefficients.

Finally, for the entrainment velocity the following equation is used

$$\frac{\partial (\Delta h)}{\partial t} = q_{en} + (\Delta h \frac{\partial T}{\partial z} |_h) + w_h$$ \quad (3.9)

where $w_h$ is vertical velocity at the bottom of mixed layer due to Ekman pumping and divergence of main currents.

Thus, we have closed system of equations for the variables $q_m, q_h, H, T_m, k_w, k_h, \Delta h, f(\sqrt{w})$.

Initial and boundaries conditions to the model (4.3.1)-(4.3.9) are prescribed:
$T_0$, $q$, $W$ — from observations, $H^*$ — from observations or from global ice-stress model,
$T_0^*, (T_0^*)_0, \Delta H^*(\tau^*), \frac{\partial T}{\partial z}, \frac{\partial H}{\partial z}, \frac{\partial S}{\partial z}$ — from observations or mean climate values at first step of calculating, and, then, for each separate step from the circulation model,
$\tau_0^*, \tau_0^*, W_0, \frac{\partial T}{\partial z}, \frac{\partial S}{\partial z}$ — from the circulation model.

In case when meteorological data are scarce the following parametrization of $q$, is used

$$q_0 = c_0 \rho_0 \frac{F(T_0 - T_0^*)}{G}$$  \hspace{1cm} (3.10)

where coefficients $F$ and $G$ in (3.10) remain to be specified. For our case these are $G = 2 \times 10^7 \text{ cal} \text{ cm}^{-1}\text{s}^{-1}, F = 5 \times 10^4 \text{ cm}^{-1}\text{s}^{-1}$.

**NUMERICAL REALIZATION**

An Eulerian-Lagrangian technique with low numerical viscosity is used to realize the ice dynamics model. Ice edge movement and lead dynamics may therefore be described accurately as well as another geometrical characteristics of ice cover. A semi-implicit scheme is used on Eulerian grid and one Lagrangian step corresponds to some numerical Eulerians step. Special Lagrangian procedures allow to realize boundary conditions at free and contact boundaries. The ocean circulation model numerical realization is based on a finite-element spatial discretization and semi-implicit Eulerian schemes with explicit description of the pressure gradients.

The spatial resolution of the numerical model was $0.1^\circ$ in latitude and $1^\circ/3$ in longitude. This resolution corresponds to 11.1 km in latitude and from approximately 13.3 km at $69^\circ$N to $5.8$ km at $81^\circ$N in longitude. Vertical resolution is provided by 10 levels: 0, 10, 20, 30, 50, 70, 100, 200, 300 and 500 m. The ocean and ice models are coupled explicitly, with each time step of the ocean model using a known state of the ice. Similarly, the ice model assumes a known constant state of the ocean during each of its time step. The ice model may take many time steps during the one ocean model step, so the state of the ocean is interpolated linearly during the ice model time step.

The calculation procedure for upper ocean model is the following. The vertical temperature and salinity profiles are calculated from the circulation model to the upper ocean model at each time step. At the same time step these profiles are substituted into the upper ocean model to account for local heating, cooling, and mixing processes in the upper ocean. Then, new transformed profiles are substituted into the circulation model to initialise the next step of the calculation. This process is then repeated.
RESULT OF MODELLING

Two personal computers IBM PC 486 DX2-66, combined in local net, were used for calculations. Initial compactness of ice in five ice thickness categories was determined from satellite information prepared in AARI (Russia). Category 1 includes the ice with thickness 10-30 cm, category 2 - 30-70 cm, category 3 - 70-120 cm, category 4 - 120-220, category 5 - more than 220. Wind velocity field was reconstructed from daily atmospheric pressure maps.

Result of modelling was represented as compactness maps in different thickness categories, ice velocity fields, ice stresses field, ocean current velocities at 0 and 30 m horizons, sea level maps, water temperatures at 0 and 30 m horizons.

Fig.1-6 show the examples of calculations in the small part of modelling area for period of April 1992. Atmospheric pressure field for 26th April, 1992 is shown at Fig 1. Broken lines are isobars. Arrows represent the surface wind direction. All other pictures correspond to the same time moment. It easy to see that zone of high stresses is formed near the eastern coast of Novaja Zemlja island under the wind forcing. Ocean current field in area under considerations is mainly controlled by sea level elevation. As a whole coupled model behaviour is rather good.

![Fig.1 Atmospheric pressure field and wind at 10 m](image1)

![Fig.2 Sea level field](image2)
Fig. 3 Principal axes of internal stresses in ice cover

Fig. 4. Ice velocity field

Fig. 5 Current velocity pattern at z=0 m

Fig. 6 Current velocity pattern at z=30 m
SUMMARY

The circulation model reconstructs the basic current pattern of the Kara Sea, despite the data scarcity. The simulated tidal elevations are in good agreement with observations. The generalised upper-layer-ice-growth model allows realistic reconstruction of upper ocean thermal dynamics and ice thickness variations. The sea ice model represents the main features of sea ice dynamics and may be used for ice behavior forecasting.

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THE MONITORING SYSTEM OF THE BARENTS SEA (SEAWATCH) AND THE POSSIBILITIES OF ITS DEVELOPMENT IN APPLICATION TO THE TASKS OF THE INFORMATION SUPPLY IN THE ARCTIC

The study of the Arctic environment always have been of high priority in connection with the tasks of navigation, industrial development, protection of biological resources. These works were carried out in the Russian sector of the Western Arctic for a long time. Some of the Russian institutions working in this region have been collecting data for more than sixty years. Nevertheless, the character and strategy of Arctic activity underwent significant changes during last years. New scientific and practical requirements to the information supply stipulate the necessity of world standard oceanographic technology.

The Barents Sea is more exposed to the environmental impacts than any other part of the Arctic ocean. It is the traditional area of fisheries and sea transport. Recent discoveries of oil and gas deposits on the Barents sea shelf started the new industrial activity which may become comparable with the same in the North and Norwegian seas. The radioactive pollution of this region caused by the military and industrial nuclear wastes is also an essential environmental problem.

The marine surveillance system for the southern part of the Barents sea was proposed by OCEANOR and designed as joint Norwegian-Russian project SEAWATCH - Barents Sea. Its main features
are the following (fig.1):

- a sensor carrier which is an oceanographic buoy moored with suitable mooring and equipped with sensors for measuring marine environmental parameters, data logging equipment and with on-board micro processors for data analysis control:

- a real time data transmission system and a land-based data control and analysis system including the necessary software (numerical simulation models, GIS and other means of data presentation);

- a user oriented menu driven information system tailored to the needs of identified user groups.

The set of parameters measured includes meteorological elements (wind speed and direction, air temperature and air pressure), wave height, current speed and direction, oxygen, phosphate (or nitrate), radioactivity; algae concentration (all these characteristics at 3m depth) and temperature/salinity profiles down to 50 m. Sensors for heavy metals, hydrocarbons and pH are developed also. The number of buoys required for the southern part of the Barents sea is estimated from 6 (minimum) to 12 (optimum). The ARGOS or other satellite system is used for the data transmission in real time. The data storage, analysis and presentation are performed by ORKAN software package developed by OCEANOR.

The implementation of the SEAWATCH project was supported by marine institutions and authorities of the Murmansk district: Arctic Marine Geological Expedition, Murmansk Marine Biological Institute. Polar Research Institute of Marine Fisheries and Oceanography, Hydrometeorological Service. Arctic and Antarctic Re-
search Institute (Murmansk Branch) and Committee of Ecology. These participants and OCEANOR made the agreement in 1992 to organise Arcticmor Seawatch Group which will coordinate the creation of the monitoring and the forecasting system.

During the following two years the SEAWATCH project was realised only partially. One buoy is exploited continuously in the observation point situated in the Stockman gas-condensate deposit area (73 N, 43 50 E). Two buoys which provided time-series of several months were situated respectively northward from Kainin and Varanger peninsulas. The data obtained as the result of these measurements may be valuable for environmental assessments and tracing of present and future anthropogenous impacts.

At present the information system of the monitoring is not adequate to the aims of the project in the Barents-region. There are two main obstacles hindering the development of the SEAWATCH communication network: a lack of information about the possibilities of the system and the weakness of the communication infrastructure of potential users.

The further promotion of the SEAWATCH project will depend on the creation of diversified information service. The main ways of data presentation and transformation are briefly discussed below.

1. Direct data transmission to the users is the most obvious application and very important, for the hydrometeorological service, The buoy data may cover remote sea areas rarely visited by ships. The presence of stationary observation points is useful not only as additional source of meteorological and sea surface data but also as the means for independent checking of sea fore-
casts. Updated information on the chemical and radioactive pollution, nutrients and phytoplankton content forms the valuable contribution to the ecological monitoring system of the Barents-region. The buoy observations may ensure the detection and tracing of pollutants immediately after their appearance in the corresponding area.

2. The probability estimations of the extremes fixed during the observations may be obtained using the available data on the climatological distributions of the hydrometeorological and chemical characteristics. At present the sea climatology is based almost totally on the shipborne observations which are very inhomogeneous in time and space. Many important characteristics, e.g. wind and wave statistics, are calculated by indirect methods and need the verification. The estimations of wave height of rare occurrence are especially sensitive to the choice of distribution law and to the precision of determining average values. Continuous time-series of wind and wave measurements are an indispensable source of the data required for the planning installation and exploitation of stationary drilling platforms (seasonal variations of the probability of the storms, duration of stormy or calm periods). The analysis of long time series, especially in comparison with the similar data of coastal hydrometeorological stations, aids to detect the natural and anthropogenic trends of the sea environment in proper time.

3. The forecasting of the sea state using the statistical methods and numerical models is the most prospective part of marine hydrometeorological and environmental service. The technology developed by OCEANOR includes modelling of currents and storm
surges (HYBOS), calculating drift, spread and seabed deposit of platform discharges (NOMAD), oil drift statistics and forecasting (DRIFTMAP, DOOSIM). This software package may be effectively supplemented by calculation and forecasting methods worked out in the marine institutions of Murmansk. Two of them were successfully tested and exploited in the Murmansk Hydrometeorological service: the numerical model of ice drift and ice-edge displacements based on the method known as "particles in the cells" and method of wave parameters calculation and prediction based on the solution of energy balance equation for the components of two-dimensional spectrum. Previous versions of these methods were realised on the Soviet computers incompatible with IBM PC but now this restriction is overcome.

There are some practical tasks which require not only the forecasting but also the retrospective analysis of the atmosphere and sea dynamics, e.g., detecting of the sources of radionuclide or chemical pollution. The buoy data permit to make necessary calculations using time series for the corresponding period or to verify the trajectories of water masses calculated with the use of synoptic charts.

Though the SEAWATCH system is self-sufficient regarding its main tasks, the needs of potential users will be satisfied better if the information system will be enriched by some additional kinds of information. The diversity of diagnostic and forecasted meteorological fields distributed by international centres is essential for improving the methods of calculation and modelling. Remote sensing data showing the situation of ice-edge are important as the source of boundary conditions data for the
numerical models of waves and currents. The monitoring system will be more effective if supplemented by the observations of coastal hydrometeorological stations.

SEAWATCH project must be also considered in the wider context of such international programs as Arctic Monitoring and Assessment Program (AMAP), Global Ocean Observing System (GOOS), Global Resources Information Database (GRID) et al. Almost all of them depend on the observation data received from somewhere else and are focused on the coordination of the activity performed on the national level. On the contrary, SEAWATCH project is based on its own sources of information and so deserves more significant support from the central and local authorities. Taking into account the current economical situation in Russia, the most difficult stage of the project is to create and to trigger the information network because for the present even the most interested users of environmental data are not ready to integrate themselves into the monitoring system.
The OCEANOR marine environmental, monitoring, forecasting and information systems

SENSORS FOR:
- Meteorology
- Waves
- Current
- Temperature
- Salinity
- Oxygen
- Algae
- Nutrients
- Biosensors
- Radioactivity
  (Being developed: heavy metals, hydrocarbons, pH)

Fig. 1 SEAWATCH System
AN EXPERIENCE OF ECOLOGICAL IMPACT ASSESSMENT (EIA) OF LARGE-SCALE OFFSHORE OIL AND GAS PRODUCTION BASED ON THE STOCKMAN PROJECT
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Exploration of large deposits of hydrocarbon raw material in the Arctic region is a part of the state's strategy of economics development in Russia. There is a serious basis to suppose that at the beginning of the XXI century the centre of oil-gas exploitation will be shifted to these regions. Besides it is clearly seen that productive exploration of the shelf areas give specialists quite different as for their seriousness problems than earlier. It is especially important for the ecology as a well-known vulnerability of nature in the Arctic is known all over the world. Much has been said and written about Stockman gas-condensate deposit during last two years. And this is explainable as this deposit is unique as for its reserves. Perspectives of its explorations and exploitations are connected with the whole Murmansk region development.

It is natural that the questions of ecological security should be part and parcel of the Stockman project.

Stockman gas-condensate deposit is situated in the central part 290 km to the west of the Novaya Zemlya archipelago and 650 km away from Murmansk, depth in the area of drilling wells is 280 -320 m. The deposit is unique as for its reserves - 3 trl cubic meters of gas and 22,5 mln t of gas-condensate.

To make it real it is necessary to develop a unique complex of equipment of very high complexity, as far as only 2 stationary deep-water platforms on the depths exceeding 300 meters are built but no one in the ice conditions now.

Gas transportation is supposed to carry out by under-water pipe-line. Stockman field Murman coast is chosen as thm main, its length is 535 km. Further on the land the pipe-line will be laid along the route Murmansk Belomorsk-Petrozavodsk- Volkov with an outlet to Vyborg (1838 km), (fig.1).

The area of exploitation and underwater transportation is characterized by severe natural climatic conditions: winds up
to 35 m/sec, negative air temperature from November to January (-2-4 to -20°C), waves heights up to 19 m and 24.4 m, high probability of floating ice in the deposit area (to 166 days of extremely cold years, for instance in 1979), find what is more dangerous—icebergs with several hundred meters parameters by all dimensions, and a large counted volume—500000 cubic meters.

Area of Stockman gas-condensate deposit and routes of the pipeline are characterized by extremely uneven bottom relief depths overfalls, the largest one is Central Cavity.

Thus, constructive and exploitation safety of the establishments and constructions is the determining factor of ecological security of the Stockman project.

Estimation procedure demands the answer to all the questions concerning environment impact. But it is necessary not only to study it well and to estimate its present state and to forecast what changes will take place in nature during implementation of the project.

Quite natural every specialist and even a very curious person should have his own opinion on the realization of the project, besides the very thought of the projects like this causes sometimes instinctive feelings of danger. Stockman project by all its range and dimensions helps to formulate a special public opinion, and to be more precise a very worried attitude to its ecological safety.

Thus, ecologists working at this problem had to prepare answers to all questions, which trouble people living in the Barents region.

A very important stage of EIA is the estimation of background (modern) state of environment including anthropogenic loads. The latter is necessary as a starting point in the estimation of ecological reserves of marine objects and its potential capability to further loads without ecosystem stability losses. Results of background environment descriptions in this presentation are not discussed in detail. We should mention only two important conclusions, necessary for further discussions: modern level of chemical contamination in the open part of the Barents sea, including the area of Stockman gas condensate deposit, is low, that is in the frames of background standards.
Concerning oil hydrocarbons it does not exceed 0.04 mg/l. Concerning other pollutants the situation is analogous, as the influence of economic activity in the open sea is not great. In the area of Stockman gas condensate deposit massive reserves of bioresources are absent, important ways of migration do not cross this area. Thus, peculiarities of geographical situation and modern ecological status of the region of potential influence turned out to be favourable from the point of view of possible ecological loss from the Stockman gas condensate deposit, first of all from the exploitation complex.

It is quite natural that arrangement and exploitation of the Stockman gas condensate deposit should have some negative influence on the Barents sea environment. The question is like this: will these influences be critical for marine ecosystems and fishery as a whole separately or together with existing. Our conclusion is quite simple: consequences forecast are in general supposed to be local. There are several points for it. First - remoteness, vast depths, non-coincidence of more important bioproductive zones and the area of fishing, low level of the open areas contamination - all these factors weaken possible negative consequences. Second - that is more important: type the raw material being exploited: at the Stockman gas condensate deposit not oil but gas with small content of condensate will be exploited; it will be methane without sulphur. This product is ecologically much safer than oil. Foreign experience that is Norway, USA testifies to the fact that accidental gas discharges do not produce serious negative influence on the environment and marine biota.

Even at the gas exploitation in the project technological operations lowering ecological risks are supposed. Refusal from the pipe-lines transportation to the coast is taken into consideration. In other words dry gas will be transported by pipe-lines from the platforms to the coast. In this case leakage, bursts and other accidental situations will take place without topical hydrocarbons spills, that is locally and they will be short-term. This case if it will take place will not practically create the picture of a typical and a well-known situation of oil contamination, when birds, animals and fishes die, the
coast suffer from it—with all possible consequences.

Gas condensate will be separated from the exploited mixture at the platform and load into tankers and transported to the places of destination. Accidents are possible when condensate will enter the sea. Our specialists have carried out voluminous computer accounts of these spills behaviour depending on all situations possible. Duration of spill drifting, its evolution, length, changeability of stormy winds, currents, strength and many other factors are estimated.

As a result of probability calculations it turned out that gas condensate spilled in the area of a platform (maximal accumulated volume is 40000t) by no way can reach the Coast of Novaya Zemlya and Murman coast. It is a conclusion as this factor plays the main role. It may be said that if the area of exploitation were in the other place, the results would have been worse for all of us.

It should be remembered that in Russia there exists a very strict law concerning nature protection which prohibits to discard drilling wastes, worked out drilling solutions, plastics, slams to the sea. More strict standards are being introduced abroad. in Russia they are already valid. For instance during investigation of the Sakhaline shelf deposits exploration of which is planned by the International consortium special attention has been paid to this factor.

Serious work is carried out to provide safety of construction establishments, development of the automatical system of control and blocking of ecologically dangerous situations. High potential of the Russian converting enterprises taking part in the feasibility study and foreign experience are directed to it. Foreign experience from the point of view of ecology is useful. We studied attentively series of generalizing materials—for instance, presentation of the independent group of foreign experts GESAMP (according to the order of UNESCO and others). These experts analyzed ecological consequences of marine oil-ins activity in different parts of the World Ocean that is in (Mexican gulf, North sea, Alaska shelf) and came to the following conclusions: This activity is noticeable but it yields to fishery, damping of the wastes contaminations, drainages from
the continent and atmosphere transfer.

As a result marine biota changes; mainly bottom populations are observed near platforms at the distance of 3-5 km, higher concentrations of hydrocarbons are as far as 8-12 km. Total area of the sea bottom under the influence is very small in comparison to the area of trawling at the bottom fish catching. The North sea may be considered an example of "coexisting of 2 main activities-fishery and oil-gas exploitation.

The second closer example is Norway. This state may be considered as one of the most advanced countries in the sphere. But besides, Norway is very serious to the questions of nature protection. Planned to the exploitation shelves deposits there are investigated as for their influence on the environment. Regions to the south-west of the Barents sea were examined in 1985-1989, and after additional introduction of several limitations this area was allowed to be exploited.

Thus, the problem is not can or cannot this shelf be exploited as it is rich in fish resources and trapping, the question is how to do it.

The problem of harmony between fishery and oil-gas exploitation is the most important in our region. To estimate strictly possible damages to fishery due to Stockman gas deposit exploitation is not easy. In the expertise much attention is paid to this problem.

Estimations of losses due to the loss to the fishery of some areas through which pipeline will be laid are much clearer. Less evident are hypothetical losses owing to the accidents but there are variants. For instance, gas-condensate spills and methanole spills are not the same as methanole is more toxic. Much depends on the location of the possible accident, thus, we calculated safety distances of tankers routes. That is how far from the coast tankers could sail without a risk of reaching the liquid product while spilled of coastal zones.

But taking all available factors into considerations possible losses to the Barents sea fishery were estimated. It is supposed to be 1 percent of yearly catch. As natural fluctuations and fishery intensity probably by an order as high, it is completely agreed with the general conclusion on low influence.
of gas exploitation on the ecology of the Barents sea.

This conclusion will be justified under strict following terms: avoidance of discharges into water toxical products, keeping to ecologically strict optimal time-table of carrying out construction work. This optimisation in the EIA of the Stockman gas-condensate deposit was carried out considering seasonal cycles of animals and plants development as well as geographical peculiarities of pipe-line routes; providing construction safety with effective control systems security of all operations in the production cycle. The main aspect here is to prevent consequences of two main accidents: gas fountain and underwater pipe-line destruction; creation of protected zones to protect and save rare and disappearing marine mammals, bird species especially at the places of breeding and living.

One principal part of the work is the most important—that is biological monitoring. As there exists many unknown problems and the consequences of some of them especially long-term processes are difficult to forecast in the process of estimation of Stockman project, outstripping development of the monitoring system is regarded as an obligatory term of the project realization—from the building to liquidation of the deposit after 20-25 years of exploitation.

In the monitoring itself the main role must be played by hydrobiologists; only control of mussels, echinoderms and other bottom species populations state may give information on the antropogenic influence. This is carried out all over the world the same must be done at the basin. Other types of observations are also important, in our case they are of secondary importance.

A reasonable question arises: do we know much enough on the hydrocarbonical contamination of marine biota and its consequences for marine environment in connection with shelf exploration. In general the answer must be negative and very cautious. Specialists point out several problems without a simple answer in the ecological grounds; these are not always correct account of the spill dimensions of oil spill in the models. There are data of natural observations giving bigger estimates—to tens times; duration of oil hydrocarbons existence in na-
tural conditions. It is lowered very often: instead of several days oil products stay in water without evaporation completely during weeks and months. The reason is slowing down of the processes of dissolution in water columns, especially at low temperature, toxicity of oil products and sublethal effects. Many scientists criticize laboratory tests available for the survival used in exotoxicology. It is considered that wrong animal species are frequently used, besides population structure in reality and its systematic reaction to the contamination are not considered; effects of chronic contamination. In modern works more attention is paid to estimation of consequences from accidental spills, than to long-term exotoxicological effects. On the one hand locality of these effects is confirmed by long control in the places and on the other- what can happen with the affected ecosystem owing to the chronic intoxication, when point of return is overcome and the last cumulative effects of oil-gas exploitation on the the ecosystem level- we mean species substitution, population decrease.

All these problems are actively discussed in literature. Their listing must not refuse all that said about potentially weak negative influence of gas condensate deposit on the marine ecosystem in the Barents sea in the Stockman deposit project but should be a warning as in the Barents sea and the Kara sea tans or Oil-gas deposits are discovered. Sooner or later they will be exploited, total influence on the environment will be increased. We should be ready for this to preserve the Barents sea with all biological life diversity.

Scientists on the international basis must continue steadily work not to face quite unexpectedly with problems of mutual trouble.
MODELLING OF INTERACTION BETWEEN ICEBREAKING CRAFTS AND ICE IN COMPOSITE MODEL ICE

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ABSTRACT

Previous works /1, 2/ submit the energetic approach developed by the author to modelling main components of ice resistance at modelling of interaction between icebreaking crafts and ice. This approach is based on comparison of breaking diagrams of model ice and natural ice by vertical concentrated force under kinematic loading Fig.1. The new criteria of similarity and requirements to model ice are submitted at modelling interaction between ice and displacing icebreaking means and icebreaking crafts on air cushion. Present work submits the analysis of completion of these requirements in composite model ice, which consists of high pressure polythene and freshwater ice Fig.2.

INTRODUCTION

Elastic mid strength characteristics of composite model ice depend only upon thickness of frozen layer of polythene $h = h_1$ and $h_2$. It seems expedient to present requirement on parameter $Eh_1^4$ to composite model ice as

$$Eh_1^{-4}/E_{h_2}^{-4} = \lambda^4,$$  \hspace{1cm} (1)

where $E$, $h$ are the elastic modulus and thickness of ice; $\lambda$ is geometrical scale of modelling. Here and further the index "H" relates to full scale factor, index "M" relates to model. The density of high pressure polythene and density of freshwater ice in structure of composite model ice are practically equal. Ratio of mass of freshwater ice $m_{h_1}$ and mass of frozen layer of polythene bowls $m_{h_2}$, i.e. constanty $m_{h_1}/m_{h_2} = k$. It seems expedient to present requirement on parameter $h$ to composite model ice as
\[
\frac{h_n}{(m_p/\rho_{1G})^{1/3} L} = \lambda,
\]

where \(m_p, \rho_{1G}\) are the mass of polyethylene beads and density of freshwater ice in structure of composite model ice; \(S\) is the area of surface of composite model ice in ice basin.

The total ice resistance to movement of displacing icebreaking means \(R\) presents sum of resistances connected with characteristic determining phenomena of interaction between these crafts and ice

\[
R = R_1 + R_2 + R_4,
\]

where \(R_1\) is icebreaking resistance; \(R_2\) is broken ice resistance; \(R_4\) is water resistance.

At modelling of interaction between ice and displacing icebreaking means in composite model ice requirements to model-ice in /1, 2/ with account (1) and (2) take form

\[
\frac{F_{BN}}{w_{BN}} = \lambda^3; \quad \frac{F_{BM}}{w_{BM}} = \lambda^4; \quad \frac{F_{HN}}{F_{M0}^3} = \lambda; \quad \frac{h_n}{(m_p/\rho_{1G})^{1/3} L} = \lambda;
\]

\[
\rho_1 = \rho_1 M; \quad f_{1N} = f_{1M}; \quad f_{2N} = f_{2M}
\]

where \(F_B\) is the breaking load at loading Ice plate of concentrated vertical force; \(w_B\) is the ice deflection under the breaking load \(F_B\); \(\rho_1\) is the ice density; \(f_1\) is the friction factor at cruch of ice; \(f_1\) is the snow friction factor.

The completion of 4th condition in (4) is provided by regulation of mass of polyethylene beads on water surface in basin

\[
m_p/S = \rho_{1G}(h_n/L) + kD.
\]

The completion of 5th condition in (4) is provided by equ
alilv of natural ice density with density of high pressure polyethylene and density of frozen layer of polyethylene bends.

The completion of 6th condition in (4) is provided by application of special materials with an appropriate friction factor (for example, teflon-plast). These materials cover the zones of model cases, participating in crush of ice.

The completion of 7th condition in (4) is provided by practical equality of friction factors of composite model ice and natural ice, covered by snow.

We consider the first three conditions in (4), which determine the modelling of icebreaking.

The natural ice parameters $P_{BH}$, $m_{BH}$, $h_{BH}$ are presented in accordance to experimental data given in /4/ and /5/.

$$P_{BH} = K_1 h_{BH}^{1/2},\quad m_{BH} = K_2 h_{BH}^{1/2},\quad h_{BH} = K_3 h_{BH}^{1/3}.$$  \hspace{1cm} (6)

The appropriate parameters of composite model ice are /3/.

$$P_{CM} = K_1 h_{CM}^{1/2},\quad m_{CM} = K_2 h_{CM}^{1/2},\quad h_{CM} = K_3 h_{CM}^{1/3}.$$  \hspace{1cm} (7)

From dependences (4), (6) and (7) we receive the dependences for geometrical scales of modelling at modelling $P_{BH}$, $m_{BH}$, $h_{BH}^3$, accordingly:

$$\lambda = C_0 (h_{BH}/\lambda)^{2/3},$$  \hspace{1cm} (8)

$$\lambda = C_1 (h_{BH}/\lambda)^{1/2},$$  \hspace{1cm} (9)

$$\lambda = C_2 (h_{BH}/\lambda) h_{BH}^{-1/3},$$  \hspace{1cm} (10)

where $C_0 = (K_1/K_1)^{1/3},\quad C_1 = K_2/K_1,\quad C_2 = (K_3/K_3)^{1/4}$.

These dependences are submitted on fig. 3.

The analysis of results shows, that the simultaneous completion of conditions (3), (9) and (10) is not reached.

We use the known way of experimental allocation of the icebreaking resistance from total resistance.
For observance geometrical and kinematic similarity geometrical scale of modelling is determined from joint completion of conditions (9) and (10). We receive

$$\lambda = C_r \cdot h_n^{1/3},$$

(11)

where $C_r = C_M^{n+1} / C_n$.

Such scale of modelling is reached at thickness of frozen layer of polythene beats:

$$\delta = (C_M/C_W)^2 \cdot h_n^{1/3}.$$  

(12)

From first ratio in (4) we receive the module of recalculation of icebreaking resistance

$$\lambda_R = k_1 / k_1 \cdot (C_M/C_W)^4 \cdot h_n^{4/3}$$

(13)

or after expressing it through geometrical scale of modelling (11)

$$\lambda_R = C_{R_4},$$

(14)

where $C_R = k_1 / k_1 \cdot C_M^{4}$.

Thus, experimental allocation of icebreaking resistance geometrical scale of modelling is determined from (11). The results of model tests are recalculated on full-scale on dependences:

- for the heaviest ice and close to it (small velocities)

$$R_n = C_R \lambda^4 R_{1M} + \lambda^3 (R_{2M} + R_{3M}),$$

(15)

for small ice thicknesses (great velocities)

$$R_n = C_R \lambda^4 R_{1M} + \lambda^3 R_{2M} + R_{3M},$$

(16)

The completion of condition (11) sometimes results in necessity of manufacturing of model series; each geometrical scale of model corresponds to researches to be made for definite thickness of natural ice. With the purpose of maintenance of
model tests for different natural ice thickness on model of the same geometrical scale factor the analysis of importance of conditions (9) and (10) is conducted.

This analysis has shown, that the condition (9) renders the heaviest influence on geometrical and kinematic the similarity of icebreaking phenomena. It is because of that the infringement of condition (9) results in distortion of similarity in ice application of icebreaking part of case on vertical. In model experiment the icebreaking will not happen, if the breaking deflections of model ice will be more of size of deflections required by similarity pursuant to (9). The purpose of geometrical scale of modelling on condition (9) provides model tests for various natural ice thickness on model of icebreaking means of one scale factor as well.

Then the partial infringement of similarity of crack geometry and sizes of ice fragments in plan happens. When small deviations from optimum model scale on (11) small errors in modelling of total resistance are expected to arise.

The condition (9) is provided in model tests at thickness of frozen layer of polythene sheet

\[ \delta = (l_{\text{min}}/\lambda)^2 h_\text{N}. \]  

In modelling in composite model ice of interaction between ice and displacing icebreaking means with smoothly varying lines in region of acting wave line (ice breakers with conventional form of case) requirements to model ice/1,2/ with account (2) and (3) take form

\[ \frac{h_\text{N}}{h_{\text{MN}}} = \lambda^4; \frac{f_{\text{MN}}}{f_{\text{BM}}} = \lambda^4; \frac{f_{\text{MN}}}{f_{\text{BM}}} = \lambda^4; \frac{h_\text{N}}{(mp/\text{ic}5)} = k_\delta \]

\[ \rho_\text{N} = \rho_{\text{BM}}; f_{\text{BM}} = f_{\text{BM}}; f_{\text{MN}} = f_{\text{MN}}. \]

The completion 3rd, 4th, 5th and 6th conditions in (18) are considered. We consider the first two conditions in (18).

From dependences (11) and (7), we receive for similarity on \( h^2 \) the condition (10), and for similarity on \( h \) we the following condition.

\[ \delta = (l_{\text{min}}/\lambda)^2 h_\text{N}. \]
\[ \lambda = C_E (h_m/b)^{5/8}, \]  

where \( C_E = (K_x K_y / k_1 k_2)^{1/4} \).

This dependence is given in Fig. 3.

The joint completion of conditions (10) and (10) is reached at thickness of frozen layer of polythene beads

\[ \delta = (C/c_b)^{2/3} h_m^{1/3} \]  

Thus the geometrical scale of modelling is determined by expression

\[ \lambda = C_0 (C/c_b)^{2/3} h_m^{5/9} \]  

Thus, executing the condition (20) for thickness of frozen layer of polythene beads, conducting model tests in geometrical scale pursuant to (21), all conditions of modelling of interaction between ice and traditional ice breakers are executed. The results of model tests are recalculated on full scale factor on dependences /1, 2/:

for the heaviest ice and close to it (small velocities)

\[ R_h = \lambda^2 (R_{1M} + R_{2M} + R_{3M}). \]  

for small ice thicknesses (great velocities)

\[ R_h = \lambda^3 (R_{1M} + R_{2M}) + R_{3N}. \]

The completion of condition (21) sometimes results in necessity of manufacturing of model series, as well as in previous case the completion of condition (11). With the purpose of maintenance of model tests for various natural ice thicknesses on model of one geometrical scale the analysis of importance of conditions (10) and (19) is conducted.

This analysis has shown, that the default of condition (10) results in reduction of sizes of ice fragments in plan. The size of ice fragments does not change the general mass of broken model ice, which is determined by width of model of icebreaking means. The heaviest interest presents the modelling
of movement of icebreaking means in heaviest ice and close to it. Here the heaviest influence renders the similarity of energy costs on icebreaking, i.e. first ratio in (18) or condition (19). Therefore it is possible to expect, that when investigating research of ice movement of icebreaking means in heaviest ice and close to it the errors in modelling of broken ice resistance will be insignificant. The purpose of geometrical scale of modelling on condition (19) provides and execution model of tests for various natural ice thickness on model of icebreaking means of one scale factor.

The condition (19) is provided in model experiment, at thickness of frozen layer of polythene beads

$$\delta = \left(\frac{CE}{\lambda}\right)^{3/5} l_N.$$  

At modelling of interaction between ice and icebreaking crafts on air cushion In composite model ice requirements to model ice/1, 2/ with account (1) and (2) take form

$$W_{BM} = \lambda; \quad W_{RN}/W_{RM} = \lambda; \quad E_N/l_N^3/E_M^3 = \lambda^4; \quad \frac{(m_D/p_1cS)}{1 + kD} = 1$$  

where $W$ is ice deflection appropriate to total destruction of ice plate by vertical concentrated force, when $P = 0$. The completion 4th, 5th and 6th conditions in (25) has been considered above. From experimental researcher, submitted in /7/ follows, that for large thickness of natural ice we have

$$W_{RN} = k_{55}W_{BM}.$$  

From experimental works of the author dependences for composite model ice are obtained as:

$$W_{RM} = k_{55}W_{BM}.$$  

From second requirement in (25), (26) and (27), we receive the condition of modelling of deflections of total ice destruction composite model ice.
\[ \lambda = C_{\text{WR}} \left( \frac{h_n}{\delta} \right)^{1/2}, \]  

(28)

where \( C_{\text{WR}} = \frac{k_2 k_5}{k_2 k_5}. \)

Dependence (28) is given in fig.3.

The conditions of completion of first and third requirements in (25) are received, (9) and (10).

The analysis shows, that the conditions (9), (10) and (28) are not executed simultaneously, and the most importance is condition (28). It is connected that at its default is not reached total destruction of composite model ice.

The condition (28) is provided in model experiment. at thickness of frozen layer of polythene beads

\[ \delta = \left( \frac{C_{\text{WR}}}{\lambda} \right)^2 h_n. \]  

(29)

When such modelling as well as at modelling of icebreaker? with conventional form of hull the reduction of sizes of ice fragments in model experiment in comparison with required size happens. The experimental researches on models in broken ice from small polythene plates have shown, that the sizes of broken ice do not render practical influence on resistance to movement /8/.

At default of condition (9) of total resistance components are deformed: the destruction resistance: the friction resistance of bow flexible protection (FP): the resistance, connected with nonsymmetrical deformation of bow and stern FP. Those total resistance components are directly proportional to depend on the ice deflection under bow FP, which in turn depends on the breaking deflection \( w_n \), as characteristic of utmost condition of ice cover before destruction. Therefore the size of discrepancy required to breaking deflection in model experiment is directly proportional to influences the size of the above mentioned resistances.

On basis said from conditions (9) and (28) we receive size of such a discrepancy

\[ c = (k_5 - k_5)/k_5 \]  

(30)
Thus, listed resistance components in model experiment are underestimated on \((9\times10^0)\) %.

Then the recalculation of results of model tests on full scale factor at small velocities of movement, when water resistance is small, is possible to present in the form as

\[ R'_{N} = \lambda^3 C' R'_{M}. \tag{31} \]

where \(R'\) is resistance of icebreaking crafts on air cushion; \(C' = 1 + C\).

On the basis of received results the model tests techniques in composite model ice arc developed. According to these methods the tests of various icebreaking crafts were conducted. The comparison of results with full-scale data obtained have shown their good convergence /1/.

REFERENCES


Fig. 1. Icebreaking Diagram

Fig. 2. Composite model ice

Fig. 3. $\lambda = f\left(\frac{h_w}{\delta}\right)$
EXPLORATION OF THE ICE COVER IN THE PECHORA SEA
AS RELATED TO SHELF DEVELOPMENT
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Transportation in the freezing Arctic Seas and practical activity concerning
development of natural resources on shelf require a comprehensive
exploration of the natural conditions in the operating areas. It particularly
refers to the ice that can be found there for a considerable period of time.

In the Pechora Sea ice remains for 7-10 months (in cold years - from
October till July, in warm years - from December till June). The maximum
development of ice occurs in April. The sea ice is of local origin, however
due to wind and currents influence some ice from the Kara Sea can also
move to the Pechora Sea after it comes through the Kara Gate Strait round
the Kanin peninsula. The dynamic and thermic factors form an ever-
changing fault ice structure which consists of floes of various forms and
sizes in the Pechora Sea. Interaction between the ice blocks in movement
and presence of different kinds of obstacles (e.g. shallow waters, islands,
coastal line) prompt the appearance hummocks and ridges that can be
rather big in size.

State enterprise "Arctic Marine Engineering Geological Expeditions"
(AMIGE S.E.) has been carrying out the Ice explorations since 1987 (Fig.1). Counting of ice cover influence during the construction on the shelf
requires the subject interpretation of archives data of weather stations, visual
and instrumental ice reconnaissances, ship ice expedition, data, which has
been performed in the Pechora Sea since century beginning). The specialists
of Murmanskhydromet, Murmansk brunch of AARI, (Russian Hydro -
Meteorological Comettee), Complex Subject Expedition of
"Arcticmoneftegazrasvedka" (CSE AMNGR) were enlisted in joint works.
The explorations of arrangement, fracturing and hummocking explorations in
the Pechora Sea has been carried out at the initial stage. Some results of
the exploration are shown below.

The degree of ice fracturing, that characterizes how many breaches there
are in the ice, has a noticeable impact on interaction between technical
installations and ice. The degree of ice fracturing in the Pechora Sea was
Initially assessed using the piled data of the aerial ice reconnaissances
carried out there in 70s and 80s. As an example, In figure 2 are shown the
summarized floe size distribution in one of the oil and gas accumulation
Fig. 1 SE AMIGE ice cover investigations in Pechora sea.

1117 - 1912
areas. Here one can see the ice fracturing data in general as well as the age (or thickness) characteristics of ice.

Aerial visual reconnaissances data are too approximate to assess the fracturing of the ice. In order to specify the characteristics of ice fracture, the processed aerial photography and side looking airborne radar (SLAR) data from the Pechora Sea was also used. For instance, in March and April 1987 three consecutive aerial photography surveys were carried out in the Prirazlomnaya site with an interval of 10-20 days. In the operating area, that was 150 square kilometers in size, the areas of 3500 ice blocks were measured. In figure 3 numerical and partial distributions of floe sizes are shown. In this case "partial fracturing" stands for ratio between total area of a given size range to the total area of all ice.

Analysis of floe area distributions displayed peculiarities of Ice structural reconstruction. On the whole the fracturing of the ice cover increased from March to April, which was due to intensification of cyclonic activity. In March the 50% probability of the areas of floes was 4 km$^2$, in April - 2 km$^2$. The area of the maximum floe was 78 km$^2$.

The data obtained by instrumental surveys gave the opportunity to define in detail the ice-floe size distributions and measure the maximum ice floes that were found. One of such extremal big fields with 1135 km$^2$ was fixed during the SLAR survey in 1982 to the west of Matveev island. Large scale ice cover fracturing features within the Pechora Sea were analyzed using satellite images.

As confirmed by a considerable amount of data, ice in the Pechora sea possesses a lot of ice-hummocks. As visual aerial reconnaissance and aerial photography data shows, the areas of the most hummocks concentration are located in the east • up to 80% of the ice area is, as a rule, covered by these formations. Flaw polynias (unfrozen patches of water in the midst of an ice-bound area) which formed by winds, prevailing in winter time, often contribute to ice-hummocks formation. After new ice fills polynias and wind situation changes to the opposite, the ice is rides up and pressure ridges appears. Tides influence considerably to this process. Hummocking also takes place at the zones of ice drift gradients.

Besides the visual assessment of hummocks' presence (orientation of the ridges and their filling in the ice cover), a great contribution to the research was aerial photography carried out in some years in special operating areas. For example, in figure 4 distribution of hammock sails height is shown on
Fig. 1 Climatic estimation of ice cover fracturing at local area.

a) total fracturing

\[ W = 27\% \quad B = 22\% \]

b) fracturing of ice \( h > 30\) cm

\[ C = 86\% \quad A = 76\% \]

- partial fracturing
- partial concentration
- climatic estimation of partial concentration

Fig. 3 The fish area distribution according to aerial photography

Pristonyma
(north-south 1967)

- number density
- partial density

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the drift ice north off **Varandey** island in May 1986. The data were obtained from processed stereopairs of aerial photographic pictures at a 5 km site long. Hummocks and ridge formations in 75 cm thick one-year-old ice occupied 55% of the area. The average height of the sails in the line was 0.8 m, the maximum, one - 4.6 m.

Hummocks can considerably increase the ice cover mass. The results of measurements of the ridge sails, based on stereo-surveys materials, were used for calculation of the equivalent ice thickness (that is an average calculation characteristic, figured out at even distribution of sails and keels in a certain area or a line). When calculating according to a specially suggested method, it was, for example, 2.26m in April 1987 for the **Prirazlomnaya** area with the average thickness of level ice 1 m.

Keels of the drift hummocks can be a great danger to the practical activity. As shown by some episodic measurements of ice by drilling, the keels' depth was up to 12 meters north of **Gulyaevskle** Koshky and near Matveev island. Consequently, in shallow waters they are likely to Influence the ground when the ice is drifting which is a danger to pipe-line and cable systems.

The ice drift velocity and it's mass determine energy of ice influence onto marine installations. Data of drift stations research icebreaker "Otto Shmidt" received in 80s became the initial material (Fig 4). By this data, after filtration of tidal component by sliding averaging method, the relation between drift and wind was elucidated. This relation was approximated by linear equation:

\[ V = KW + C, \]

where \( V, W \)- vectors of the ice drift and wind, \( K \) - wind ratio, \( C \) - vector of discrepancy.

In order to define parameters of such relationship and assess how close it is the method of **Vatanabe - Gudkovich**, was used. In compliance with the data on time drift and wind data figured out coefficients of correlation which turned out rather high - 0.86. Discrepancy in all cases was negligible and never exceeded 2 cm/s.

So the calculated coefficient pattern for the **Pechora** Sea is as follows: wind coefficient becomes smaller further east. In the ice edge area \( K = 0.038 \) and for the most a easternt drift stations \( K = 0.022 \). Closer to the shore according to the **SLAR** data becomes still smaller.
Fig. 4 Bail height distribution of floating hummocks. Varandey in May 1988.

Fig. 5 Drift of R/V "Otto Schmidt" in Pechora sea in 1980, 81, 83, 90.

\[ V = kW + C \]
Basing ourselves on the above we assessed the ice drift intensity in the Pechora sea using the estimated parameters of relationship and regime wind flows distributions. As far as extremal speed values are concerned it turned out that in the southern part of the Pechora sea the estimation of wind drift component can be 60 \( \text{sm/s} \) once in 50 years. Contribution of the tidal components to the overall drift was assessed by a special method. All things considered, the drifting speed can be 140 \( \text{sm/s} \). The most probable direction of this maximum drift is north-east. (fig.5).

Performed in 1992-1994 joint international expeditions allowed to receive complex data on the arrangements, structures, physical and mechanical properties of sea ice. Having combined our experience, financial investments and technical facilities, our common activity allowed to collect for the last several years new ice data on a scale of the whole Pechora Sea as well as in the local areas. Concurrently with the Polar Institute of Fishery and Oceanology (PINRO) some airphotography and SLAR surveys were carried out in 1993.

Helicopter ice inspections and field offshore investigations on the base of the Varandey, located in the southern part of the Pechora Sea, allowed to observe in detail the offshore areas. With the purpose of fixing the stamukhas formation areas. Stamukhas (or grounded hummocks) of the greatest size were found in the fast ice of the Pechora Bay. In the areas of unstable fast ice and considerable variations of sea level, comprising the offshore zone of Varandey island, one can see a great variety of stamukhas shapes and sizes. In this area there are some stamukhas that move slowly along the seabed due to wind influences and sea level fluctuations.

All in all we carried out 19 detailed topographic surveys of stamukhas in the Pechora Bay near the islands Varandey, Matveev, Dolgy. It gave us the opportunity to measure precisely their linear dimensions and calculate volumes of those parts which are above the tile sea level. In figure 6 we showed an example of the geodetic survey's processed results one of stamukhas. The biggest observed stamukha's overall dimensions were 460 to 115 m. The height of the above-water parts was 15 m. Using the materials of aerial photography data and fast ice zones near the islands Varandey and Matveev we compiled schemes of stamukhas locations in the fast ice and measured the linear dimensions of 150 hummocks.

In the course of the offshore field observations some drilling operations were performed as related to ice-hummocks, stamukhas and level ice.
rig. 6 Upper part of **Stamukha la Pechora sea.** 1992.
applying auger and core barrel motodrill. With quite a lot of material it was possible to measure the keels of hummocks and samukhas and take samples for exploration of physical and mechanical properties of the ice. We also measured the size of the ice blocks that hummocks consisted of. In each area either site measurements of the level ice and snow's properties was carried out. The complex of physical and mechanical characteristics defined includes air and water temperature measurements, ice temperature measurements in different layers, its salinity, density, texture and structure. During three field work seasons we selected 535 ice samples, made 800 ice temperature measurements. The natural material collected by expeditions is a basis for common characteristics of physical and mechanical properties of the ice in the southern part of the Pechora Sea.

In 1995 AMIGE S.E. essentially modernized its field and laboratory equipment for exploration of the ice. We installed GPS and DGPS (positioning systems), have at our disposal highly productive core barrel and motor augers, salinometers. The expedition also has a unit for uni-axial compressive testing of ice samples solidity and bending strength. Technical equipment and the experience in the aerial, marine and offshore field observation will give SE AMIGE the opportunity to carry out a wide range of ice exploration work in the Barents and Kara Seas and the adjacent areas as well.
METOD FOR CALCULATION OF FLOW ACTION OF THE SCREW
ON BOTTOM IN THE PORT WATER BASIN IN PROCESS ON
MOORING TESTS OF SHIP

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ABSTRACT

It is told about the method for calculation of flow action of the screw on bottom in the port water basin on work of main ship energetic installation in mooring front and back the way of regimes.

In the process on mooring tests of main ship energetic installation in the port water basin it is not admitted that flow of the screw washed bottom.

By preparation to passing on mooring tests of main ship energetic installation at specially accomplish the place in the port water basin necessary by special metod it is calculated maximal possible of flow action on the bottom in the port water basin of the screw on work in mooring front and back the way of regimes (figure).

It is admitted the next admissions: it is absented influence of ship body on bottom water flow speed values of the screw by working in mooring back the way of regime and it is absented influence near bottom in the port water basin.

Admit unwash surface layer of bottom soil of water basin of speed $V_s$ depended on monobasic and middle greatness of particle for unbind (sand) ground or calculated hook-up for bind (clayey) ground.

In work mooring regimes of main ship energetic installation
of resistance value \( T \) is cited in the ship technical documentation not always. It is calculated in this case.

It will consider completely plunge under free surface water of ship screw for which basic work regime near to mooring regime (ice-breakers-fish trawlers and another). By ideal mover theory of resistance value \( T' \) of ideal the screw can be defined as follow [1]

\[
T' = 1.167 \times (D \times R_d)^{0.666}, \text{kN},
\]

(1)

here \( D \) - diameter screw, m;

\( R_d \) - consumption screw power, kW.

For real ship screw necessary it is known performance \( \eta \) which take into account the losses of lead energy determined in basic of influence of fluid viscosity and coherent with this of profile losses, of rotation of current behind the screw (hydraulics losses resistance). It is taken \( \eta = \eta_T \), here \( \eta_T \) - hydraulics performance of screw. Augmentation energy of fluid flow received of screw working in mooring regime it will definite as useful power.

For real ship screw of resistance value can be defined as follow

\[
T = T' \times \eta_T, \text{kN}.
\]

(2)

Maximal value \( \eta = 0.75...0.775 \) for overt screw [1]. Performance raise to value \( \eta = 0.90...0.945 \) for movement complement of screw - directive plant [2, 3, 4].

Then it is taken into account that increase of relative diameter of nave of screw \( d/D \) from 0.2 to 0.3 had reduced performance dependent on step relation value \( P/D \) on \( 2...5 \) % [2].

It will use of preservation energy law and it will define of central speed of liquid flow across real screw disk to the following formul
\[ V_0 = \frac{D_p \times \eta}{R_n}, \text{ m/s.} \]  

Axial flow speed of screw in the centre \( V_c \) if distance of screw disk \( X \leq 2.6 \times D \) (unestablished current of zone) it will taken \( V_c = V_0 \) \(^5\) and if of distance of screw disk \( X > 2.6 \times D \) (established current of zone) it will define to the following formul \(^5\)

\[ V_c = 2.6 \times V_0 \frac{D}{X}, \text{ m/s,} \]  

about botton \( V_b \) it will define to formul 5 taking slope of axle of screw of free surface water

\[ V_b = V_c \times e^{\left[-22.2 \times \left(\frac{r + X \times \tan \psi}{X^2}\right)^2\right]}, \text{ m/s,} \]  

here \( r \) - distance from axle \( X \) which it is positioned to parallel of free surface water of surface botton ( \( r \) is calculated to zero level of free surface water of ocean if it is watched of regular flow in the port water basin , m ;

\( \psi \) - corner of slope of axle of screw to axle \( X \) ( it is taking with the sign of plus if axle of screw is inclined to helm of ship),".

In formul 5 the sign of plus it is taken for back way of regime of the screw and the sign of minus it is taken for front way of regime of the screw.

A surface of layer of soil of botton in the port water basin it is washed if \( V_b > V_s \). In this case necessary it is calculated suppositional surface of wash from condition \( V_b = V_s \) on surface of wash.

For definition of surface of wash necessarily it is calculated the speeds in some points on various distances \( r \) from axle of
screw with step up to 0.5 m and on various distances X from disk of screw with step up to 1 m in mooring front and back the way of regimes of main ship energetic installation.

A wach flow action is depended of consumption screw power, resistance and corner of slope of axle of screw, depth in the port water basin, physical property of soil of botton and another factors.

For prevention of wach flow action of ship screw on botton in the port water basin on stage of production preparation necessarily it will make excavation the part of botton to allowable depth out of undestruction condition of wharf and (or) it will substitute upper layer of botton soil up of stable soil to wach or another means.

Offer metod is permited of executing of preliminary calculation and of realizing of necessary measures by prevention of wach flow action of screw on botton in the port water basin.

REFERENCES

Fig. A scheme of flow action on bottom in the port water basin of ship screw on work in mooring front and back the way of regimes.

1 - wharf; 2 - tree surface water; 3 - wash surface (possible); 4 - bottom profile; 5 - screw (it is not shown of ship body which placed with certain the angle to direction of wharf); 6 and 7 - water flow of screw working in mooring front and back the way of regimes (suitable).
Usage of ice heat cutting in mines and leads in ice cover
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Arctic and Antarctic Research Institute

1. Introduction

The equipment and technology of ice heat cutting used in the Arctic and Antarctic are considered.

Compared to mechanical cutting, ice heat cutting needs more power consumption for ice destruction. Such a method would be appropriate for use in limited volume of cutting as well as when other methods are not worthwhile or cannot be used at all. Heat cutting is appropriate for use in preparing mines, leads in ice cover, breaking ice around vessel, releasing different constructions from ice, protection of vessels and constructions from compacting, building of ice constructions and others.

2. Principals of ice heat cutting

Ice drilling by means of hot water jet or steam is widely known and of considerable use. Water or steam jet melts the ice. A hole filled with the mix of melt water and exhausted heat-transfer agent (water, steam) is formed. The same principle is used in ice heat cutting. A cutting instrument (a heat cutter) has a row of parallel outlet nipples. Heat-transfer agent (water, steam) arriving through the above nipples to the face melts a row of parallel holes which merge together and form a split. The mix of melt water and heat-transfer agent melts the ice walls and makes the split wider. Ice walls warm-up retards rapid water freezing. It allows to sling, take out or remove the ice blocks.

The efficiency is 18-25 percent for ice cutting by means of hot water and 30-40 percent when exhausted water is used. It runs to 60 percent for steam cutting but the powerful steam generator and fresh water supply is needed. Ice water cutting is worth of limited volume of cutting when hot water sufficient for work can be prepared in advance.

A general-purpose heat cutter GTR-1000 is represented schematically in Fig.1 as an example. It consists of a hollow body 1 with outlet nipples 2 installed on it. A tube 3 with stiffeners is welded to the centre of the body, bushes 5 to fix guide tubes 6 are mounted at the ends of the body. There are outlet nipples
of the relevant diameter on the tube 3 and bushes 5. Water or steam supply is carried out by means of a steam-transfer hose and a delivery pipe 7. Heat cutter models of other designs have been developed and tested. Steam cutting speed is to 10 m/min at a pressure of 5 kg/sq cm. To work with hand-operated cutters at such a cutting speed is rather difficult. Heat cutters of increased cutting speed can be installed on a tool carrier.

An experimental heat cutter GPB-2200 is shown in Fig.2. It consists of a heat cutter 1 with a delivery pipe 2. It is installed on the tool carrier 3 of an oversnow vehicle "Buran". For permanent contact between the heat cutter and the ice a spring 4 is fixed. Steam is delivered by a rubber hose. Trials of the heat cutter in fast ice showed a high quality of the split for direct and curved cutting directions.

Table 1

Main technical characteristics of GTR-1000

<table>
<thead>
<tr>
<th>Technical characteristics</th>
<th>Heat-transfer agent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of melted ice, m</td>
<td>up to 3-5, up to 3-5</td>
</tr>
<tr>
<td>Cutting speed, m/min</td>
<td>0.5-0.7, 0.5-0.7</td>
</tr>
<tr>
<td>Split length, mm</td>
<td>1000, 1000</td>
</tr>
<tr>
<td>Split width, mm</td>
<td>25-40, 25-40</td>
</tr>
<tr>
<td>Steam consumption at a pressure of 3-4 kg/sq cm</td>
<td>-, 200-300</td>
</tr>
<tr>
<td>Water consumption at a temperature of 80 °C, cubic m/h</td>
<td>4-5, -</td>
</tr>
<tr>
<td>Overall dimensions without delivery pipe, mm</td>
<td>1000x300x36</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Auxiliary equipment

The auxiliary equipment includes a heat source, pumps, pipelines are fitting. The equipment for work on floating ice is
given in the block-scheme (Fig.3). With steam, the equipment consists of a steam generator 1, a snow melter 2, hoses 3, a valve 4, and a heat cutter 5. With hot water, the equipment includes a water heater 1, a service tank 2, a pump 3, delivery hoses 4, a heat cutter 5 and reverse hoses 6. Without exhausted water, the reverse hoses 6 are not applied.

3. Technology of ice cutting and fulfilment of certain work

Ice cutting by means of cutters GTR-1000 can be carried out in vertical, horizontal and inclined directions. In work on floating ice the first split is made with outlet nipples fixed on side bushes. In so doing two holes are formed at the edges of the split. Thereafter the nipple is abandoned in favour of a guide tube. In further cutting the tube is mounted into the hole at the end of the split. During ice cutting an operator holds the heat cutter for the delivery pipe, controls heat-transfer agent supplied and conditions of the hose and remounts the cutter. To prepare the inclined splits the heat cutter is located at given angle and held in this position during cutting. To cut ice of land origin and water-covered ice depending on local working conditions the heat cutters GTR-1000 as well as other models and relevant technologies to carry out such a sort of work can be used.

Certain work carried out by means of ice heat cutting

Ice blocks are cut and removed under the ice or on it in preparation for mines. During cutting the block one (front) edge of it is made inclined. A rope is fixed to the opposite ice block edge, the ice blocks can be pulled out on the ice surface or under it with the help of a winch or a tractor. From working experience the volume of the ice blocks pulled out by means of the tractor DT-54 was 4-5 cubic m and the tractor T-100 reached 809 cubic m. Ice block removal on the surface is shown in Fig.4. Versions of ice block removal under the ice is given in Fig.5. The tractive force in block removal will be maximum at the end of turn of the block during its movement along the inclined mine edge.

The maximum force was 15 t (1.32 times as much as buoyancy
of the block) during the removal of the ice blocks of 15×5×2 m under the ice 2 m thick. The winch of 20 kWt was used and the removing speed was 6 m/min. In making leads the successive cutting and removal of the ice blocks on or under the ice is in order. It is appropriate to make the direct splits by means of more productive mechanical devices but the inclined and auxiliary splits should be done with the help of heat cutters. There is an area of the ice of two or threefold in thickness near the leads (mines). This area can be used as discharging platforms and roads.

It is sufficient to make cutting and removal of the ice blocks along one board of a vessel in order to break the ice around the vessel. The splits around the vessel are to be done further. In the case of emergency and repair works onboard the vessel, when the damage site has to be accessible, the mine can be prepared by means of heat cutting and the above technology. In releasing any constructions from ice the ice heat cutting allows to cut the ice in parts not easily accessible without any deleterious effects on the construction.

4. Summary

The main data on ice heat cutting developed at the AARI as well as the data on certain works where such a method is used are given in the report. The technologies of ice heat cutting can be applied profitably in building and service of hydrotechnical constructions in the Arctic Seas (for example: in building of temporal discharging platform, 'nines and roads on ice, in protection of constructions against ice impacts and repair works connected with ice destruction).
References

1. Certificate 1844465, USSR. The ship equipment for ice fracture. Morev V.A. In Otkrytia, izobretenije, 1974, #18, p. 73-74 (in Russian)


Fig 1 Scheme of heat cutter GRV-2200 on a tool carrier of snow vehicle "Buran".
1 heat cutter GRV-2200; 2 inlet tube; 3 tool carrier of snow vehicle; 4 spring.
Fig 2. Scheme of heat cutter GRV-2200 on a tool carrier of snow-vehicle "Buran".
1 heat cutter GRV-2200; 2 inlet tube; 3 tool carrier of snow-vehicle; 4 spring.
Fig. 3. Scheme of the equipment for the work on the floating ice.
A) 1 steam generator; 2 snow-melter; 3 pipe-line; 4 pipe; 5 heat cutter.
B) 1 water heater; 2 service tank; 3 pump; 4 inlet pipe-line; 5 heat cutter; 6 reverse pipe-line.
Fig 4 Creation of small mines by removing of ice blocks.
A) Using powerful pulling mechanism ($F = 1.1...1.3$ of ice block weight).
B) Using weak pulling mechanism.
Fig 5. Creation of No mine* by pushing of left blocks under the ice cover.
1 Ice cover
2 Ice block
3 Winch (F = 0.1 of Ice block weight)
MATHEMATICAL MODELLING AND NAVIGATION SAFETY ALONG THE NORTHERN SEA ROUTE

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S.O. Makarov

Introduction

Navigation safety in Arctic conditions can be raised by use of up-to-date methods of mathematical modelling based on solution of the "shallow water" equations. Author of this report obtained some generalization of these equations in the year 1975. He used non-trivial approach of their derivation from equations in primitive form. The derivation was based on the simplest form of self-simulation namely on vertical permanency of all summarized functions. He managed to reduce the three dimensional equations to the two dimensional ones using the hydrostatic approximation. He also managed to keep all differential operators (of reduced dimensionality) analogous to the initial equations. The momentum balance equations included, therefore, operators with density. They became closed in respect to density by use of equations of turbulent diffusion of heat and salt. A well-known model, which connected velocity and density fields ("the dynamic method"), became natural part of general model of viscous incompressible fluid dynamics [1]. Form of the equation right side was refined in the year 1987 and it obtained apparently a full-blown form of limiting generalization for the viscous incompressible fluid [2].

Mathematical formulation of the fluid dynamic model and some results of numerical simulation for the Kara Sea the Gulf of Ob [3] are given below. These simulations were carried out during problem formulation [1]. Proposals are stated for use of mathematical models in order to obtain information additional to the standard hydrometeorological and hydrographic information for navigation safety support in the Arctic conditions, where navigator manoeuvre freedom can be limited by ice conditions.

The Dynamic Model Formulation

The model equations are as follows:

\[
\frac{\partial U}{\partial t} + \frac{\partial}{\partial x} \left[ U U H - K \frac{\partial}{\partial x} \left( \frac{U}{H} \right) \right] + \frac{\partial}{\partial y} \left[ U V H - K \frac{\partial}{\partial y} \left( \frac{U}{H} \right) \right] - \tau_v = - \frac{1}{\rho} \left[ \frac{\partial}{\partial x} \left( \frac{H^3}{2} \right) + \frac{H}{2} \frac{\partial \rho}{\partial x} \right] + \tau_v - \kappa |U| / H
\]

\[ (1) \]
\[
\frac{\partial \mathbf{V}}{\partial t} + \frac{\partial}{\partial x} \left[ \frac{\mathbf{V} \mathbf{U}}{H} - K \frac{\partial \mathbf{U}}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \frac{\mathbf{V} \mathbf{V}}{H} - K \frac{\partial \mathbf{V}}{\partial y} \right] + \mathbf{U} \mathbf{U} = 0
\]  
(2)

\[
\frac{\partial H}{\partial t} + \frac{\partial H}{\partial x} \mathbf{V} + \frac{\partial H}{\partial y} \mathbf{V} = 0
\]  
(3)

\[
\frac{\partial \mathbf{C}}{\partial t} + \frac{\partial}{\partial x} \left[ \mathbf{C} \mathbf{U} - \mathbf{K} \frac{\partial \mathbf{C}}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \mathbf{C} \mathbf{V} - \mathbf{K} \frac{\partial \mathbf{C}}{\partial y} \right] = 0
\]  
(4)

\[
\rho = \rho(S,T)
\]  
(5)

Initial and boundary conditions are as follows:

\[
\zeta \mathbf{U} \mathbf{V} \bigg|_{t=0} = 0
\]  
(6)

\[
\mathbf{C} \bigg|_{t=0} = \mathbf{C}^0
\]  
(7)

\[
\mathbf{U}_a \bigg|_{t=0} = 0
\]  
(8)

\[
\mathbf{U}_a \bigg|_{t=0} = \mathbf{U}_a^*(\eta, \psi)
\]  
(9), (9a)

\[
\mathbf{U}_a \bigg|_{t=0} = \mathbf{U}_a^*
\]  
(10)

\[
\mathbf{C} \bigg|_{t=0} = \begin{cases} 
\mathbf{C}^0 = 0, & \text{if } \mathbf{U}_a \bigg|_{t=0} < 0 \\
\mathbf{C}^0 = 0, & \text{if } \mathbf{U}_a \bigg|_{t=0} \geq 0
\end{cases}
\]  
(12)

where \( \mathbf{U}, \mathbf{V} = (u, v) \) are velocity fluxes \((\text{m}^2/\text{sec})\); \( u, v \) are "Eulerian" velocities \((\text{m/} \text{sec})\); \( H \) is water depth; \( \zeta \) is dynamic excess of sea level over the initial condition (6); \( \rho \) is water density; \( K, \mathbf{K} = (k_1, k_2) \cdot \mathbf{H} \); \( \mathbf{K} = \mathbf{a} \mathbf{W} \cdot \mathbf{W} \) is "wind stress"; \( \beta \) is the Coriolis parameter; \( \mathbf{C}_l, \mathbf{C}_s, \mathbf{C}_h \) are diffusive admixtures; \( \mathbf{f}_1 \) is a solid boundary; \( \mathbf{f}_2 \) is a liquid boundary; \( \mathbf{f}_3 \) are sources; \( \mathbf{n} \) is outside normal; \( \ast \) marks out determined values; \( \eta, \psi \) are magnitude and phase of tidal fluxes.

**Some Results of Simulation**

Results obtained in the work [3] during sea level calculation in the Gulf of Ob are given in Figure I. Grid steps \( \mathcal{A}, \mathcal{B} \) were equal to 10 km, and time step of...
numerical integration was equal to 240 sec. We used explicit numerical scheme. One can see changes of sea level surface of approximated area of Gulf of Ob caused by changes in wind direction during 48 hours (wind speed was equal to 10 m/sec). These wind characteristics (modulus and period of action) correspond to "mean" extreme wind conditions in the Gulf of Ob. Figure 1 illustrates evident merits of mathematical modelling of sea level conditions for shallow water basin, compactness and availability of means simulating extreme sea level conditions in the Gulf of Ob, but simultaneously it illustrates a priori unpredictability of results.

The following peculiarity of the calculation results engaged our attention: in shallow water region \((h \leq 5\,\text{m})\), it is the southern and central part of the gulf) isolines of sea level values for long waves are normal to the wind direction, i.e. these isolines behave as wind wave fronts. This perpendicularity was achieved in the first several hours of wind action and remained up to the moment when the solution became steady \((=12.5\,\text{days})\). The perpendicularity at the depths above 5 m is obtained "in the vicinity of steady-state of solution". It corresponds to a very simple image: a greater mass has a greater inertia. The steady state for all the movement components (including sea level and admixtures) on the whole water area is reached through stable interaction of separate parts of gulf circulation namely of circulation eddy cells. As this takes place, not only initial data (depths and densities) are of significant value for sea level surface behaviour but also their spatial-compositional asymmetry relative to direction of external force action (wind, tide). That is the reason, why estimates based on a priori symmetry notion (phenomenological, statistical) can have unpredictable mistakes.

Contribution of density gradients to sea level inclination for the Kara Sea was equal to 80 cm (salinity variations 27 ppt over the water area) and it was equal to total kinetic energy brought by 10 m/sec wind in barotropic case. This solution was obtained as steady state using initial density values. It should be mentioned that densities as initial data should be taken as vertically weighted-averaged values. Crude estimate of horizontal density gradient contribution to form of the sea level surface of the Kara Sea and the Gulf of Ob obtained as a result of these numerical simulations equals 2-3 cm for 1 ppt. Thus the density gradient \(\rho / \rho_0 = 10\) ppt causes the sea level inclination (for steady state case) being equal to 20-30 cm.
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Proposals

Analysis of the modelling results of the sea level dynamic conditions for the Kara Sea and the Gulf of Ob allows us to formulate a series of proposals.

1. It is necessary to put into use as an obligatory element of depth mapping technique hydrodynamic simulation in the form mentioned above.

2. The simulation results should be used as preliminary project work, which allows one to obtain the following estimates:
   - to simulate extreme state of sea level conditions, which is determined by combined action of all significant factors: form of coastal line, depth, wind, tides, currents (river-sea), density gradients;
   - to simulate environmental impacts caused by drifted material, erosion, urbanization (for example by hydrotechnical construction);
   - to make optimum choice of places of stationary and temporary gauges thus eliminating problem of statistical basis of gauge net representativity.

3. The abovementioned approach to the "shallow water" model can be used for hydrodynamic level study of the World Ocean and for determination of sounding datum of the World Ocean in particular.

4. To create a priori diagnostic albums or electronic maps of sea level surfaces for navigation routes with depth limited according to navigation safety and to use this information on board of ships or in headquarters of navigation management in a form of "forecast" (meteorological) + "diagnosis" (hydrodynamic).

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Figure 1. Sea level surface in the Gulf of Ob.
LOCAL AND INTERACTIVE EFFECTS OF ICE FAILURE AT SHIP MOTION IN A COMPRRESSIVE ICE

ABSTRACT

According to the results of the joint research project "A ship in compressive ice" fulfilled by Helsinki University of Technology, Ship Laboratory and Institute for Problems in Mechanics, RAS typical schemes of ice cover failure at the initial stages of interaction between ice cover and wide obstacle are studied. The models of the interaction mechanisms at different scales and boundary condition forms are considered.

1. INTRODUCTION

The processes of ice failure under ice compression near to the icebreaker board (as an obstacle) are connected with an action of several interacting mechanisms. Each of these mechanisms forces both real failure at a certain scale and forms boundary conditions for other mechanisms. In particular, ice cover failure is essentially non-local process, forced by non-local interaction.

Studying an Interaction between ice cover and vertical wide obstacle one can distinguish the following main mechanisms of ice cover edge failure-crushing, flaking, bending failure (sector formation). The boundary conditions on the contour of a region under Interaction depend on the combination of direct contact
between ice and obstacle, accumulation of failed products, mechanism of that products removal from the region and specific mechanism of ice failure, leading to transformation of horizontal loading in vertical one, which is necessary for failure organization.

Using the results of the joint research project "A ship in compressive ice" fulfilled by Helsinki University of Technology, Ship Laboratory and Institute for Problems in Mechanics, the Russian Academy of Sciences let us consider typical examples of ice cover local failure at the initial stages of interaction between ice cover (with straight-line edge) and wide obstacle. Some separate elements of this process (such as ice edge flaking, eccentricity of loading, effect of intermediate layer of failed ice, etc.) were discussed earlier[1,2].

2. LOCAL FAILURE

Contact failure at the region of direct contact (crushing, flaking etc.) precedes to ice edge break-of under bending. Bending failure occurs as a result of accumulation of transversal deflection of ice cover edge during contact failure process. According to the results of the joint research project [3] there are two regimes of this process (fig.2). At the first stage the transversal deflection has non-regular character and shows a big scattering of deflection values at the same ice cover displacement along an obstacle (fig.3a). (The mechanism of transversal deflections at the ice cover edge at the initial stage of the interaction process can be connected with loading eccentricity occurring during flaking process [2,3]). Then, after reaching of some characteristic level of deflections the process stabilizes. All the tests show practically linear correlation between longitudinal displacement S_l of ice and transversal
deflection $D$, where upon the deflection value is nearly the same in the different tests, including the change of ice cover velocity (0.05 m/s and 0.1 m/s) (fig.3b). This correlation can be expressed by the following empirical formula

$$D \sim 0.155S + 0.01[m]$$

according to the model test results for model ice thickness about 0.02 m.

Let us consider a model for transversal deflection at the second stage, taking into account correlation (1) between displacements and deflections and the conservation of contact failure mechanism (flaking). As a result of this failure, the microblocks of ice with a characteristic orientation relative to the ice surface break-off. After each act of failure the ice edge can slide along the break-off surface. During an accumulation of failure products these ice microblocks are retaining at the obstacle surface under an action of their weight, friction and adhesion to the obstacle surface. Ice edge, sliding along them, undergoes the transversal deflection, accumulating during new blocks break-off (fig.4). So that some value of ice cover displacement relative to the obstacle corresponds to each act of transversal sliding. As a result an ice cover edge takes some transversal deflection, controled by ice cover displacements. According to formula (1) one can write for the transversal deflection velocity $V_1$:

$$V_1 = \frac{dD}{dt} \approx 0.15 V \quad ; \quad V = \frac{dS}{dt}$$

By incorporating the condition of a beam break-off under dynamical failure of the region of load action (the beam edge is forced to the motion with constant velocity $V_1$) [4], one can estimate the transversal size of the forming (under bending) sector.
\[ l_i = C h \left( \frac{C_p \cdot \sigma_t}{\sigma_p} \right)^{0.5} ; C_p = \sqrt{\frac{E}{\rho}} ; C \sim 0.45 \] (3)

where \( h \) - the ice thickness, \( C_p \) - the velocity of elastic excitation, \( \sigma_t \) and \( \sigma_p \) - the strengths of Ice at the tension and compression, respectively, \( E \) - Young modulus, \( \rho \) - the ice density.

Some estimates of sector sizes according to (3) in comparison with test values of the test conditions are given in Fig.5.

Presented estimates show the effects of contact conditions in the region of direct contact between Ice cover edge and an obstacle on the parameters of successive failure of ice under bending (that is the sector formation process).

Let us recall that, according to many observations, the ratio of longitudinal and transversal sizes of a sector is nearly constant for different loading conditions, i.e. \( b/l_i \sim \text{const} = 4 \) [9], where \( b \) - the length of sector, \( l_i \) - its wideness. Estimating \( l_i \) from (3), one can determine the geometrical sizes of sector.

3. GLOBAL SCALE

Let us suppose that the sector formation occurs at some place of (initially solid) straight-linear contact between ice cover and obstacle. According to test load measurements [1,2] and other observations [6], local and global loading of the obstacle decreases - the medium resistance does not act at the place of the forming sector. From the point of view of fracture mechanics it's similar to some defect (stress concentrator) appearing.

Under constant level of averaged external compressive stress \( \bar{\sigma} \) the local stresses (compression) Increases at the region near to forming concentrator. Thus the successive act of tee break-of is
more probable near to the first one. In this case the longitudinal size of
the defect increases, as well as a level of the stress and
displacement concentration at it's end regions (fig.6). This case is
very similar to development of a compressive crack at the ice cover
edge [10]. One can determine the effective value of the fracture
toughness for such defect (ridge formation resistance [10]).

In the framework of the external problem of ice cover edge failure the effective stress intensity factor can be written as:

\[ K_{le} \sim \sigma \sqrt{a} \] (4)

where \( a \) is the half-length of a defect.

Here it is assumed, that the shear component of stresses in
the defect tip is small as a result of small friction effects, that is \( K_{ll} \ll K_{ll} \).

The critical stress intensive factor (ridge formation resistance [10]) can be estimated from the relation:

\[ K_{lc} = K_{le} \sim \sigma_c \sqrt{a} \] (5)

where \( \sigma_c \) is the characteristic stress at the region of local failure at
the defect tip, \( d \) is the characteristic size of this region.

Sector break-of occurs at the end region in case under consideration. Thus \( a_r \sim P_{max}/bh \), \( d \sim b \) where \( P_{max} \) is the load for
one sector break-of.

Assuming for limit equilibrium of system: \( K_{h} - K_{le} \) one can
find the correlation between average stresses in Ice cover and
parameters of ice cover edge failure near to an obstacle:

\[ \bar{\sigma} \sim \sigma_c \sqrt{b/a} \] (6)

or, using \( \sigma_c \sim P_{max}/bh \), \( \bar{\sigma} \sim \frac{P_{max}}{h \cdot \sqrt{ba}} \).
Since the value of $P_{\text{max}}$ along the obstacle length changes weakly, the value $a$ is mainly influenced by the defect size. Maximum average pressure on an obstacle occurs when this size is minimal. Taking a hypothesis about proportionality of the Initial defect size to the length $L$ of the whole line of contact, one can derive from (6)
\[
\bar{\sigma} = \frac{P_{\text{max}}}{h \cdot b \cdot L} \propto \bar{\sigma} \sim K_s / \sqrt{L}
\]  
(7)

Hence, the correlation between parameters of the external ($\bar{\sigma}, L$) and internal ($P_{\text{max}}, b$) problems is realized through formulae (6) and (7). Estimates of these parameters can be made on the basis of both the presented failure model and interpretations of test data. The pointed out in [6] correlation between average stress value $a$ and contact square ($Lh$) in case of a wide support can be used to estimate the ridge formation resistance $K_h$ according to formulae (7). For average ice thickness $h \sim 1\text{m}$, $K_h \sim 1.5 \text{ MPa} \cdot \text{m}^{1/2}$.

Another estimates can be made on the basis of data for average stresses under ice compression. The maximal line load under ice compression (3 balls) is estimated as $10^5 \text{N/m}$[7]; that for ice with the thickness about $1\text{m}$ corresponds to average stresses about $0.1 \text{ MPa}$. One can estimate $K_s$ from (7) supposing, that this ice compression corresponds to the level of critical conditions for ice cover failure (that is effective strength of wide ice cover) and the scheme of macrofailure is ice cover edge break-of for an ice field of large blocks (the size of different ice flos-about 100-1000 m). Under these assumptions $a$ correlates with maximal compressive stresses, and $L$ with the size of individual failed floe. Then $K_s \sim 1-3 \text{ MPa} \sqrt{m}$. 
Let us point out the following essential feature. A model ice in the Ice basis is, as a rule, more compliant and has smaller contact strength, as the modeling criteria require (for bending strength and geometry of interacting objects). Thus the picture of the interaction can be distorted.

It's obvious, that in the field conditions the region of contact failure (flaking, crushing) at the juts of ice cover edge, which precede the sector break-of has relatively small square, smaller than relative transversal deflection of the ice cover edge under it's break-of. This fact makes more difficult the interpretation of model test results. However, if the failure mechanism by sector break-of under ice edge bending is the same, it's possible to calculate the model test results on the basis of the dependencies for ice failure scheme, in particular, to correct the values of average stresses, acting on wide ice-resistant structure. Indeed, one can write:

$$\bar{\sigma}_{\text{mod}} = \bar{\sigma}_{\text{Ice}} \cdot \lambda \cdot m$$

(8)

where $\lambda$ - the modelling scale, $m$ - some coefficient.

The value of $m$ can be obtained as a ratio of $a$, calculated according to (7) for model criteria, to the same parameter from (7) for Ice parameters, which are used in fact.

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Fig. 3

Fig. 4

Fig. 5

\( S_1 \)
High power microwave radiation destroys the bindings between microcrystals in the bulk of sea ice. Thin destruction of sea ice structure is a result of microwave energy absorption in the liquid brine fractions on the surface of microcrystals. Theoretical approximations and experiments reveal abrupt decreasing of the sea ice breaking strength when the intensity and exposure of microwave radiation are increased. The effect of microwave radiation may be utilized in the icebreakers and for protection of Arctic sea platforms from the moving ice.
1. **Sea Ice structure.** As is known [1] sea Ice consists of pure-water ice microcrystals and liquid brine fractions. These fractions are situated at the surface of microcrystals. At low temperature the liquid fraction has the form of unconnected droplets. When the temperature is increased, the volume of liquid fraction is increased too and the brine droplets are transformed to well-connected skins and capillaries. In spite of small specific volume, the liquid fractions form various physical properties of Ice. So far the liquid fractions are placed at the microcrystal boundary, they control the binding force between the adjacent microcrystals and solidity of the whole Ice sample. Increasing of liquid brine fraction volume gives rise to an abrupt decreasing of binding force. As a result, the elastic limit, shear strength and the bending strength of ice are decrease also.

2. **Destruction of Ice structure under microwave radiation.** The energy of microwave radiation is absorbed in the bulk of sea ice and transformed into the heat. The absorption of microwave radiation takes place in the liquid brine fraction only. Absorption in the microcrystals is in many times smaller. Therefore, at first moment the energy of microwave radiation heats the liquid fraction only. The absorbed energy of microwave radiation is consumed to the melting of microcrystals. This part of microwave energy gives rise to Ice destruction process. Some later the heat propagates in all directions from the brine fractions and increases the temperature of microcrystals and the ice bulk.

The generated heat power in the unit volume, \( P_f \), controls the sea Ice destruction process under microwave radiation. This
fundamental parameter \( I_a \) directly proportional to density of microwave radiation (microwave power flux through unit surface). The effective destruction process may be realized only for sufficiently large values of \( P_r \). In such a case the energy of the microwave radiation is directed to the destruction of bindings between the microcrystals and the energy loss due to bulk ice heating are minimal. It is necessary to note, that the breaking force must be applied simultaneously with the microwave radiation, since the ice is far from the thermodynamic equilibrium state. The breaking force appears as a result of ice pressure to the vessels, sea platform post etc.

For small values of \( P_r \) (\( P_r < 1 \) \( \text{W/cm}^2 \)) the microwave energy is consumed to the microcrystal melting as well as microcrystal heating and the energy losses are maximal.

The experiments with sea ice were carried out in 1991 together with Arctic and Antarctic Research Institute and Moscow Motional Technical University. In the experiments we used microwave radiation with frequencies 2450 MHz and 915 MHz and intensity up to 15 W/cm\(^2\).

The results of experiments confirm our theoretical evaluations. It was founded, that the bending and breaking strength abruptly decrease with increasing of microwave radiation intensity. Fig. 1. The details of calculations and experimental result are presented else were (2,3).

3. Application of microwave ice destruction. Power microwave radiation may be utilized in the Icebreakers and for the protection of Arctic sea platform from the moving ice and icing.
An example we consider here power microwave source for protection of platform pont from the moving Ice (Fig. 2). (velocity of Ice up to 0.5 m/sec, Ice thickness 1 m). The frequency of microwave radiation to 915 MHz, calculated microwave power is about 1 MW. Microwave generator and antenna are placed in the moving unit. The waveguide slots antenna is used for focusing of microwave radiation to the moving Ice surface. The microwave radiation is directed to the point of maximal stress on the Ice surface In front of the pont.

The power of anti-icing microwave systems may be sufficiently smaller - from ten to hundreds kilowatts.

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Bending strength \( \sigma \) depending on the time \( t \) for sea Ice with temperature \( T \) and salt content \( S \).

I and \( f \) are Intensity and frequency of microwave radiation.

1. \( S=7.6\% \), \( T=-19^\circ C \), \( f=2450\text{MHz} \), \( I=2.8\text{W/cm}^2 \). 2. \( S=9.8\% \), \( T=-16^\circ C \), \( f=915\text{MHz} \), \( I=8\text{W/cm}^2 \).
High power microwave source for protection of platform post from the moving ice.
1-platform. 2-pot. 3-moving ice. 4-moving microwave unit. 5 high-voltage source. 6-microwave radiation.
MARKET AND TECHNOLOGY OF ICEBREAKERS SINCE 1970

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1. Background and introduction

Icebreaking by ships to support commercial activities was introduced a little more than 100 years ago. The activities in ice covered waters have expanded slowly but steadily both by the extension of the season of ice operation and also by the extension of the area where icebreaking takes place.

This paper covers market and technology development from about 1970. The primary reason for the selection of 1970 is the fact that the development of icebreaking technology was considerably intensified in the western countries at about that time. This expansion was dictated by visions of various people in various countries of the potentially expanding market of icebreaking ships. Apart from mostly unpublished work done in the Soviet Union, the systematic research of icebreaking technology and icebreaking ships was started in real volume at the turn of 1960/1970. This work was initially intensified in Finland but rapidly industries, research organizations and governments followed suit in many other countries such as the United States, Canada and Germany.

These four countries and the Soviet Union can really be credited for the active technological development of icebreaking ships.

1995 is as natural a finishing point for this review as is 1970 for as the starting point. Over the last few years, the activities related to icebreaking ships and technology have stagnated or even declined considerably. To our view there are three fundamental reasons to this stagnation:

- the collapse of the Soviet Union has dramatically changed the priorities of all Arctic activities in Russia,
- Arctic oil and gas exploration activities are de facto halted in Canada and Alaska and will obviously remain so as long as the price of hydrocarbons is at the present low level,
- in subarctic areas, the icebreaking operation and also related technology have become fairly well established and the technology is adequately developed for all the needs in these areas.

Thus, 1970 - 1995 covers accelerated development of the market and technology and decreasing activities towards the end of the period.

This paper is intended to be a fairly simplified review of business and technical activities related to icebreaking ships and technology. We do not discuss any technical details but we paint the picture of broad perspectives.
2. Terminology

The terminology related to icebreaking vessels is worth a consideration as there have been changes over the time of various terms as a result of the technological development and there also is potentially a risk for misuse of various words. Both authors have been involved in the design and construction of icebreakers and icebreaking research from the beginning of the 1970s until today and as we have been involved in this work in the most active industrial enterprise in this field, we believe that we have a sound and authoritative approach to all the words used. As there are a fairly limited number of people involved in icebreakers and icebreaking research in the world, we realize that those among us who worked at Oy Wartsila Ab Shipbuilding Division, predecessor to Kvaerner Masa-Yards Inc, have influenced the terminology to a certain extent. We know, in fact, that colleagues around the world share our interpretations as we have been using these words throughout the last 25 years in a very logical manner realizing that technological development has influenced the use of the words to some extent.

Initially, the word icebreaker was used for a ship, which was intended to break ice and particularly to assist other vessels in ice operation. As many single purpose icebreakers were built in the early 1900s, the use of the term icebreaker was very solidly established to cover a single purpose icebreaker to support other ships operating in ice.

In the 1960s cargo ships were introduced with icebreaking capability on their own. Earlier cargo ships used in ice were predominantly only strengthened for some ice operation. A confusion was born initially these ships with a defined icebreaking capability were called icebreakers, but as more ships of this type came to the market, there was a need to differentiate the terminology. This resulted to the use of a term icebreaking ship, which was primarily introduced to differentiate these cargo carrying "icebreakers" from more or less conventional but ice strengthened cargo ships. It goes without saying that a single purpose icebreaker also included in the category of icebreaking ships.

The use of the term icebreaking ship as described above was generally accepted in the beginning of the 1970s.

In today's terminology, which is really the same as the terminology used 20 years ago, we have a unanimous agreement of the use of the terms as follows:

- **Icebreaker** is a ship intended primarily to support operation of other ships (or offshore structures) in ice. The ship may have secondary functions in ice and also in open water, particularly as regards ships which are needed as ice breakers only a part of the year.

- **Icebreaking ship** covers both purpose built single purpose icebreakers and ships which have been designed for a certain commercial function like cargo carrying so that they can penetrate through unbroken ice in certain areas predominantly by their own capabilities. What is important here is that the ship in this category has been designed and constructed to do icebreaking by herself in defined ice conditions.

- **Ice strengthened ship** means a ship which has been designed for her primary function in icefree conditions but has been strengthened to be able to operate in certain ice conditions but not to be able to break sea ice of varying characteristics over her whole route. Of course every icebreaker and every other icebreaking ship defined above is also ice strengthened.
but the term ice *strengthened* ship is really being used for ships which are basically only *strengthened* to withstand ice forces and typically as required by the rules of a *classification* society for ice strengthening.

As one can understand there cannot be any absolutely strict limits between the three categories above. The words are to be used in the right context i.e. they refer to real ships which are being used in real ice conditions such as those in the Northern Baltic or in the Arctic.

The need of this definition can be clarified with the following. It is of course clear to everyone that independent of the configuration of the hull of the ship or the propulsive thrust every conceivable ship can break some ice. Even a 20 horse power motor boat with any typical hull configuration can break ice of say 2 cm thick. This, however, does not mean that that particular motorboat would be called an icebreaking ship. Therefore we have to use these terms in perspective with the technological development, the ice conditions where the ships operate during the period of 1970 to 1995 etc.

It is also important to note that icebreaking has changed dramatically over the last century. Icebreakers then were small and operated in very marginal conditions compared to today’s ships. and by today’s measure are not considered to be icebreakers.

Our paper is restricted to icebreaking ships, which also includes single purpose icebreakers.

3. Market of icebreaking ships

In 1970 there was a total of about 90 icebreaking ships in the world, of which about 75 were single purpose icebreakers.

Table 1 lists all the icebreaking ships in use at that time. As can be seen the dominant countries were the Soviet Union, Canada, Finland, Sweden and US.

Table 2 lists all the icebreaking ships delivered during the review period, totally about 270 icebreaking ships. As some of the ships listed in Table 1 are not any more in use the total number of icebreaking ships in the market/operation as of the mid of 1995 is about 350.

We would like to point out that the numbers above are not absolutely accurate as the borderline between icebreaking and non-icebreaking ships can never be absolutely established and as our files are not absolutely complete either. The tables, however, show very clearly the trends and volumes of the specialized icebreaking fleet.

During the review period the icebreaking fleet has become quite diversified. This is illustrated by the following list of ships built during the review period.

- **icebreakers** about 90 ships
- **icebreaking cargo ships** about 150 ships
- **icebreaking research vessels** about 30 ships
- **other icebreaking vessels** about 15 ships.

Another feature worth emphasizing is the dominance of the Soviet Union/Russia in the expansion of the fleet over the review period.
A short description of the development of icebreaker fleets in major countries with icebreaker operations is given in the following

3.1 The Soviet Union and Russia

Because of the huge Arctic area in the Soviet Union, vast resources in the north of the country and heavy ice conditions both in the Arctic ocean and on major rivers, the Soviet Union has been, during the review period, by far the most active user of ships in ice. This covers the extent of the area of ice operation, the variety of ice conditions such as ocean and rivers as well as the volume of commercial shipping activities in ice. Therefore one can also conclude that our terminology is very much influenced by the development of ice operations in the Soviet Union during the review period.

Arctic shipping activities were steadily increased in the Soviet Union from 1970 to 1987. The major activity was transportation of goods to northern communities and transportation of forest, mining, and similar products from the North and to a limited extent the operation through the north-east passage. These activities required an increase in a number and size of icebreakers and also an increase of the size and capability of icebreaking cargo ships, which were designed and constructed to be able to operate independently of icebreakers in certain summer conditions albeit not in all of the Soviet Arctic. The ultimate in this development was nuclear-powered icebreakers with altogether eight ships built and a series of nineteen icebreaking cargo ships of the SA-15 type and a nuclear-powered Arctic LASH carrier. Although the ice conditions are to some extent similar in northern Canada and the northern Soviet Union, Canadian activities have been only a fraction of what was achieved by the Soviet Union.

After the collapse of the Soviet Union the northern Arctic area of course became part of Russia. For the development it is perhaps fortunate that all of the former Soviet Union Arctic today lies within one country, Russia and is not divided between several FSU countries, which would have made it more difficult to develop Arctic activities than is the case today.

The shipping activities in the Arctic have dramatically decreased in Russia since the collapse of the Soviet Union. The latest icebreakers for Russian Arctic activities are the nuclear-powered icebreakers Taymyr and Vaygach, which were ordered in 1985. Thus there has been a quiet period of ten years during which both icebreakers and icebreaking cargo ships are aging and the capacity of the fleet is decreasing.

Arctic marine operation in the Soviet Union and Russia has consisted predominantly of cargo shipping. There have been some offshore-related activities undertaken during the late 70's and 80's but this has been in areas which are icefree part of the year. Therefore, almost all operations have been undertaken in icefree conditions, and there is no real offshore experience in Russia yet.

3.2 Canada

Canada is the other country with great parts of northern waters covered by ice. The Manhattan project to transport crude oil from Alaska to the East coast of the United States through the Northwest passage was a kind of start-up of the consideration of real
commercial ice operation in the Canadian Arctic. As we all know, that project did not lead to anything beyond the experimental phase since a decision was made to transport oil by pipeline through Alaska to an icefree port. That project, however, awakened many Canadians and intensified activities to exploit areas in the Canadian Arctic.

Shipping activities have not developed beyond a relatively small scale compared to Russia, and marine transportation in the Canadian Arctic has been limited to three to four months a year. That operation has been supported by Canadian government-owned icebreakers and most of the cargo fleet used has been what we call ice strengthened ships only. The only exception is the 28,000 tdf ore/oil carrier MV Arctic, which was purpose built for Canadian Arctic operation as a government-supported experimental program. The ship has been in operation close to twenty years and has been retrofitted considerably over time. She has obviously performed relatively well technically although from the purely business perspective the ship has been a disaster. The extent of the disaster is not very well known as the losses have been hidden in the Federal Government budget in Canada. All things considered, MV Arctic has played an instrumental role in establishing the year after year seasonal ice operation in the Canadian Arctic with a gradual extension of the season over time.

In Canada on the other hand, there was a major growth of activities related to offshore oil and gas exploration, particularly in the Beaufort Sea. This took place between 1976 and about 1984. With the anticipation of an ever-increasing oil price, Canadian companies started a very dynamic operation with considerable support from the Federal Government of Canada. This led to a major technological breakthrough but was economically a disaster. Canadian oil companies and support shipping companies ordered a great amount of icebreaking supply ships and other support equipment as well as a number of offshore structures intended for either seasonal or year-around operation. Canadian companies gained a lot of valuable expertise and experience in the operation and have over time shared it with others in the business. The growth of Arctic offshore activities in Canada was very rapid and so was the collapse. Most of the equipment specially designed and built has been sold elsewhere, scrapped, or is presently laid-up. The whole exercise was a huge nisinvestment but in the field of technology, it produced a lot of useful experience, which will be over time applicable to operations in other areas. Although there were initially restrictions as regards the confidentiality and proprietary rights of the technology developed by the companies with government money, de facto, the results are available to every user through various channels, particularly through individuals who have moved around the industry after the collapse.

Today Canada's Arctic is almost as dormant as it was before the Manhattan project.

In the Gulf of St. Lawrence area, a traditional subarctic, shipping in ice operation is routine. The traffic volume is heavy and ice strengthened cargo ships are supported by government-owned icebreakers.

3.3 The United States

The development of icebreaker operations in the United States has been practically nonexistent during the 25-year period of review. Apart from some limited operation in the Great Lakes area, there are no other real commercial activities requiring shipping in ice.
Manhattan project, referred above, could of course have changed everything but unfortunately a pipeline was selected.

In the United States icebreakers and icebreaker operation are in reality limited to US Coast Guard operated ships, the function of which is predominantly typical Coast Guard tasks and not supporting commercial operations. All large icebreakers are being used for research, certain rescue and other Coast Guard functions as well as showing political and defense presence. Those icebreakers are being used both in the Arctic, Alaskan and Greenland waters as well as in the Antarctic waters.

As the matter of fact the United States has fewer sea going icebreakers in 1995 than it had in 1970.

3.4 The Baltic Sea

As regards icebreaker usage Finland and Sweden are very similar. In both countries the governments own and operate the icebreakers, which are being used to support merchant shipping in the northern part of the countries. The size of the fleet of icebreakers has not considerably increased during the review period but older ships have been replaced by new ones, which are much more efficient than the earlier ones. Merchant shipping in ice has expanded considerably in volume although the number of ships operating in ice has not necessarily increased as the size of the vessels has grown. The operation has become very well established regarding both ship technology and operational techniques, and as a result there is nothing dramatic in the operation anymore.

In the late 70s the question was still asked whether it makes sense for the countries to keep all the northern ports open every winter or should the merchandise be transported by other means.

The development has been steady and the operation in the northern Baltic is the best show piece in the world of well-established and managed commercial ice operation.

Ice conditions in the southern Baltic and the North Sea around southern Sweden, Germany and Norway are so marginal that these areas are not worth considering in this connection.

3.5 Antarctica

Operation in the Antarctic waters has expanded as a result of more countries becoming involved in Antarctic activities. There was a wave of Antarctic research and logistics vessels built in the mid to late 80s and overall activities have increased to some extent, but there has also been a reduction of activities as for example the Soviet Union/Russia has reduced the intensity of their activities considerably. Some Antarctic vessels have been called icebreakers but that word is not well in line with the terminology explanation in the beginning of this paper. The ships are typically intended for research and/or logistics support and they need icebreaking capability to support their primary functions. De facto they are icebreaking ships and some of them are so restrictively icecapable that they should be considered only ice strengthened.

A dominant feature in icebreaking ships of today is that most of the ships are government owned and operated. One exception was icebreaking ships built for the Canadian Arctic.
offshore exploration of the late 70's and mid 80's. Although these ships were privately owned, even they were in a way government ships as their construction was very heavily subsidized by Canadian taxpayers, in most cases approximately 80 per cent. In the Soviet Union of course everything, including merchant cargo ship operation, was government owned and managed. Thus we can make a very blunt conclusion that icebreaking ships even for commercial operation have been government owned or supported. The only real exceptions are certain Finnish dry cargo and liquid cargo ships designed and constructed for operation in the northern Baltic and for limned Arctic operation.

Although the picture is not as simple as discussed above because of the difference in systems in various countries we can however conclude that there has so far been very limited profitable, purely commercial marine operations in the Arctic or Antarctica.

All the development until 1995 has been at least heavily supported by the Governments with a few exceptions. This shows how far we actually may be from a real commercially feasible shipping operation in heavy ice in the high Arctic.

4. Technology of icebreaking ships

Breaking ice is not a meaningful purpose itself. Even ships, which we call icebreakers, are not really made only to break ice but to assist other ships going through ice fields.

Another fundamental issue is that when we talk about breaking ice, the actual breaking of ice, which means releasing of ice floes from a solid ice field, is only a part of the problem. Penetration through an ice field requires technologically much more than just breaking the ice.

Most of the ships, which we design and construct for ice operation have a function to fulfill in icefree conditions as well. The relative importance of icebreaking versus operation in icefree conditions vary greatly from ship to ship. Only pure single purpose icebreakers are really designed with only icebreaking in mind but even they have to be able to operate in icefree conditions and they have to fulfill all the regulations applicable to a seagoing ship of that size and functional capability.

Theoretically we could think of a ship which would be designed and constructed only for breaking and displacing ice. If there were no displacement, stability, performance etc requirements related to icefree operation a pure single purpose icebreaker would probably be very different from ships which we have in operation today. However this is only an academic and theoretical issue and does not come even close to reality as regards real ships designed and constructed for ice operation.

Since icebreakers have to also be able to operate in icefree seas, the design history reflects conventional open water ships with some added features to improve their ice going capability. We can say, although it might be somewhat simplified, that until late 60's all icebreaking ships were based on open water ship concepts with certain modifications to take into account the requirements to move through ice fields and break ice. Before the time of ice model tests in the laboratories the development of icebreaking technology and icebreaker technology was very primitive. It is amazing how poor the understanding of the physical mechanisms and the interaction between a ship and ice was even after the Second World War.
We will discuss in more detail three aspects related to icebreaker design, which are by far the most important fundamental technological features related to ice operation. These are:

- hull configuration
- strength of hull and appendages
- propulsive machinery

4.1. Hull configuration

Icebreaking ships built before 1970 were all downwards breaking and with what we call conventional icebreaking hull form. There was a basic understanding that icebreaking performance could be considerably affected by changing so-called hull angles. However, although some theoretical and model testing work had been done the material was so limited in 1970 that very fundamental basic and simple research was needed. One of the most instrumental research programs was completed by V.I. Kashtelyan in the Soviet Union and Dr. E. Enkst in Finland. The work of these two gentlemen laid the basis for progress in research.

In addition to the systematic, analytical and design work, testing the development has been somewhat impacted by inventions. Some of the inventions are based on systematic analysis and creative thinking on the basis of research results and some are just layman thinking without too much real technical understanding behind it.

The following list covers new ideas and inventions which presented something different from conventional downwards breaking bow:

- bow propellers, introduced before the Second World War
  - forefoot
  - landing craft bow (and a further fine-tuning in the form of so-called WAAS bow)
  - cylindrical bow
  - conical bow
  - bow with a flat stem
  - reamers
  - ice plow
  - ribs under the hull
- upwards breaking bow
- breaking by mechanical tools like a multitude of saws
- breaking by explosion

Some of the above have not been thoroughly tested as an analytical analysis has shown that their potential is marginal or non-existent, some have been tested, some others have been both tested and installed but not accepted in wide use and some of them have been thoroughly tested, accepted and present a real positive progress in icebreaker hull form development.

Bow propellers were used particularly in subarctic conditions, where no multi-year ice exists, on ships which were ordered as late as 1975. The history of bow propellers is interesting and also shows how primitive (he earlier technology development was initially), a tingle bow propeller was selected and installed to prevent ice accumulation in front of the
bow of the ship. This obviously worked at least reasonably well. The idea of an increase in bow propeller power led to the installation of two bow propellers, i.e., side propellers at bow. In the beginning of the 70’s it was very well established by model tests and also by full-scale measurements that the bossings of side propellers at bow increase ice resistance considerably. On the other hand, the operation of bow propellers eliminates most of that resistance. The net effect was in some ice conditions positive, in some negative. An overall assessment during the mid-70’s led to the elimination of bow propellers in future icebreakers. It is thus quite certain that we will not see bow propellers in future icebreakers.

The invention of the cylindrical bow and the Hat bow was the result of very systematic and intensive research. The research was initiated by the fact that scientists discovered that there is a considerable crushing of ice involved at the stem of a ship. Something had to be done to eliminate or minimize crushing, which considerably increases ice resistance. After analytical work and model testing it was discovered that by reconfiguring the stem area, crushing could be minimized considerably. This led to patenting of the two new bow forms: cylindrical stem and flat stem. The elimination of crushing was considered to be the driving force in the research although it was obvious that reconfiguring the stem area to a large cylinder or large flat area would lead to a considerable improvement overall. Thus the result of the research and benefits from the patented inventions turned out to be considerably broader than anticipated when initiating the research program.

It is quite well established now, at least between scientists in Russia and Finland, that a cylindrical form, or a flat form, or a modification of the cylindrical form like a conical type bow, would be an optimum solution for icebreaking ships. The detailed configuration of the cylindrical/flat stem/conical stem would very much depend on the type of ship, operation of the ship and ice conditions to be encountered by the ship. The best example is that the minimum width of the flat part of the flat stem would of course be very much dependent on ice conditions.

It is also obvious that a very large cylinder or a very large flat part would adversely affect the performance of an icebreaking ship in an open sea. Thus the result is a compromise which of course is always the case when designing any ship.

One typically has to compromise between performance in ice conditions and open water or even open water with heavy seas.

The other two inventions which have been taken into use for some ships are the WAAS bow and reamers. Both can be considered as technological tricks which are optimized for certain limited conditions only. It is well demonstrated that the WAAS bow is beneficial in certain types of level ice conditions. However, it has been quite extensively demonstrated by the Russians that the WAAS bow even with extensive fine tuning would not be an acceptable solution to an Arctic going icebreaker.

Reamers have predominantly been used in icebreakers, but even then reamers have disadvantages. Taking into consideration the variety of ice conditions and operational requirements in open water reamers are not recommended.

Both the WAAS bow and reamers are so-called one designer proposals and have not been accepted any wider in the industry. It is quite likely that we may have seen the end of the applications of reamers and the WAAS bow in the real world.
4.2 Hull strength

Icebreaking is a multitude of collisions between two solid pieces, namely the ship and ice. The first design criterion is that in the collision it is the ice which fails and breaks and not the ship.

Before 1970s the real forces on a ship's hull due to icebreaking and the ice failure forces were not well known. In this particular field research has been very intensified over the last twenty years. This has covered both analytical work, laboratory testing and most importantly testing in full scale with ice blocks and also with instrumented ships. As a result, the characteristics of sea ice and failure mechanisms are today adequately known. This has been an area where the role of classification societies has constantly increased. Traditionally, the role of classification societies has focused on the strength of the hull designed for whatever conditions. Therefore it was quite natural for the classification societies to become very active in this field.

The role of the classification societies is explained partly by the fact that the strength against ice forces is important not only for icebreaking ships but for all ice strengthened ships as well. Thus the market for the classification society role in this area is very wide.

Again quite considerable development was made in this area in the Baltic. The research in the beginning of 70's concentrated on structural failure cases which were fairly common on ice strengthened cargo ships. On icebreakers further development was made by reducing the loading conditions used in ships such as the Tarmio class ships to the successor Urho class ships. This was done quite successfully and as a result the optimum level has now been quite well established for the Baltic.

For the Arctic operation there is still considerable work needed. We have designed and constructed icebreakers, which operate decades without structural problems but presuming a ship is operated in a wise manner, but there is much work to be done through continued research in order to establish the optimum level with an accuracy similar to that achieved in the Baltic. There has been established an international panel with the objective to harmonize the Arctic rules.

4.3 Propulsion

The three basic requirements of the propulsion system for an icebreaking ship are:

- high enough thrust to facilitate penetration through desired ice fields
- structurally strong enough propulsion components to withstand ice forces
- high dynamic performance of the system to facilitate operation under external ice loads

Until the 60's the propulsion train of icebreakers and other icebreaking ships was designed primarily on the support of not too well documented full scale experience. In the late 60's systematic research was introduced in the field of propeller ice loads, strength of propulsion train elements and dynamic behavior of propulsion systems.

During the period of 1970 - 95 the knowledge of the propulsion - ice interaction has been increased dramatically through fundamental research related to ice loads, full scale
measurements of ice loads in actual operation and tests related to propulsion system behavior in various types of ice conditions. This work has been undertaken by shipyards and research institutions but also to some extent by propulsion train component suppliers. Designers with experience on real ice operations are today able to design propulsion systems for any ice conditions in the world.

Of course there is still a lot of room for further development and research particularly towards fine tuning of all components of the system, the system as a whole, the control system, and also towards new and innovative technical solutions.

In the following the latest history and status of various propulsion train components are discussed. The primary components are prime mover, transmission, and propeller.

The dominate prime mover in today's icebreakers is the medium speed diesel. It is interesting to note that in icebreakers designers jumped almost directly from reciprocating steam engines to medium speed diesels. Apart from a very few examples steam turbine machinery based on fossil fuel and slow speed diesel where never really accepted for icebreakers although these two machinery types were extensively used in non-ice vessels for a long period.

In the early 70's a nuclear reactor based steam turbine machinery looked very attractive to many people. There are many advantages of nuclear machinery for an icebreaker, which operates in remote arctics with limited refueling opportunities. I believe that many still believe that from the technological point of view nuclear machinery would be the ultimate and perfect solution to an Arctic icebreaker. However, in today's world of high environmental debate it seems very unlikely that we will see any further nuclear powered icebreakers built in the future. A total of nine nuclear powered icebreaking ships have been built, seven of them in the Soviet Union and two in Finland. All the ships have been and are in operation in the Russian Arctic and are de facto limited to operate in the Russian Arctic. Only one of these nine ships is a cargo carrying ship while all others are single purpose icebreakers.

Gas turbine has also been considered as a potential alternative for icebreaking ships because of their extremely beneficial machinery weight/power ratio. However, only one class of ships, namely the US Polar Star class, has been constructed with partial gas turbine machinery. The rapid development of medium speed diesels both as regards increase in power level, performance, efficiency and reliability has pretty well outplaced gas turbines in the icebreaker market.

Medium speed diesel is today solidly the preferred concept for icebreaking ships as the required power level has not gone beyond 50 megawatts.

As regards the transmission between the prime mover and propellers there are basically two alternatives, mechanical gear and electric. At the time reciprocating steam engines were used in icebreakers the transmission was not an issue as the rpm of the engine itself matched quite nicely with the requirement of a propeller. The transmission became a consideration as a result of the change from steam to diesel.

Because of the torque requirements an electric transmission was considered superior to diesel machinery with a mechanical gear. Electric transmission with a DC-DC system was accepted in spite of the relatively high efficiency losses in the transmission.
In the beginning of the 70s the comparison of geared and electric transmissions gained interest primarily because electric transmission was considered to be fairly expensive to construct and also expensive in operation as a result of efficiency losses in the transmission. The disadvantage of a mechanical transmission as regards torque characteristics was partially offset by installing additional inertia to the propeller shaft to secure higher torque figures for at least a short time in case a severe ice loading.

In recent years there has been a tremendous development in the electric transmission side as a result of the change from DC-VC to AC-AC transmission systems. Cost of an electric transmission system has become thus closer to being competitive with a mechanical transmission system, efficiency was increased by some five percent and weight was considerably reduced.

Initially mechanical transmission for icebreaking ships was considered to be a feasible solution only on small vessels but increased knowledge and development of the systems especially the CP-propeller have led to mechanical systems being considered feasible on even larger vessels and severe, if not extreme, ice conditions.

The debate on the electric versus mechanical transmission system is still underway today but as a result of considerable scientific work the discussion has become very intelligent compared to that in earlier times.

As a curiosity in early 80s a hydraulic transmission system was also under discussion but did not find any real applications, mainly because of complexity and low efficiency.

As a result of controllable pitch (CP) propellers having become the dominant solution for sophisticated vessels overall versus fixed pitch propellers (FP) the debate on CP versus FP spilled over onto icebreaking ships. Traditionally of course all the icebreaking ships had been equipped with FP propellers. In early years, i.e. beginning of 70s conservatively oriented people considered CP to be positively unacceptable for icebreaking ships without realizing the potential of technical development.

The first icebreaking ships with CP propellers were the three cargo ships of the Finncarrier class, the first ship delivered in 1969. This was at a time the ice loads on propellers and ice loading mechanism on propellers were not too well known and therefore some difficulties were experienced. However, as a result of the intensified ice loading versus propeller investigation the CP propellers were developed in less than ten years to be a feasible solution to icebreaking cargo ships and to smaller size icebreakers.

Since a CP propeller inherently brings a higher level of propulsion maneuverability it affects considerably the discussion on the transmission system to be selected. Replacing electric transmission by mechanical transmission was only possible after the technical feasibility of CP propellers on icebreakers was comprehensively demonstrated.

Another fairly heated issue has been whether to install propeller nozzles on icebreaking ships. There is no simple solution to that. There are two partially contradicting issues. A nozzle around the propeller physically protects a propeller against extreme ice loads, although the situation is not as categorically clear as the statement would indicate. The nozzle unquestionably increases the thrust produced by a certain power plant compared to
an unnozzled propeller. The downside is the risk for the nozzled propeller to get blocked by ice, which could produce a very difficult operational situation in heavy conditions.

There does not seem to be an all encompassing solution of nozzle versus non-nozzle. The discussion has been overheated as certain specialists who are for a nozzle have tried to present the nozzle as the feasible solution to all icebreaking ships and some other specialists who have been against the nozzle have again been categorically against nozzles on icebreaking ships. Because of this polarization the discussion has been less than intelligent.

We however know today much more about the ice propeller nozzle interface than 25 years ago. It would be safe to say that the benefits of a nozzle can be safely obtained in certain types of ships in certain operation and in certain ice conditions while it would be advisable to install a propeller without nozzle in certain extreme conditions. This is an area where significant further research is justified.

Only propulsion systems based on a conventional horizontal shaft line were discussed above. The recent development has created new concepts for icebreaking ships. One of these is an azimuthing propulsor unit, the major benefit of which is its superior maneuverability and also that a separate rudder does not have to be installed.

There are two versions of this concept in the market.

- a mechanical Z-drive system with a fairly complex set of mechanical components
- an Azipod system, which is based on an electric motor installed in the hub (pod)

The first system has been installed in icebreaking ships with power levels of about 7 MW/propeller. The latter system is being used in icebreaking ships with 11.4 MW/propeller. Thus the Azipod system is clearly much more advanced for icebreaking ships than the mechanical Z-drive system.

It is also fairly evident that a mechanical system is becoming unfeasibly clumsy and expensive as the power increases while Azipod is becoming more competitive in cost the higher the power level without any disadvantages related to technology. At the moment the Azipod propulsion is available up to 20 MW power per unit.

The development of Z-drive and Azipod for icebreaking ships is quite recent. There has, however, been enough work done so that we can conclude that the market share of Z-drive/Azipod will increase in the future and perhaps at least as regards Azipod will dominate the market of icebreaking ships in the future.

This will, however, take a fairly long time as the market of icebreaking ships is very slow moving today.

Other technical features

One major area of progress achieved in the beginning of the 70's is in reduction of friction between ice and a ship's hull. The scientists of course understood even at earlier times that friction a a factor in resistance of ships in ice. However, it was not until 1972 that the magnitude and importance of friction on the performance of icebreaking ships was fully understood.
understood. An accelerated research program was then initiated in Finland which led to two new solutions to improve the operation in ice.

- a solvent free epoxy paint (trade mark INERTA 160)
- a stainless steel belt on the ship's hull, particularly that part of the hull which is mostly in contact with ice.

During the 25 years period under discussion major progress has been achieved. Today almost all icebreaking ships are painted by Inerta 160 and some heavy icebreaking ships intended for extreme ice conditions have been, for at least part of the hull, covered by stainless steel plate. To reduce the cost of this latter concept we use a plate where a thin stainless steel belt is clad on a black steel plate instead of having a 25 - 45 mm thick all stainless steel plate.

Another area worth discussing is various auxiliary systems intended to improve the performance of ships in ice. This has been an area for wild creativity. The only system which gained a wide acceptance is the air bubbling system developed by Wartsila and marketed as Wartsila Air Bubbling System. This system was developed in the late 60's and the system was installed in about 80 vessels. For half of them the system was installed by Wartsila shipyards in Finland for ships constructed by Wartsila and for the remaining 40 vessels Wartsila sold license to either ship owners or shipyards. That system was considered very advantageous during the 70's and 80's. However, it has lost its popularity which is primarily due to the fact that improved friction conditions between ship and hull due to Inerta 160 and stainless steel have reduced the importance of an auxiliary device.

On other auxiliary system, which has been installed is the water lubricating system, in which water is pumped onto ice in front of the ship. There are, however, only three ships equipped with this system and we have not seen any credible documentation which would prove the overall feasibility of such a system. Heeling system is a standard device on most single purpose icebreakers and a considered state-of-art on Baltic as well as on most Arctic icebreakers.

5. Summary and Future

5.1 Market

The market of icebreaking ships experienced a considerable upturn, stagnation and even a down turn during the 25 years period under consideration. The growth was remarkable compared to times before 1970.

The market is almost zero today and there are only some very occasional newbuilding programs under consideration.

A new growth is waiting for the development of Arctic oil and gas programs in Russia to be organized. It is very difficult to predict how long this will take since everything is moving very slowly in Russia today.

Opening up of business opportunities is more likely in the oil and gas related sector than in year-around marine transportation through the north-east passage. There is today a lot of fundamental technical work underway in regard to the north-east passage.
this work is not yet backed up by credible business people like ship owners. It consists only of engineering and consulting work funded by governments. Most shipowners approached so far are not presently interested since they do see regular use of the north-east passage as feasible.

Arctic Canada represents a major challenge for icebreaking ships in the future. However, it is impossible to predict any time frame as it is very much dependent on global development in energy prices, which in turn are also dependent on environmental issues, energy saving culture development, political issues, etc. The Arctic development in Canada and US has dried up so completely that even the resources capable and experienced of development and operation have been lost.

Activities in subarctic areas like the Baltic and the Gulf of St. Lawrence will continue and expand and become well established almost routine operations.

Antarctica has never represented a major market and will not represent one for the foreseeable future of several decades.

Exclusive passenger cruising on converted icebreakers is an emerging business both in the Arctic and Antarctica.

5.2 Technology

In our opinion the most dramatic technological achievements, which have a considerable economic impact on commercial ice operation during the period of 1970-95 are the following:

- Hull form improvement, presented by the flat stem, cylindrical/conical stem or a mixture of these features.
- Accurate knowledge on ice loads on structures enabling optimum structural design for subarctic conditions and safe structural designs for Arctic conditions without excessive margins.
- Geared transmission to icebreakers.
- CP propellers for icebreakers.
- Use of a nozzle in icebreakers in certain conditions.
- Coating ships'side shell with ice-resisting and low friction materials.
- Introduction and demonstration of azimuth propulsion units for icebreakers.
- Air bubbling system, the significance of which disappeared after a successful usage of 20 years.

Overall we can state that the technology of icebreaking ships has been raised to a considerably higher level than it was in 1970.

The market of icebreaking ships does not today justify very intensive development work. However, research is being undertaken at lower intensity to utilize research opportunities in connection with ship operations and to maintain skillful resources for improved market.

There is every reason to be optimistic with regard to the acceleration of both market and technology activities in the Arctic but it is very difficult to predict anything about timing of such acceleration.
We, who have played an active role in the icebreaking ship market and technology during the period of 1970 to 1995, can be proud of our achievements as the work has resulted in solid progress which form a sound basis for the continuation of the work when the need again arises.

### Icebreakers and other icebreaking ships in use in 1970

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<tr>
<th>Year</th>
<th>Name/Class</th>
<th>Flag</th>
<th>No. of ships</th>
<th>Length</th>
<th>Beam</th>
<th>Draught</th>
<th>Propul-ion</th>
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70. Harri Eronen  
71. Samuel J. DeFranco  
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следует читать: V.N. Moltchanov