Northern Sea Route Reconnaissance Study
A Summary of Icebreaking Technology

Devinder S. Sodhi

June 1995

Abstract

Since the advent of steam power, icebreakers have been built to navigate in ice-covered waters. The hull forms of early icebreakers were merely an adaptation of open water hull shapes, by sloping bow angles more to create vertical forces for breaking ice in bending. However, these bow forms were found to be unsuitable for sea-going vessels because they push broken ice ahead of them. This experience led to construction of all sea-going vessels with wedge-shaped bows from 1901 to 1979. With the introduction of low-friction coatings and the water-deluge system, it is now possible to operate ships with blunt bows efficiently in broken ice. New developments in marine propulsion technology have also been incorporated to obtain better icebreaking efficiency and performance. Both fixed-pitch and controllable-pitch propellers are in use. Nozzles surrounding the propellers are also used to increase the thrust and to reduce ice–propeller interaction. Electrical and mechanical transmission systems have been used in icebreakers to improve the characteristics of the propulsion system. Though many types of prime movers are used in icebreakers, medium-speed diesel engines are the most popular because of their overall economy and reliability. Appendix A is a description of the Russian icebreaker Yamal, which is one of the largest and most powerful icebreakers of the world today. Appendix B contains an inventory of existing ships that are capable of navigating in at least 0.3-m-thick ice. Some of the present icebreakers are capable of navigating almost anywhere in the ice-covered waters of the Arctic and the Antarctic, and multi-purpose icebreakers have been built to operate not only in ice during the winter but also in open water doing other tasks during the summer. With sufficient displacement, power, navigation equipment, and auxiliary systems, future icebreakers that can operate independently year-round in the Arctic and the Antarctic are well within the known technology and operational experience.

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of Engineers**
Cold Regions Research &
Engineering Laboratory

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PREFACE

This report was written by Dr. Devinder S. Sodhi, Research Engineer, Ice Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory. It represents a part of the investigations supporting a Reconnaissance Study of the Northern Sea Route. The project was funded by the U.S. Army Engineer District, Alaska. Dr. Orson Smith was the Project Manager.

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CONTENTS

ILLUSTRATIONS

TABLES

Northern Sea Route Reconnaissance Study
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DEVINDER S. SODHI

INTRODUCTION

In the last four to five decades, many developments in icebreaking technology have taken place through the application of modern marine technology to the design and the operation of polar ships. Innovative ideas have been implemented to improve the propulsion systems and to reduce the resistance encountered during icebreaking. Present navigation and information systems (e.g., ice maps, satellite images, etc.) aboard polar ships enable navigators to identify ice features along the transit route in near real time and to chart a tactical course. As a result of this, it is possible to travel by ships to remote polar regions that were thought to be unreachable only a few years ago. Many nations have contributed to this development by designing and building polar ships and by launching voyages to various regions of the Arctic and the Antarctic. Some of the landmark voyages during the last four decades are listed in Table 1 (Brigham 1992). Recently, Russian nuclear-powered icebreakers have regularly traveled to the North Pole. In August of 1994, the U.S. icebreaker *Polar Sea*, the Canadian icebreaker *Louis S. St. Laurent* and the Russian nuclear icebreaker *Yamal* (App. A) met at the North Pole (Fig. 1).

The impetus behind these technological advances has come from:
1. The exploration for natural resources around the Arctic Basin.
2. The development of the Northern Sea Route by the former Soviet Union, as an integral part of development of the entire Russian Arctic.
3. The need for multi-mission ships for the transportation of personnel, logistics and marine research in the Antarctic.

Although exploration for hydrocarbon resources in the southern Beaufort Sea has almost stopped, plans are being discussed for developments in the offshore areas of the Russian Arctic to produce hydrocarbon resources and to transport them to world markets. Future shipments of these resources will have significant effects on the development of the Northern Sea Route.

From the perspectives of a master mariner, the performance of icebreakers depends on the construction limitations of the vessels and the skills in ice navigation of their captains (Toomey 1994). Although the technological improvements incorporated in the design and construction of an icebreaker help to increase its performance in ice, it is essential to have a skilled captain and crew operating the ship to exploit these advantages to the maximum extent. Therefore, the training and the experience of the crew operating an icebreaker are important elements in its performance. A knowledgeable, skilled captain, supported by extensive information, can prevent or quickly overcome many difficulties along a route.

Early history

Johansson et al. (1994) have given an account of the early history of icebreaking ships. Breaking ice with ships was not possible before the advent of steam power. One of the earliest icebreakers, named *Norwich*, was introduced in 1836 on the Hudson River. She had paddle wheels for propulsion and was very effective in breaking ice, remaining in service for 87 years.

By the end of the nineteenth century, only fixed-pitch, screw-type propellers driven with steam power were installed on new icebreakers. Early icebreakers were not powerful, and the hull form was basically adapted from open water hull shapes by sloping the bow angles more to create a vertical force to break the ice in bending. Many innovative designs were proposed and built to increase icebreaking efficiency. For instance, the highly suc-

Table 1. Selected important icebreaking voyages in recent years (after Brigham 1992).

Polar ship/flag	Time of year	Route/location	Significance
Lenin USSR	Summer 1960	Northern Sea Route	World's first nuclear surface ship commences icebreaking escort duties
Manhattan USA	Autumn 1969	Northwest Passage	Experimental voyages to test the feasibility of commercial tankers in the Arctic
Louis S. St.Laurent and *Canmar Explorer II* Canada	Aug 1976	Northwest Passage	Successful escort of a drill ship from the Atlantic to the Canadian Beaufort Sea
Arktika USSR	Aug 1977	Murmansk to the North Pole and return	First surface ship to reach the geographic North Pole (17 Aug)
Sibir' and *Kapitan Myshevskiy* USSR	May–Jun 1978	Northern Sea Route (north of Novosibirskiy Islands)	First high-latitude "trans-Arctic" ice escort
Polar icebreakers and icebreaking carriers USSR	Navigation season 1978–79	Barents and Kara seas	First successful year-round navigation from Murmansk to Dudinka on the Yenisey River
Polar Star and *Polar Sea* USA	1979–86	Bering, Chukchi, and Beaufort seas	Arctic marine transportation ("trafficability") studies around Alaska
Polar Sea USA	Jan–Mar 1981	Bering Sea to Beaufort Sea	First winter transit to Pt. Barrow, Alaska
Polar Star USA	Dec 1982–Mar 1983	Antarctica	First high-latitude (above 60°S) circumnavigation of Antarctica in modern times
Leonid Brezhnev and 12 other icebreakers USSR	Oct–Nov 1983	North coast of Chukotka, Siberia	Rescue of 50 cargo ships trapped in ice
Arctic Canada	Aug 1985	Bent Horn, Cameron Island	First cargo of crude oil from the Canadian Arctic
Vladivostok and *Somov* USSR	Jun–Sep 1985?	Near Russkaya Station, Hobbs Coast, Antarctica	Rescue of Soviet Antarctic Expedition flagship drifting in heavy ice
Three SA-15 icebreaking carriers USSR	Nov–Dec 1985	Northern Sea Route	Experimental navigation season extension with sailings from Vancouver to Arkangel'sk
Icebird FRG	Fall 1985– Summer 1986	Australian Antarctic stations and Japan to Prudhoe Bay, Alaska	Bipolar resupply operations to Antarctica and Prudhoe Bay
Polarstern FRG	Jul–Aug 1986	Weddell Sea, Antarctica	Winter oceanographic operations
Sibir' USSR	May–Jun 1987	Central Arctic Basin	Evacuate drift station 27 and establish drift station 29; second surface ship to reach the geographic North Pole (25 May)
SA-15 icebreaking carriers USSR	Summer 1989	Europe to Japan via the Northern Sea Route	Soviet arctic carriers under charter to Western shippers for commmercial voyages across the top of the Soviet Union
Rossiya USSR	Aug 1990	Central Arctic Basin	Transit to the North Pole (8 Aug) with Western tourists aboard
Arctic Canada	Jun 1991	Northwest Passage to the Polaris Mine, Little Cornwallis Island	Earliest seasonal surface ship transit in eastern reaches of the Northwest Passages; mine reached 23 Jun
Sovetskiy Soyuz USSR	Jul–Sep 1991	Central Arctic Basin and Northern Sea Route	Transit to the North Pole and along the Northern Sea Route with Western tourists
Oden and *Polarstern* Sweden and FRG	Aug 1991	Central Arctic Basin	International Arctic Ocean Expedition; reached the North Pole on 7 Sep
Sovetskiy Soyuz Russia	Jul and Aug 1992	Central Arctic Basin	Reached the North Pole on 13 Jul and 23 Aug
Yamal Russia	Jul and Aug 1993	Central Arctic Basin	Reached the North Pole three times on 13 Jul, 8 and 30 Aug
Yamal and *Kapitan Branitsyn* Russia	Jul 1994	Central Arctic Basin	Reached the North Pole on 21 Jul
Yamal Russia	Aug 1994	Central Arctic Basin	Reached the North Pole on 5 and 20 Aug
Louis S. St. Laurent and *Polar Sea* Canada and USA	Aug 1994	Trans-Arctic Ocean Bering Strait to Svalbard	Reached the North Pole on 22 Aug; encountered *Yamal* at the North Pole

a. Near the North Pole.

b. View from Yamal (Polar Sea *is last in line).*

Figure 1. The Russian icebreaker Yamal, *the Canadian icebreaker* Louis S. St. Laurent, *and the U.S. icebreaker* Polar Sea *during the expedition to the North Pole in August of 1994 (photos courtesy W.B. Tucker, III).*

U.S., Canada, Japan, and Federal Republic of Germany

Former Soviet Union and Finland

Nuclear = N
Gas Turbine = GT
Steam Turbo-Electric = STE
Diesel-Electric = DE
Geared Diesel = GD

1955
1960
1965
1970
1975
1980
1985
1990
1995

GLACIER (US) DE. Deep-Draft Icebreaker

JOHN A. MACDONALD (Can) DE. Deep-Draft Icebreaker

1st Ice Model Tank (Leningrad)

LENIN (USSR) 1st Nuclear Surface Ship

MOSKVA (USSR) Wartsila. DE. Deep-draft Polar Design

Wartsila's Ice Model Tank (Helsinki)

LOUIS ST. LAURENT (Can) STE. Deep-Draft Icebreaker

MANHATTAN (US) Icebreaking Tanker, White Bow

POLAR STAR (US) GT & DE. Deep-Draft Icebreaker with Controllable-Pitch Propellers

1st US Ice Model Tank (Arctec, Columbia, Md.)

M/V ARCTIC (Can) GD. Icebreaking Cargo Ship

PIERRE RADISSON (Can) DE. River and Arctic Icebreaker Design

CANMAR KIGORIAK (Can) GD. Spoon Bow, Beaufort Sea Icebreaker

SHIRASE (Japan) DE. Antarctic Icebreaker

POLARSTERN (FRG) GD. Polar Research & Supply Icebreaker

POLAR-Class (US) Operate with Real-Time Satellite Imagery (APT)

M/V ICEBIRD (FRG) GD. Icebreaking Polar Resupply Ship

MUDYUG (USSR) GD. Converted to Thyssen-Waas Bow. FRG Design

ODEN (Sweden) DE

FINNICA (Finland) DE, Multi-purpose Ship with 360° Azimuth Propulsion

KAPITAN SOROKIN (USSR) DE, Converted to Thyssen-Waas Bow

KAPITAN NIKOLAYEV (USSR) DE, Converted to Conical Bow

NORDICA (Finland) DE

SEVMORPUT (USSR) N. Icebreaking LASH Ship

KAPITAN EVDOKIMOV (USSR) Wartsila. DE. Extreme Shallow-Draft River Design

KOSMOS-1500 Satellite (USSR) Launched with first Aperture Imaging Radar

NORILSK (USSR) Wartsila & Valmet. GD.

1st SA-15 Icebreaking Cargo Ship

KAPITAN CHECHKIN (USSR) Wartsila. DE. Shallow-Draft River Icebreaker Design

KAPITAN SOROKIN (USSR) Wartsila. DE. Shallow-Draft Polar Icebreaker Design

ARKTIKA (USSR) N. World's Most Powerful Icebreaker (75,000 SHP)

ERMAK (USSR) Wartsila. DE. Deep-Draft Icebreaker.

Figure 2. Significant events in the development of polar ship technology since 1955 (after Brigham 1987).

4

Soviet Nuclear Ship Technology

Nuclear Classes	LENIN Deep-draft Polar 33 MW (44, 000 shp)	ARKTIKA Deep-draft Polar 56 MW (75, 000 shp)	ROSSIYA Deep-draft Polar 56 MW (75, 000 shp)	TAYMYR Nuclear Shallow-draft Polar 39 MW (52, 000 shp)
	1. Lenin (1959)	*1. Arktika (1975)* *2. Sibir' (1977)*	*1. Rossiya (1985)* *2. Sovetskiy Soyuz (1990)* *3. Yamal (1992)*	*1. Taymyr (1989)* *2. Vaygach (1990)*

Finnish Shipbuilding Technology

Diesel–Electric Classes	MOSKVA Deep-draft Polar 16 MW (22, 000 shp)	YERMAK Deep-draft Polar 27 MW (36, 000 shp)	KAPITAN SOROKIN / KAPITAN DRANITSYN Shallow-draft Polar 16 MW (22, 000 shp)
	1. Moskva (1959) *2. Leningrad (1960)* *3. Kiev (1965)* *4. Murmansk (1968)* *5. Vladivostok (1969)*	*1. Yermak (1974)* *2. Admiral Makarov (1975)* *3. Krasin (1976)*	*1. Kapitan Sorokin (1977)* *1. Kapitan Dranitsyn (1980)* *2. Kapitan Nikolayev (1978)* *2. Kapitan Khlebnikov (1981)*

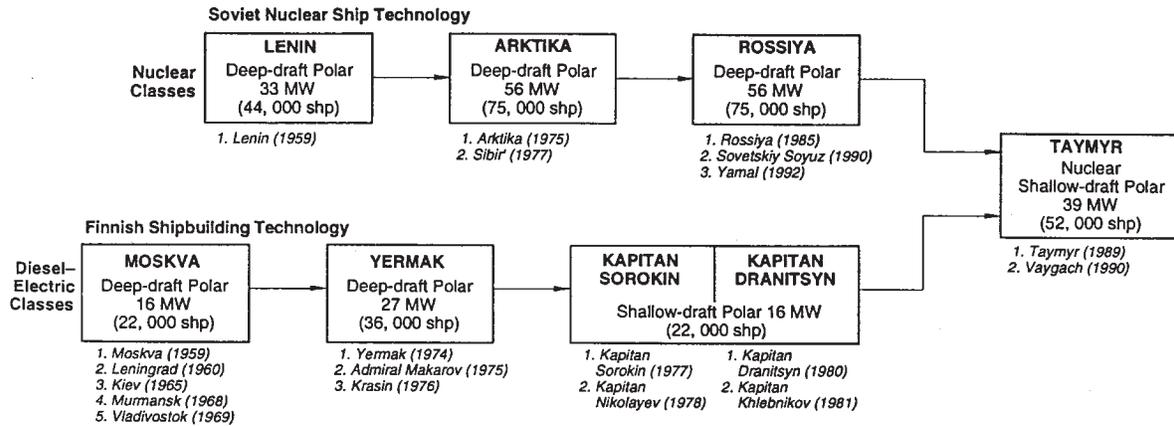*Figure 3. Design evolution of Russian polar icebreakers (after Brigham 1991).*

cessful "spoon-shaped" bow was first proposed and built by Ferdinand Steinhaus of Hamburg in 1871. In 1892, Weedermann invented and patented a device to be placed in front of a ship having a bow not suitable for icebreaking on its own. These devices are still used on Dutch rivers and canals.

By 1900, it was well understood that, while ships with blunt bows are efficient in breaking level ice in sheltered areas, such as rivers, lakes and other protected areas, their performance in rubble ice is poor because they have a tendency to push broken ice ahead of themselves. On the other hand, ships with wedge-shaped bows and sharp stems did not have any tendency to push rubble ice. This experience led to all sea-going ships built between 1901 and 1979 having a wedged-shaped bow and a sharp stem (Johansson et al. 1994). Over the years, the wedge-shaped bows became known as "conventional" bows, and the other shapes as "unconventional" bows.

The development of the bow form remained stagnant in the early and middle part of the 20th century (Johansson et al. 1994). This can be attributed partly to other priorities caused by the two World Wars and by the slowdown of economic acivity during the large-scale recession of the 1930s. Despite this stagnancy in bow design, other innovations were introduced during this time. The Russian icebreaker *Yermak*, built in 1899 and fitted with propulsive machinery of 7.46 MW (10,000 hp), had considerable effect on the icebreaking technology at the turn of this century by becoming a pioneer in many untested offshore areas. In 1933, diesel-electric propulsion was introduced on the Swedish icebreaker *Ymer*. In 1947, twin bow propellers were introduced on the Canadian icebreaking ferry *Abgeweit*. (However, the use of bow propellers has now been discontinued because of their interference with ice.)

Recent history

Figure 2 shows a summary of significant advances in the polar ship technology during the past four decades, as outlined by Brigham (1987), made by Finland and the former Soviet Union, and by the U.S., Canada, Germany and Japan. Together, Finland and the Soviet Union have made enormous contributions to the development of polar ships.

The Soviet Union first used nuclear technology to power the icebreaker *Lenin*, which was built in 1959 with a propulsive power of 29 MW (39,000 hp). The Finnish shipbuilder, Wärtsilä Shipyard (now Kværner Masa-Yards), built many icebreakers for the Soviet Union and created extensive design evolution during the years of the development of conventionally powered icebreakers. Recently, these two technologies have merged, as shown in Figure 3, to develop the *Taymyr*-class (Fig. 4), shallow-draft polar icebreakers built in Helsinki with Soviet nuclear propulsion systems installed in St. Petersburg.

Similarly, developments in the U.S. and Canada have contributed to changes in key areas of icebreaking technology (e.g., hull and bow form, gas turbines, and controllable-pitch propellers). In 1969, the U.S. modified tanker *Manhattan* had tenfold the displacement of earlier icebreakers, giving her great ramming capability. In the early 1980's, modern hull and propulsion technologies were also applied to Antarctic ships (e.g., Japan's *Shirase,* and Germany's *Polarstern*). The bows of three icebreakers were converted to the newly developed Thyssen-Waas bow: *Max Waldeck* in 1980, *Mudyug* in 1986 and *Kapitan Sorokin* in 1991. The results of full-scale trials in open water and in ice indicate that this change in the bow of *Mudyug* has increased her icebreaking capability in level ice at reduced power requirements (Milano 1987). However, there were problems with wave slam-
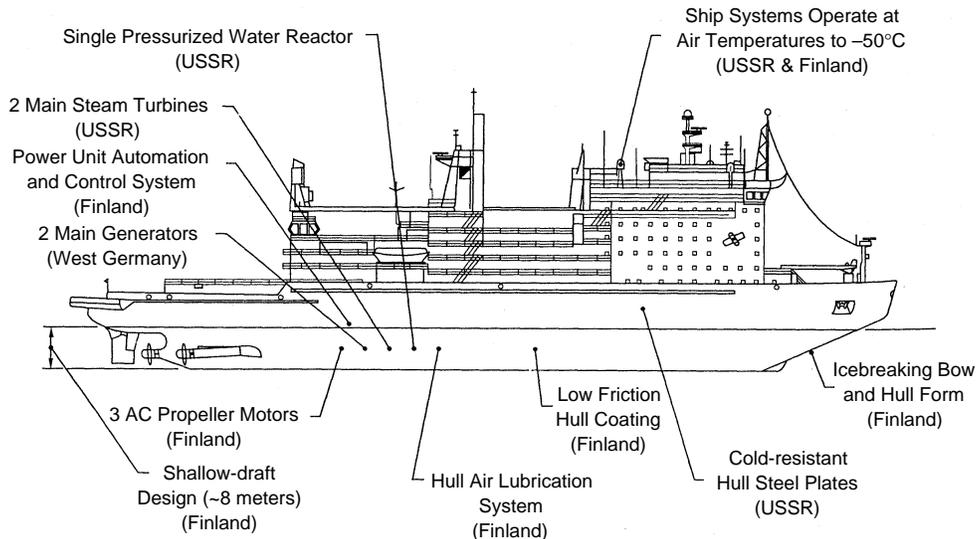
Single Pressurized Water Reactor
(USSR)

2 Main Steam Turbines
(USSR)

Power Unit Automation
and Control System
(Finland)

2 Main Generators
(West Germany)

Ship Systems Operate at
Air Temperatures to –50°C
(USSR & Finland)

3 AC Propeller Motors
(Finland)

Shallow-draft
Design (~8 meters)
(Finland)

Hull Air Lubrication
System
(Finland)

Low Friction
Hull Coating
(Finland)

Cold-resistant
Hull Steel Plates
(USSR)

Icebreaking Bow
and Hull Form
(Finland)

Figure 4. Taymyr-*class shallow-draft nuclear icebreaker (after Brigham 1991).*

ming in open water operations during high seas, and with the front of the ship pushing rubble ice (Ierusalimsky and Tsoy 1994).

In 1979, the Canadian icebreaker *Kigoriak* was built with a spoon-shaped bow for operations in the Beaufort Sea. Extensive full-scale experience indicated that even this modern version of the spoon-shaped bow was not immune to the ice-pushing problem. However, these problems were solved by using epoxy paint and a water-deluge system to reduce friction between the broken ice pieces and the hull. The water-deluge system lifts several tons of water every second and pours it on top of the ice in front of the bow. This helps to move the ice pieces past the ship by submerging them. In the early 1980s, several ships in Canada were built with spoon-shaped bows. Some of the recent icebreakers built in Europe have also been built with these bows, e.g., the Swedish icebreaker *Oden,* built in 1989, the Russian icebreaker *Kapitan Nikolayev,* converted in 1990, and the Finnish ice-breakers *Finnica* and *Nordica,* built in 1993 and 1994.

With the introduction of low-friction coatings and auxiliary systems, the capabilities of present icebreakers are greatly enhanced so that they can make steady progress in all types of ice conditions. With sufficient displacement, power and auxiliary systems, future icebreakers that can operate independently year-round in the Arctic are well within the known technology and operational experience (Keinonen 1994). As in the past, the construction of future icebreakers and icebreaking cargo ships will be closely linked to economic conditions and pressures. Choices between dedicated icebreaking ships and multi-purpose ships will be dictated by the needs of future developments and trade.

INVENTORY OF ICEBREAKING SHIPS

Icebreaking ships that will be built in the future may have their designs based on the present state of icebreaking technology and may also incorporate innovative developments in many areas of marine technology. Past experience can help designers avoid mistakes, but accepting the present status too rigidly can also discourage them from innovation. Improvements in the design of ice-breakers should result from a full understanding of the current status of icebreaking technology.

Information on most of the icebreaking ships in the world is given in the appendix of the review paper by Dick and Laframboise (1989), and an updated and a modified version of this list is also included in the appendix of a report by Mulherin et al. (1994). The latter database contains information on icebreakers and icebreaking cargo ships from the following countries: Argentina, Canada, Denmark, Finland, Japan, Sweden, United Kingdom, Russia (or former Soviet Union), U.S. and Germany.

An inventory of all ships that are capable of navigation in at least 0.3-m- (1-ft-) thick ice has been prepared for this study. This information has been assembled in an electronic database and is also presented in Appendix B. The database con-

tains technical and other forms of information on each series of ships. Technical information consists of length, beam, depth, draft, deadweight, displacement, propulsion machinery, nominal speed, bow shape, propulsion power, fuel capacity, fuel rate, etc. Non-technical information consists of the name (or former name), names of sister ships, ownership, shipyard and year of construction, home port, ice classification, etc.

SIZES AND DIMENSIONS

The main dimensions of a polar ship are its length, beam width and depth. The draft is the depth of the ship's keel below the waterline, whereas the depth is the distance between the keel and the deck. The depth of water in which a ship can operate without touching bottom depends on the draft. Figure 5a shows plots of the dimensions of icebreakers (cargo ships not included) as compiled by Dick and Laframboise (1989), whereas Figure 5b shows the dimensions of all ships as compiled in the database given in Appendix B. The scatter in the plot of data in Figure 5b is greater than that in Figure 5a, because ships listed in Appendix B are not only icebreakers but also other ships having some icebreaking capability. The trends of the lines shown in Figure 5a pertain only to icebreakers, whereas the lines of best fit shown in Figure 5b pertain to the data on vessels listed in Appendix B.

Beam
In Figure 5a, the mean length-to-beam ratio of icebreakers varies from 3.6 to 4.6 for lengths from 40 to 140 m respectively. North American vessels are narrower than those from Finland, Sweden and Russia. This may be attributed to the practice of convoy escort used in the Baltic Sea and Russian Arctic. The line of best fit in Figure 5b has an intercept of 6.7 m and a slope of 0.102 m/m.

Depth
In Figure 5a, the mean length-to-depth ratio of icebreakers varies from 8.9 to 8.2 for lengths from 40 to 140 m respectively. This ratio is high for supply vessels and low for conventional icebreakers. The line of best fit in Figure 5b has an intercept of 0.6 m and a slope of 0.08 m/m.

Draft
In Figure 5a, the mean length-to-draft ratio of icebreakers varies from 11.4 to 12.2 for lengths from
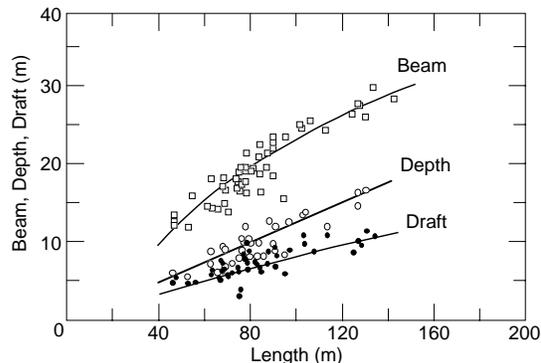
a. Icebreakers (cargo ships not included) (after Dick and Laframboise 1989).
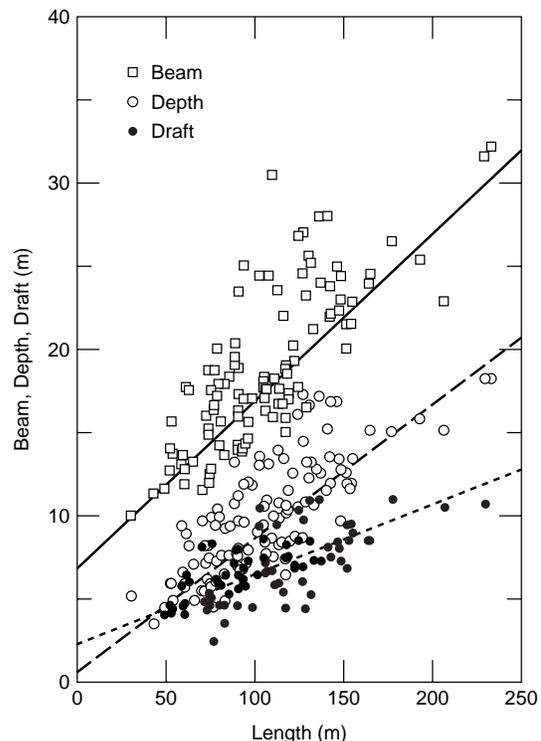
b. All vessels included in the inventory of ships listed in Appendix B.

Figure 5. Dimensions of vessels.

40 to 140 m respectively. Draft, like other dimensions, is usually defined by the operating requirements of the ship. The line of best fit in Figure 5b has an intercept of 2.2 m and a slope of 0.042 m/m.

Maximum deadweight
Figure 6 shows a plot of deadweight at maximum draft vs. the overall length of the vessels listed in Appendix B. The curve shown in Figure 6 is a best fit quadratic curve having the following equation

$$D_{\max} = -4545 + 18.81\,L + 0.61\,L^2$$

where $D_{\max}$ is the maximum deadweight and L is the overall length of a vessel.

HULL FORMS

The primary consideration for the choice of hull form of an icebreaking ship is the lowest power required to make progress in ice. Power in open water, maneuvering and protection of propellers from ice are some of the secondary considerations. The following are factors that need to be considered while selecting a hull form (Dick and Laframboise 1989):

1. Performance in ice of all types.
2. Performance in open calm water.
3. Performance in heavy weather in open water.
4. Maneuvering capability.
5. Overall dimensions.
6. Ease and cost of construction.
7. Ease of repair and type of ship (e.g., cargo, icebreaker, etc.).

Because some of the objectives listed above are in conflict with each other, the best hull shape is one that takes into account the overall operations of a vessel. Most of the sea-going icebreaking ships have been constructed with conventional bows. However, there have been a few departures from this trend in the recent past, and a few ships have been built with unconventional bows out of par-

ticular considerations of costs, icebreaking efficiency or maneuvering. Auxiliary systems have to be furnished so that a ship with an unconventional bow can operate effectively in rubble ice as well as in level ice.

Bow shape

The bow shape of an icebreaker is characterized by five basic design features, shown in Figure 7. Flare angles contribute to the efficiency of icebreaking and ice block submergence, whereas waterline angles contribute to clearing efficiency. Buttock angle and stem angle are associated with the flare and waterline angles, and these also contribute to breaking and submergence efficiencies.

The progression in the design of icebreaker bows over the last two decades has been to increase flare angles, to reduce waterline angles and to reduce stem and buttock angles (Dick and Laframboise 1989). These changes have resulted from a systematic series of model tests to produce a more efficient icebreaking bow. Over the years, the values of stem angles of icebreakers have decreased from 30 to 20°.

The selection of bow shape is greatly influenced by the mission profile of a polar ship. Different bow shapes that have been used are shown in Figure 8 (Dick and Laframboise 1989), and a brief discussion of each follows.

Straight stem with parallel buttocks

This shape has been commonly used for Soviet and Finnish icebreakers since the 1950s, as dem-
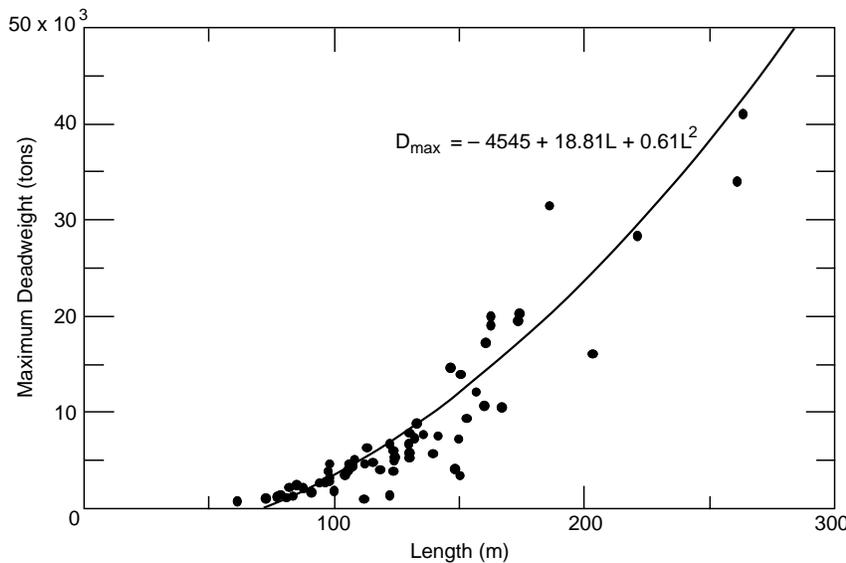

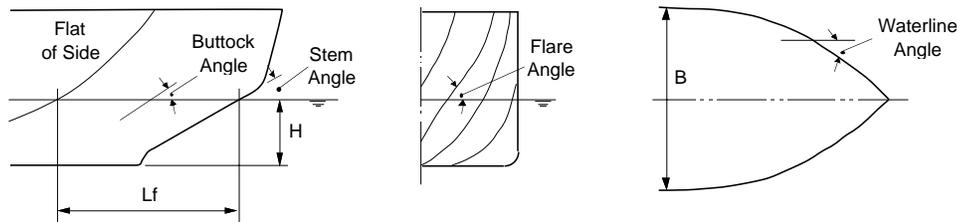*Figure 6. Maximum deadweight vs. overall length of all vessels listed in Appendix B.*

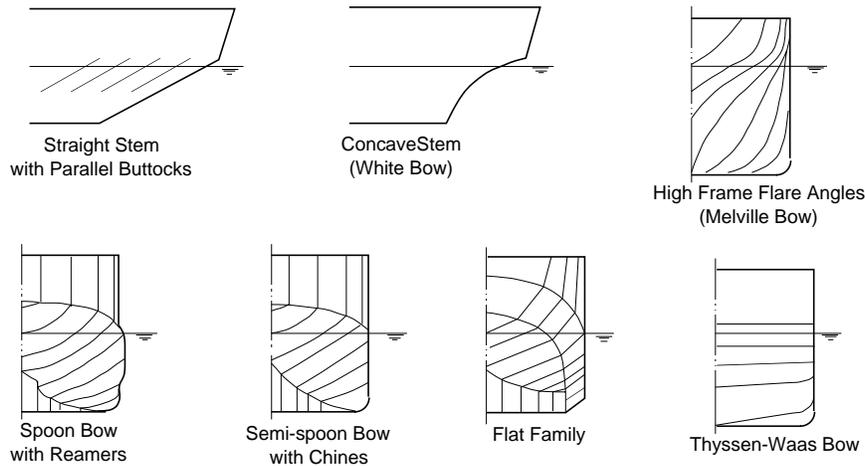*Figure 7. Main features of bow forms (after Dick and Laframboise 1989).*

Figure 8. Different shapes of icebreaking bows (after Dick and Laframboise 1989).

onstrated by the *Moskva*-class icebreakers in the 1960s, and the *Urho*-class Baltic icebreakers in the 1970s.

Concave stem (White bow)

Although the concave stem had been used in earlier icebreakers, R. White developed this particular shape in 1969 for efficient icebreaking and ice clearing. This bow shape was used in the U.S. icebreakers *Polar Star* and *Polar Sea*, built in the mid-1970s, in the Canadian icebreaking cargo ship *Arctic*, built in the late 1970s, and in the Canadian R-class icebreakers, built between 1978 and 1984. Because of the concave stem, this bow shape has higher frame flare angles close to the stem.

High flare angles (Melville bow)

This shape was developed to reduce the icebreaking component of ice resistance. Recently, the Canadian icebreaking cargo ship *Arctic* was modified to this type of bow, and its performance increased from 1 to 4 m/s (2 to 8 knots) in 1-m-thick ice.

Spoon bow with reamers

The spoon-shaped bow has been more efficient because this shape allows a constant frame flare angle throughout the bow length. As mentioned earlier, this shape was used in the past, but its use was discontinued because of its high resistance in heavily snow-covered ice, and its tendency to push broken ice in front of the ship. With the introduction of bubbler systems or water wash systems, these problems have been overcome.

A modification of this shape was reintroduced on the Canadian icebreakers *Canmar Kigoriak*, built in 1979, and *Robert Lemeur*, built in 1981. The extended beam at the shoulder (reamers) with the abrupt change in shape eliminates midbody resistance by cutting a wider channel in ice, but it causes extra resistance in open water. Recently, this shape was also used in the European icebreakers *Oden*, *Kapitan Nikolayev*, *Finnica* and *Nordica.* The hull form of the Finnish multipurpose icebreakers *Finnica* and *Nordica* is shown in Figure 9, which also shows the icebreaking stern and the bi-directional reamers on the sides.
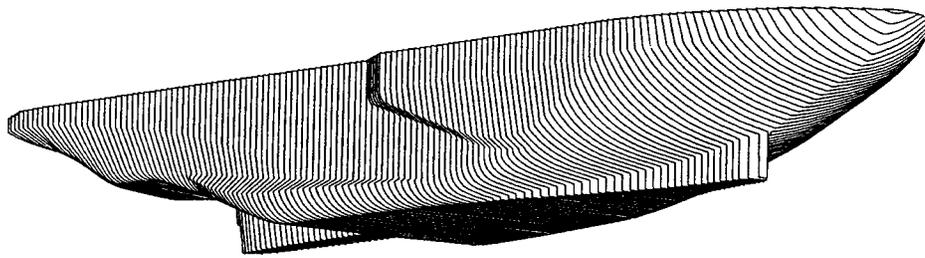
9

Figure 9. Hull form of the Finnish multipurpose icebreakers Finnica *and* Nordica *(after Lohi et al. 1994).*

Semi-spoon bow with chines

This shape is similar to the spoon bow shape, except that the extended beam (reamers) are replaced by shoulder chines. This shape has been used on vessels working in the Beaufort Sea, and it has improved icebreaking performance. But it has had some detrimental effect on the open-water resistance.

Flat family

These shapes are similar to the spoon bow and semi-spoon bow shapes, except that flat plates have been used to reduce the construction costs. This shape was developed as a compromise between icebreaking capabilities and construction costs. This type of bow has been used on the Canadian vessels *Arctic Nanabush,* built in 1984, and *Arctic Ivik*, built in 1985, both being used for ice management in the Beaufort Sea.

Thyssen-Waas bow

This type of bow shape is a significant departure from a conventional icebreaking bow. The bow first breaks the ice by shearing at the maximum beam of the ship, and then breaks the ice in bending across the front of the bow. This shape is characterized by flat waterlines at the extreme forward end, extended beam, a low stem angle with an ice clearing forefoot, and high flare angles below the waterline. The ice clearing capability is so good that the channel behind the ship is about 85% free of ice. As mentioned earlier, the vessels that have been fitted with this type of bow are the *Max Waldeck* (1980), the *Mudyug* (1986) and the *Kapitan Sorokin* (1991).

Of the seven bow shapes listed above, the first three can be called "conventional" or "traditional," because these shapes retain the smooth hull, which offers the least resistance in open water. The other four shapes are "unconventional" or "nontraditional," in that these shapes are a distinct depar-

ture from the smooth hull shapes. Each shape has some benefits and some drawbacks. Therefore, the selection of a bow shape should be based on a full understanding of the operational requirements of a ship.

Midbody shape

The midbody shape of a polar ship is characterized by three parameters: flare angle, parallel sides and longitudinal taper (Dick and Laframboise 1989). The objective of midbody flare is to decrease the resistance caused by it while passing through the channel broken by the bow. Some of the icebreaking cargo ships have a long, parallel midbody. Some of the icebreakers have forward shoulders to break a wider channel to eliminate any ice resistance from a parallel midbody. Similarly, a midbody with longitudinal taper eliminates ice resistance aft of the forward shoulders. This shape has been used on barges pushed by small tugs that operate in sheltered water. The drawbacks of longitudinal taper in the midbody are higher construction costs and an increased probability of getting stuck in pressured ice. A longitudinally tapered midbody is not used on icebreakers or icebreaking cargo ships.

Stern shape

All icebreakers must move astern in ice. Some icebreakers may move back only in the previously broken channel or in broken ice. But there are those icebreakers providing a support role that must break ice while moving astern. Depending upon the mission profile, these ships may have an ice breaking–deflecting stern shape, as shown in Figure 9. The main concern while moving astern is the ingestion of ice blocks into the propellers. Despite many innovative stern designs and shrouded propellers, there is still considerable interaction between ice and propellers (Dick and Laframboise 1989).

Icebreaker performance with different hull forms

Ierusalimsky and Tsoy (1994) presented the results of full-scale tests conducted on three Russian sister ships of the *Kapitan Sorokin* series with different hull forms: *Kapitan Sorokin*, converted to a Thyssen-Waas bow in 1991, *Kapitan Nikolayev,* converted to a conical bow (similar to the spoon-shaped bow) in 1990, and *Kapitan Dranitsyn,* still with the original, wedge-shaped bow. The data on the performance of these ships were obtained over 3 years, enabling a determination of any cost saving resulting from the conversion to bows of different shapes.

For breaking a level ice sheet in forward motion, Figure 10 plots ship performance in terms of the continuous speed of these three ships in equivalent ice thicknesses. The plots in Figure 10 show that *Kapitan Sorokin* with the Thyssen-Waas bow has the best icebreaking capability among the three in level ice, closely followed by the *Kapitan Nikolayev* with the conical bow. The performance of these two ships is much better than that of *Kapitan Dranitsyn* with its original bow. While breaking a channel in fast ice, *Kapitan Sorokin* left up to 40% of the ice in the channel behind it, whereas the other ships left 80–90% of the channel filled with ice. A similar test for backward motion in level ice revealed their performance in reverse order as that for forward motion.
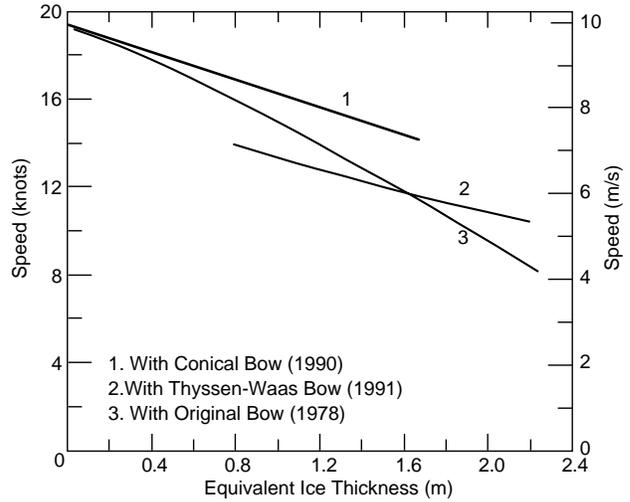
Figure 11. Ship speed vs. equivalent ice thickness during tests in broken ice with three sister ships having different bow shapes. The ships were tested in their own channels (after Ierusalimsky and Tsoy 1994).

Figure 11, giving the results of the tests conducted in freshly broken ice in their own channel, shows that the performance of *Kapitan Nikolayev* is better than that of the other two ships. For tests conducted in broken ice in old channels, *Kapitan Nikolayev* performs better than *Kapitan Dranitsyn*. In old channels full of broken ice, *Kapitan Sorokin* had a tendency to push broken ice ahead of itself when it was not able to reach a speed of 3–4 knots (1.5–2 m/s). Three rounded knives in the bow of *Kapitan Sorokin* work efficiently to break level ice, but they also obstruct the flow of broken ice underneath the bow. At times, the buildup of an ice pile can bring the ship to a standstill, and force it either to ram through the pile or to seek a new path. While operating in drifting broken ice at speeds up to 3–4 knots, *Kapitan Sorokin* showed tendencies to push ice. The performance of *Kapitan Nokilayev* improved in drifting ice fields.

Both ships with the Thyssen-Waas and conical bows must reduce speeds in severe seas because of considerable wave slamming in a head sea, resulting in longer travel times.

Ierusalimsky and Tsoy (1994) have compared the cost savings as a result of conversion of bow shapes from conventional to the two types of unconventional shapes. According to them, *Kapitan Nikolayev,* with the conical bow, had reduced operational costs and increased profitability, whereas similar measures for *Kapitan Sorokin,* with the Thyssen-Waas bow, were less favorable than those for the ship with the original bow. It should, how-
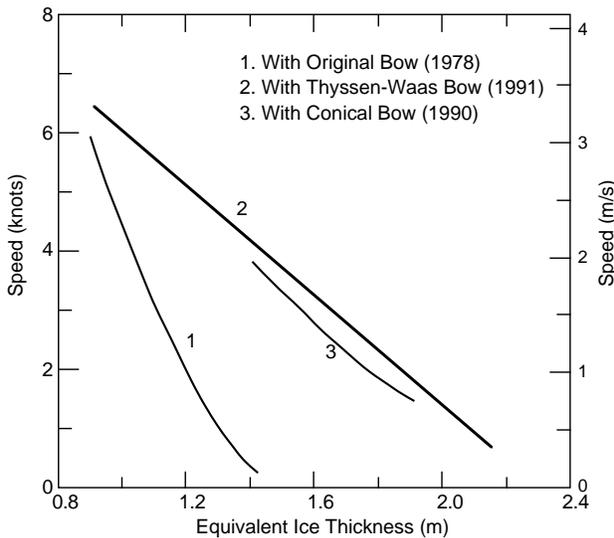

Figure 10. Icebreaking capabilities of three sister ships with different bow shapes in terms of speeds in level ice of different thicknesses at a power level of 16.2 MW (after Ierusalimsky and Tsoy 1994).

ever, be noted that *Kapitan Nikolayev* is fitted with stainless steel compound plate in the ice belt area, which may be effective in reducing the chances of getting stuck in ice.

STRUCTURAL DESIGN OF POLAR SHIPS

Structural design involves the selection of material and sizes of plates and frames for maintaining the structural integrity of a polar ship under loads from waves and ice during its normal operation (Dick et al. 1987). As a result of research and experience, much has been learned about the nature of ice loads and the mechanics of ice failure. Full-scale measurements of ice loads on many ships have yielded an empirical description of ice forces and pressures that is used in design. The magnitude of ice loads, the existence of significant damage and the emergence of affordable nonlinear finite element analysis packages have together led to the wide use and acceptance of plastic design (plastic design allows some deformation of the structure under extreme ice loads).

Classification of polar ships

All commercial vessels, including most icebreakers, but excluding government-owned vessels, are classified according to the rules developed by six classification societies: Lloyds Register (LR), Det norske Veritas (DnV), American Bureau of Shipping (ABS), Bureau Veritas (BV), Germanischer Lloyd (GL), and Russian Register of Shipping (RS). Besides the rules of the classification societies, there are three national sets of rules to control navigation in ice-covered waters: Finnish–Swedish, Russian and Canadian. The classification of a vessel is used for insurance and to comply with the international regulations, such as the Safety of Life at Sea (SOLAS) and prevention of pollution. Government-owned vessels are also surveyed for compliance with recognized national and international standards.

The classification societies are responsible for approving the design and supervising the construction of individual vessels to ensure conformity with the standards set by international conventions and by the classification of that vessel. The vessels are subjected to annual and special surveys throughout their lives (Toomey 1994).

The ice classification of a vessel depends on its capability to resist damage while navigating in ice

under normal handling conditions. Unfortunately, there are so many classifications by the different societies that it is difficult to establish equivalency among them (Santos-Pedro 1994, Toomey 1994). A limited equivalency among the ice classifications of the various societies is given in the Appendix A of a companion report by Mulherin (1994). At present, an effort is underway to standardize ice classes as international navigation through Arctic routes, such as the Northern Sea Route and the Northwest Passage, becomes more attractive for shipping products between the North Atlantic and the North Pacific (Santos-Pedro 1994). While comparing the ice-strengthening requirements according to the Russian Register Rules and Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR), Karavanov and Glebko (1994) have presented an extensive comparison of the ice loads, section modulus and shear area of frames, and thickness of shell plating. The new CASPPR (1989) regulations call for smaller scantlings and thinner shell plates than those required by Russian Rules because CASPPR allows a certain amount of plastic deformation of the structure under extreme ice loads.

Ice loads and pressures

Compression of ice at low strain rates results in creep deformation with or without micro-cracking. The constitutive relations between stress and strain for creep deformation at low strain rates are well known. At higher strain rates ($>10^{-3}$ s^{-1}), the ice fails in a brittle manner, resulting in instabilities caused by macro-cracking. The failure mechanism for brittle failure has not been fully understood. Failure loads or pressures also depend on the state of stress, e.g., uniaxial vs. multiaxial. At present, the dependence of compressive failure of ice under multiaxial loading at different strain rates is being studied by researchers all over the world (e.g., Frederking 1977, Richter-Menge et al. 1986, Smith and Schulson 1994, etc.).

There have been attempts made to relate the forces exerted on a ship or a structure by crushing of ice to the uniaxial compressive strength of ice, but these attempts to obtain empirical relationships through the use of many coefficients have not been fruitful. Although much has been known about the forces from flexural failure and compressive failure of ice at low strain rates, the understanding of brittle failure is still incomplete at high rates of loading and in a multiaxial state of stress. Results of small-scale indentation experiments on freshwater ice indicate that brittle failure is activated at

high rates of indentation, resulting in nonsimultaneous contact between the ice and the indentor.

Design values are taken from empirical relations obtained from full-scale measurements of ice pressure. The data on effective pressures obtained from full-scale measurements during ice–ship and ice–structure interactions (Masterson and Frederking 1993) are plotted with respect to contact area in Figure 12, and these data provide empirical values for effective pressure to be used in design.

Materials

Considerable effort has been devoted by classification societies and regulatory authorities to the selection of steel grades suitable for use in the structure of ships that are exposed to very low tempera-
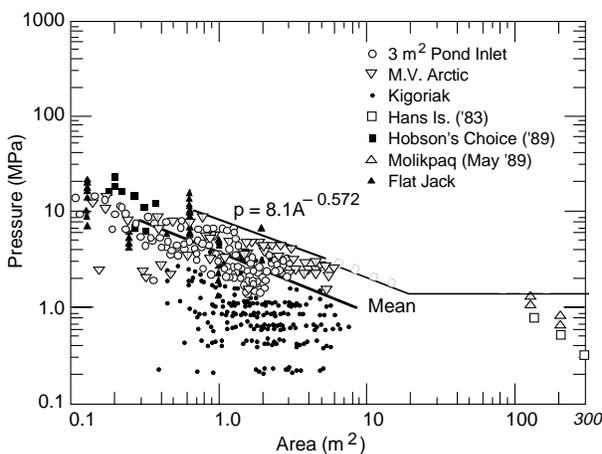
Figure 12. Measured effective pressure vs. contact area (after Masterson and Frederking 1993).
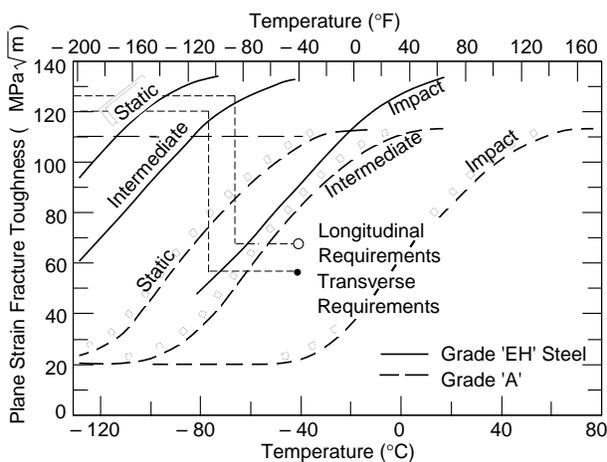
Figure 13. Plane strain fracture toughness vs. temperature for two grades of steel ("A" and "EH") (after Dick et al. 1987).

tures. The fracture toughness of steel depends on the operating temperature and on the rate of loading. In Figure 13, the plane strain fracture toughness of two types of steel has been plotted with respect to temperature for three rates of loading.

Steel fractures in a brittle manner, without any warning of impending failure, when the stresses are of sufficient magnitude to propagate a crack from a flaw or small crack in the material. The criterion for crack propagation in linear elastic fracture mechanics is that an existing crack will grow when the stress intensity factor at the crack tip is greater than the fracture toughness of the material. For nonlinear material behavior, the causes for brittle fracture have now been established, and the relationships among the cause of fracture, the toughness of the material, the flaw size and shape, the loading rate of the structure, and the temperature are understood. From this understanding, materials and welding techniques have been developed to increase the reliability of ship structures. It is the consensus of many operators that the steel used in the present generation of polar ships is mostly adequate (Dick et al. 1987).

There are currently two procedures for specifying the type of steel to be used in different parts of a ship: "design by rule" and "design by analysis." Design-by-rule procedures require the designer to consider service temperature and to select steel grades that have adequate notch toughness. Design-by-analysis procedures require the designer to consider the magnitude and the rate of loading that may be applied during the life of a component, and to design that component with adequate reliability according to its importance. The design-by-analysis approach places a large responsibility on the designer, but it may provide a more reliable and economical design than that by the design-by-rule approach.

The midbody region of a ship will experience vibrations excited by shocks at the bow, but the vibratory stresses have much longer rise time than shock-induced stresses, resulting in small chances of initiating a fracture. However, the static stresses from vibrations may be high enough to cause fracture in the primary structure of a ship. Ships have experienced brittle fracture in the midbody region, and because damage in this area is potentially more catastrophic than damage to the bow, materials and welding techniques should prevent both crack initiation and propagation. Because small cracks and defects in a material are inevitable, the material selected must have crack arrest properties to stop crack propagation.

Welding

After selection of steel, welding is the next most important component in the reliability of the structure of ships (Dick et al. 1987). Welds in ships must withstand the corrosive effects of seawater, stresses caused by cargo, icebreaking operations and wave-induced motions. The biggest variable in welding technology is the skill of the welder, especially when working in confined spaces. To determine the reliability of a structure, the designer of a ship must take into consideration the flaws in the material as well as in the welds. The importance of quality control in welding can be assessed from the statistics that 95% of all defects in a structure originate from defects within the welded zone.

The fracture toughness of a weld depends on the method of weld deposition, including the rate, the number of passes, heat input and electrode size. The variations in weld toughness may be larger than those of the parent materials. Caution should be exercised not to degrade the toughness properties of a weld by using large electrodes and fast rates of deposition in the interests of cost saving. Research on reducing the accelerated corrosion of welds is under way in different parts of the world.

Plating

The plating contributes the largest component to the structural weight of most ships and, together with the frames and the stringers, it forms the stiffened panels that resist the loads on a ship (Dick et al. 1987). While the weight of a ship can be reduced by reducing the plate thickness and by increasing the framing, this increases the cost of fabrication.

When a rectangular plate supported by frames on four sides is loaded by uniform pressure that acts perpendicular to its surface, the deflections and the stresses in the plate can be calculated by the small deflection theory of plate bending, as is usually done for structural analysis. This theory ignores the membrane stresses that develop because of large deflections and yielding of the material. As a result of ignoring the membrane action, the load carrying capacity estimated from small deflection theory is small compared to those obtained from large-deflection theories and experiments.

Figure 14 shows plots of load vs. deflection obtained from experimental results and two plastic analyses—one that considers elastic flexure followed by formation of three plastic hinges without any membrane action, and the other that considers only ideal plastic membrane action. The loads in the plots have been made nondimensional
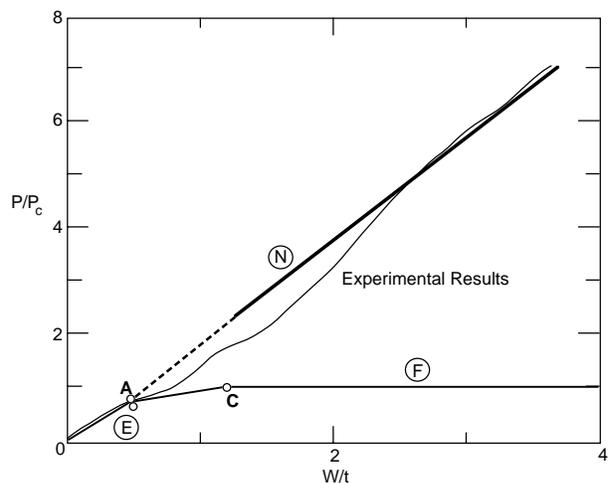

Figure 14. Pressure vs. deflection, showing domains of different behaviors from small to large deflection (after Ratzlaff and Kennedy 1986). Along the vertical axis, the applied pressure P *is made nondimensional by* P_c*, the pressure at which collapse (point C) is assumed to take place by formation of three hinges without membrane action. Along the horizontal axis, the maximum deflection* W *is made nondimensional by the plate thickness* t*. The curve labeled E represents elastic flexure with an elastic membrane up to the complete formation of an edge hinge. The curve labeled F represents elastic flexure without membrane action, followed by the formation of the first hinge and then three hinges. The curve labeled N represents ideal membrane action.*

with respect to the collapse load predicted by the formation of three hinges without membrane action, and the deflection is made nondimensional with respect to the plate thickness. Figure 14 shows that the curve depicting the experimental load-carrying capacity of a plate is initially close to that predicted by elastic flexure theory for small deflections, and then it approaches that predicted by the plastic membrane action theory for large deflections. This suggests that thick plates form plastic hinges before the membrane action is activated (Ratzlaff and Kennedy 1986).

Framing

The frames support the shell plates and resist the loads on the shell by bending and shear deformation. Inspection of ice-damaged vessels has revealed that failure takes place consistently in the supporting frames rather than the hull plating (Dick et al. 1987, DesRochers et al. 1994). Frames have several components: the shell plate that acts as a flange, a web, an internal flange (optional), end brackets (optional), tripping brackets (optional) and cutouts (optional).

14

The proposed CASPPR allow a certain amount of plastic deformation of the structure under extreme ice loads, and they provide factors to account for the post-yield buckling of stiffened structures. DesRochers et al. (1994) compared the stability of flat bars with that of angle sections in a stiffened structure. When a structure is designed for buckling according to linear analysis, flat bars are avoided because angle sections have large moments of inertia to resist bending. However, DesRochers et al. (1994) found that the use of flat bar sections increased the stability of the composite structure beyond the yield point of the material, whereas the structural stability decreased with the use of angle sections as yielding progressed through the frame. The structure of the Canadian icebreaking cargo ship *Arctic* has been redesigned according to CASPPR to carry full ice loads without failure.

The Swedish icebreaker *Oden* is the first icebreaker designed according to the technology behind the proposed CASPPR, making it possible to use a large frame spacing of 850 mm instead of the normal 400 mm (Johansson et al. 1994). This has resulted in considerable cost savings in construction. After the voyage of *Oden* to the North Pole, inspection of the structural damage revealed some indents in the shell plating between frame stations 30 and 76 on both sides, and some deformation in the side and bottom frames (flange, web and bracket), but this damage was not serious. The damaged frames were reinforced, but the indents in the steel plates were left as they were (Backman 1994).

PROPULSION SYSTEM

The major components of the propulsion system of an icebreaking vessel, or any ship, are the propellers, shafts, transmission systems and prime movers. The number of propellers varies between one and three. Developments in propulsion systems that have taken place during the last four to five decades are reflected in those of existing icebreakers and icebreaking cargo ships, and these become apparent in the plot of shaft power vs. the year of construction (Fig. 15). Some of the special features of propulsion systems, such as controllable-pitch propellers and mechanical transmissions, nozzles and various electrical transmissions, have been highlighted in Figure 15.

The dc–dc electrical transmission has been commonly used since its introduction on the Swedish

icebreaker *Ymer* in 1933. Although this system is still being used on many icebreakers, new mechanical and electrical transmissions have been introduced on newer icebreakers and icebreaking cargo ships. Since 1966, the number of ships with controllable-pitch propellers and mechanical transmissions is steadily increasing. The Russian LASH vessel *Sevmorput*, delivered in 1986, placed all of its propulsion power on one shaft using a controllable-pitch propeller and mechanical transmission, thus doubling the power transmitted per shaft from 16.65 to 29.42 MW (Fig. 15b).

One of the main reasons to use direct mechanical transmission is to cut down the losses in transmission. Since 1978, propeller nozzles have been fitted to icebreakers to increase thrust and to prevent propeller damage by reducing ice ingestion. Nozzles have been installed on most of the Beaufort Sea ice management–supply vessels, whereas *Polar Sea* and *Polar Star* have operated in ice without nozzles since 1976. Recently, azimuth-mounted propulsion units have been installed on the Finnish icebreakers *Finnica* and *Nordica* and it is
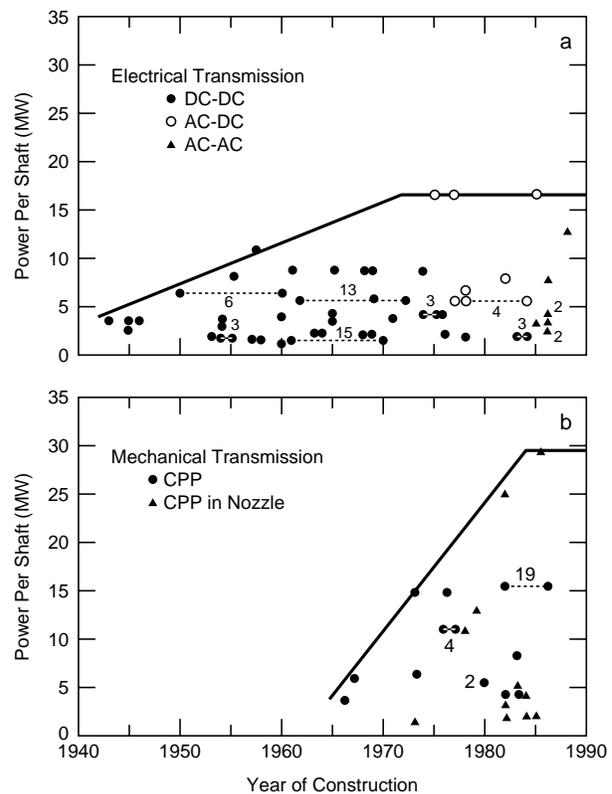

Figure 15. Shaft power vs. year of construction for icebreaking ships: (a) electrical transmission system, and (b) mechanical transmission system (after Dick and Laframboise 1989).

15

likely that this system will be used in future ships, because it offers good maneuverability in broken and intact ice.

The selection of a suitable propulsion system is based on the intended functions of an icebreaking vessel. The requirements of a propulsion system are:

1. Reliability of full power on demand to navigate safely in the Arctic.
2. Flexibility of operating efficiently and economically in open water as well as in heavy ice at a range of power levels.
3. Maneuverability to allow rapid change of load, speed and power.
4. High power-to-weight ratio to deliver the required power, with machines as compact and light as possible.

While many combinations of prime movers, transmission systems and propellers may be proposed for a given ship, very few particular systems would fit a given mission profile (Dick et al. 1987). Ships requiring a large range of power can be fitted with multiple engines or combined-system installations, which permit the numbers of engines to be run according to the power requirements of various ice conditions, to achieve the best combination of fuel efficiency and performance. In the following sections, a brief discussion is given of each of the main components of a propulsion system.

Propellers

Both fixed-pitch and controllable-pitch propellers have been installed on polar ships. Fixed-pitch propellers have been used for many years, and these are still being installed on most icebreaking ships. However, controllable-pitch propellers have been used on polar ships with increasing frequency since 1966 (Dick and Laframboise 1989). A plot of shaft power versus propeller diameter is shown in Figure 16, where fixed-pitch and controllable-pitch propellers have been identified. The azimuth thruster units installed on the Finnish icebreakers *Finnica* and *Nordica* have fixed-pitch propellers in a nozzle.

The selection of propeller type depends on the propulsion system used. Nonreversing transmission systems, such as diesel–geared or gas turbine–
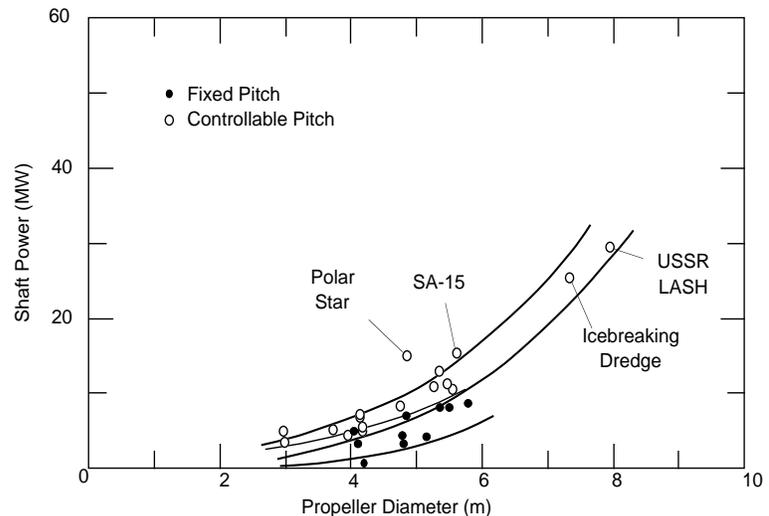

Figure 16. Shaft power vs. propeller diameter for icebreaking ships (after Dick and Laframboise 1989).

geared, may use controllable-pitch propellers to obtain astern thrust and to ease over-torque requirements. Reversing systems, such as any of the electrical systems, may used fixed-pitch propellers because over-torque does not affect an electrical system.

The design requirements of a propeller depend on the mission profile of a vessel. The aspects influencing the design of a propeller are (Dick et al. 1987):

1. Loads and strength requirements.
2. Selection of material.
3. Effects of nozzles.

There are two types of interactions between ice and propellers: ice milling and ice impact. Ice milling takes place when an ice block is large or is trapped between the hull and the propeller. During an instance of milling, ice is either crushed or sheared by the blades, and the loads can be damagingly high. Ice impact is caused by small-size ice pieces that are accelerated through a propeller or thrown out radially and pushed around the edge of the propeller disk. The loads from ice impact are relatively moderate, but it happens more frequently.

For propellers in a nozzle, the chances of ice milling are small, and the magnitude of the loads generated are also small in comparison to those for open propellers. The factors that influence the ice loading on a propeller have been identified, but the ability to determine the ice milling–impact loads is not well developed because of the complex interaction between ice and propellers. The

design of an ice-strengthened propeller must meet the dimensions and the strength requirements of the classification societies.

The material used for the propeller blades of polar ships must have high stress and impact resistance qualities. Stainless steel and bronze are commonly used for ice-strengthened propeller blades. Because stainless steel has a higher erosion resistance and higher ultimate and yield strengths than does bronze, stainless steel propellers have a slender and efficient blade profile. Most of the existing bronze controllable-pitch propellers are operating in nozzles, whereas most stainless steel controllable-pitch propellers fitted to icebreakers are open propellers. For example, bronze has been selected for the propellers of recent Canadian icebreakers, and the open propellers of the U.S. icebreakers *Polar Star* and *Polar Sea* are made of stainless steel.

Propeller nozzles are used to increase the thrust over a range of ship speed, and to protect the propeller from ice. Thus, the nozzles have an indirect influence on the design of a propeller by reducing the load levels and thereby reducing the strength requirements. Ships equipped with nozzles, e.g., *Kigoriak* and *Arctic*, have operated successfully in ice with very few problems. Some of the shallow-draft vessels, however, have occasionally experienced clogging of their nozzles in rubbled or ridged ice. Nozzles have been installed on the azimuth-mounted propellers of *Finnica* and *Nordica*, and these are being considered for future high-powered ships.

Shafting

For large icebreaking ships, the diameters of propeller shafts are large because of high power and high torque requirements. The range of diameters of the shafts installed in existing icebreakers is from 380 mm in *Polar Stern* to 980 mm in the Russian SA15 cargo ships. The basis for designing shaft diameter is that the propeller blade should fail before the shafting. The method to calculate the shaft diameter depends on the modulus of the propeller section and on the ratio of the ultimate strength of the propeller blade material to the yield strength of the shaft material. The requirements of hydrodynamic torque and ice-induced torque are specified by the classification societies. Shafts are generally made of forged carbon steel, although in some cases low alloy steel forgings are also used. There is considerable saving in weight when high-strength steel is used.

One of the major problems found with large vessels is the misalignment of the shaft bearings. The sources of the misalignment problem are (Dick et al. 1987):

1. Deflections in the hull.
2. Eccentric thrust on the propellers, which causes bending moments in the shaft.
3. Insufficient axial and radial bearing flexibility.
4. Changes in the height of bearings, gear case or the engine because of thermal expansion.

Dick et al. (1987) have discussed other elements of the shaft line components, such as couplings, seals and bearings.

Mechanical transmission components

The operating speed of steam reciprocating engines and slow-speed diesel engines is low enough that the power can be transmitted directly through a shaft between the engine and a propeller. This is the most efficient form of transmitting power to a propeller, because the only losses incurred are at the bearings. However, most prime movers, such as medium-speed diesel and steam and gas turbines, have an output speed that is too high to obtain the best propeller efficiency. A speed-reducing transmission must be used to deliver power to the propellers at the optimum speed.

As shown in Figure 15b, many icebreakers and icebreaking cargo vessels have been fitted with mechanical transmission of power since 1966. Most of these vessels are driven by one or more medium-speed diesel engines and a set of single-reduction gears, except the Russian LASH, which is driven by a steam turbine. A clutch or fluid coupling is used between an engine and a gear system. In a few icebreakers, flywheels have also been used to smooth out the transient, ice-induced torque.

The gearboxes that are installed on polar ships are within the experience of the manufacturers. The largest gearboxes installed on any icebreaker are those on the U.S. icebreakers *Polar Sea* and *Polar Star*, which are powered by combined gas turbine and diesel-electric systems. The Russian SA15 cargo ships have been fitted with large gearboxes with twin inputs, each delivering 7.5 MW, and connected through fluid couplings to limit overload torque.

Electrical transmission systems

Four types of electrical transmission systems are available for polar ships. These systems are listed according to their chronological order of develop-

ment: dc–dc, ac–ac, ac–dc, and ac–FFC–ac. An ac system is preferred because of its light weight and higher efficiency. The problems of commutation in dc systems are not present in ac systems.

The advantages of an electrical transmission over a mechanical one are that the characteristic of the drive can be exactly matched with the mission profile of a ship, and that the total power for the ship can be divided among a number of engines. There is flexibility in the placement of generators in a ship. An electrical system also isolates the prime mover from the overload torque caused by ice loads on the propellers. The disadvantages of an electrical transmission system are the higher costs, greater weight and larger space requirements.

With medium-speed diesel engines as prime movers, the dc–dc system is most commonly used in icebreakers. The maximum speed of a dc generator must be less than 100 rpm owing to the limited capacity of the commutator brushes to transmit current. The advantages of a dc system are its simplicity, ease of control, good torque characteristics (especially at low speed) and lower cost than other electrical systems. In comparison to mechanical transmission systems, the disadvantages of this system are its higher cost, greater weight and volume, lower transmission efficiency (about 85%) and a relatively high requirement for manpower.

The ac–dc system combines the advantages of ac generators with the precise speed control of dc motors. The generated power, in three-phase alternating current, is converted with low losses to direct current by the use of thyristors, which were developed in the 1960s.

The ac–ac propulsion system is based on synchronous motors. The speed is changed by changing the speed of the prime mover. It is the simplest and least expensive. This system, while perhaps being the economical choice for open water ships, is not suitable for icebreaking ships. The generator and the motor may fall out of synchronization when the propellers are subjected to large ice loads. Other disadvantages of this system are the low torque at start up and the excitation of resonant vibrations.

The ac–ac system with Full Frequency Control (FFC), or a cyclo-converter, is the most suitable but also the most expensive ac–ac system. It has been used in the Finnish icebreakers *Otso*, *Finnica* and *Nordica,* in the Russian *Taymyr*-class icebreakers and in Canadian light icebreakers. By employing cyclo-converters, the motors can be precisely and steplessly controlled by a highly reliable control setup. Its advantages are the availability of full torque over the entire range of speed, no loss of synchronization, operation of the prime mover at its optimum speed, and the availability of power for auxiliary systems from the main generators. Its main disadvantages are the high capital cost, high volume and weight, and relatively poor overall transmission efficiency of 90–92% (estimated), although the transmission efficiency of ac–FFC–ac systems is higher than that for ac–dc and dc–dc systems.
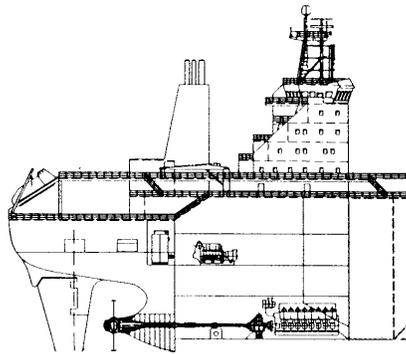
Azimuth propulsion drive

Azimuth propulsion drives have been installed on different types of vessels, such as icebreakers, cargo ships, ferries, cruise ships, etc. One of the *Lunni* series tankers, *Uikku*, was converted in 1993 to accommodate 11.4-MW azimuth propulsion drives (one of the world's most powerful units), replacing the original medium-speed diesel, gearing, shafting and controllable-pitch propellers. Installation of these units on the multipurpose icebreakers *Fennica* and *Nordica* has produced excellent icebreaking and maneuvering capabilities. With their advanced hulls (designed to give excellent seakeeping in open waters [Fig. 9]), these vessels can make continuous progress through 1.8-m-thick ice. Their icebreaking capabilities are also very good when they are moving astern. The azimuth thruster units allow these ships to turn on the spot in ice conditions. Lohi et al. (1994) give the results of full-scale ice tests with *Fennica* during her trials in the Baltic.

There are two commercial azimuth propulsion systems available—Aquamaster and Azipod. In an Azipod unit, an ac electrical motor is located inside the pod, whereas the motor is located above the azimuth thruster units in Aquamaster drives. The motor, controlled by a frequency converter, directly drives a fixed-pitch propeller, which is either open or placed in a nozzle. These drives azimuthally move 360° and supply full power in all directions.

Figure 17 shows the difference between conventional diesel–mechanical and azimuth propulsion systems on an arctic tanker. The azimuth system has the following advantages:

1. Gives excellent dynamic performance and maneuvering characteristics.

2. Eliminates the need for long shaft lines, transverse stern thrusters, controllable-pitch propellers and reduction gears.

3. Allows new ways for designing machinery and cargo spaces.

Diesel-mechanical Propulsion System
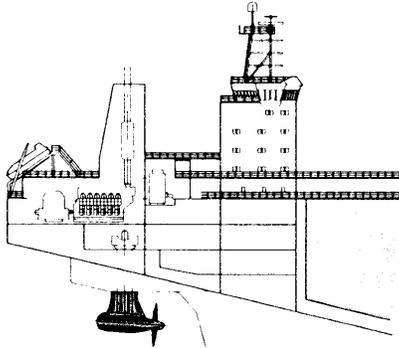
Azimuth Propulsion System

Figure 17. Differences between diesel-mechanical and azimuth installations (after Kværner Masa-Yards and ABB, no date).
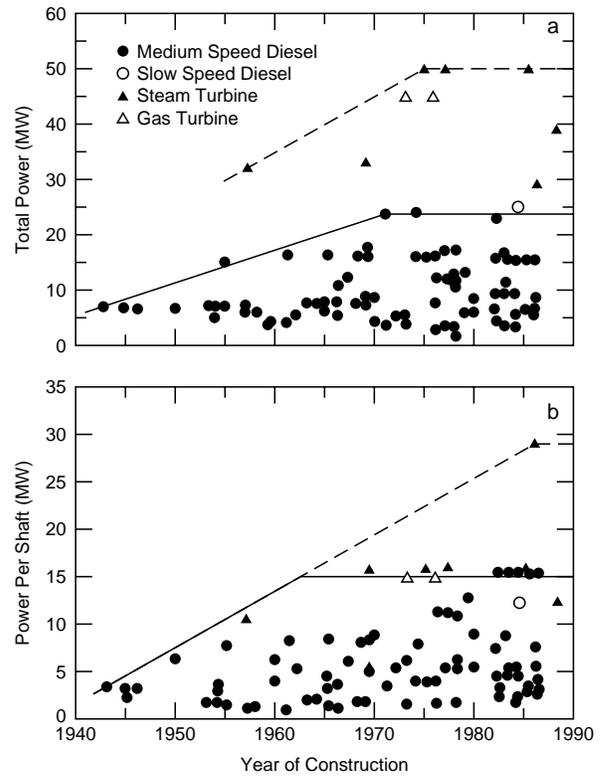

Figure 18. Prime movers installed on icebreaking ships: (a) total power vs. year of construction, and (b) power per shaft vs. year of construction (after Dick and Laframboise 1989).

4. Reduces noise and vibrations.

5. Provides operational flexibility, resulting in lower fuel consumption, reduced maintenance costs, fewer exhaust emissions and adequate redundancy with less installed power.

In late 1990, the propulsion system of the Finnish waterway service vessel *Seili* was converted from diesel-mechanical propulsion to azimuth (Azipod) propulsion. The performance of this vessel was tested in 65-cm-thick, level ice in the Gulf of Bothnia. Laukia (1993) reported that, besides good maneuverability and icebreaking capability in level ice and first-year pressure ridges, the vessel broke ice better when moving astern than while moving ahead. There are unconfirmed reports that new vessels with two types of hulls at each end are on the drawing boards of shipyards: a smooth bow for moving forward in open-water, and an icebreaking stern for moving astern through first-year ice in sheltered areas.

Prime movers

The characteristics of an ideal prime mover for an icebreaking ship are reliability, flexibility, ma-

neuverability, robustness and over-torque capability (Dick and Laframboise 1989). These characteristics have been discussed earlier for the propulsion system. The prime movers used currently in polar ships do not have all these characteristics, but in combination with a suitable transmission, the overall propulsion system can approach the above-mentioned ideal characteristics.

Figure 18 shows two plots of total installed power and power per shaft versus the year of construction. In Figure 18 different types of prime movers have been identified. Each type is briefly discussed in the following.

Gas turbines

Only two icebreakers, the USCG *Polar Star* and *Polar Sea*, are fitted with gas turbines. Each ship has three aero-engine derivative gas turbines, each driving a controllable-pitch propeller through a gearbox. These turbines are used only for heavy icebreaking, and a medium-speed diesel-electric propulsion system is used for cruising and light icebreaking. The Canadian icebreaker *Norman McLeod Rogers* was initially fitted with two indus-

trial turbines, but they were replaced with medium-speed diesel engines because of high fuel consumption.

Turbines are unidirectional engines, and the astern operations must be provided by the transmission, usually through an electrical system, a reversing gear or a controllable-pitch propeller. The advantages of gas turbines over other prime movers are their high power-to-weight ratio and their compactness. Their main disadvantages are the high fuel consumption and maintenance requirements.

Steam turbines

Only the Russian nuclear-fueled icebreakers and icebreaking cargo ships are fitted with modern steam turbines. The Canadian icebreaker *Louis S. St. Laurent* was fitted with a steam-turbine–electric system, but a diesel-electric system was installed during the ship's major reconstruction program, completed in 1993. The efficiency of a steam turbine is about 20%, compared to 50% for modern marine diesel engines (Dick et al. 1987). Similar to gas turbines, steam turbines are unidirectional engines, and astern operations must be handled by the transmission. Turbines can operate at any power level, but the fuel efficiency is poor at reduced power levels.

Medium-speed diesel engines

Medium-speed diesel engines have most commonly been used as prime movers for the propulsion of polar ships because of their compactness, light weight, fuel efficiency and good reliability (Dick and Laframboise 1989). Their disadvantage for use as prime movers is their lack of significant over-torque capacity. However, this shortcoming is overcome by using an electrical transmission, which damps out the high torque transients and stops them from being transmitted to the engine. A few icebreakers are fitted with these engines driving controllable-pitch propellers through gears. Some of the direct drive systems consist of fluid couplings to prevent engine stall under the most severe propeller overloads.

In the past 15 years, medium-speed diesel engines have undergone developments that have allowed them to have better fuel economy, burn heavier grades of fuel, increase routine maintenance intervals and increase the power per cylinder. Some of the largest engines of this type can generate about 22 MW at 400 rpm in 18 cylinders arranged in a vee form (Dick et al. 1987). The engines operate in one direction, and separate pro-

visions, in the form of controllable-pitch propellers or reversing gears, are used for astern operations. Typical specific fuel consumption of the engines is between 170 and 200 g/kWh, and the consumption of lubricating oil is between 1.5 and 3 g/kWh. Most medium-speed diesel engines for icebreakers use turbochargers to improve their fuel efficiency in open water. Diesel engines are basically constant torque machines in the 50–100% range of speed. At a given load, torque may exceed the rated capacity by about 10%. The flexibility of diesel engines is acceptable because they can operate between 25 and 35% of their rated speed, depending upon the characteristics of a particular engine. It is expected that medium-speed diesel engines will continue to be the preferred prime movers for polar ships of all sizes in the near future (Dick et al. 1987).

Slow-speed diesel engines

The Russian LASH ship *Alexey Kosygin* is the only polar ship fitted with two slow-speed diesel engines, each delivering 13.4 MW to directly drive fixed-pitch propellers (Dick et al. 1987). This type of engine was specifically developed for ship propulsion. They operate on the two-stroke cycle, are reversible, and are directly coupled to propellers, mostly of the fixed-pitch type. The range of their rotational speed is between 60 and 225 rpm. The range of cylinder bore diameter is from 250 to 900 mm. The maximum power per cylinder is about 3.7 MW. This type of engine is large and heavy, and it can only be fitted to vessels that can provide a large engine room and carry the extra weight: bulk cargo ships, oil tankers and container ships. Ferries, Ro/Ro ships and barge carriers have limited head room and are generally fitted with medium-speed diesel engines. These engines are not suitable for polar ships because of their poor maneuverability and flexibility.

Developments in the last 15 years include the use of constant pressure turbocharger technology and the adoption of extra-long strokes. This has enabled slower propeller speeds without the use of gears, resulting in higher propulsion efficiency in large bulk carriers and oil tankers. The specific fuel consumption of these engines is below 160 g/kWh for large economical engines, and about 175 g/kWh for small engines.

Combined prime movers

The reason for combining two different prime movers in a ship is to improve the overall fuel economy. This is done by either recovering the

waste heat and converting it to mechanical work, or by operating each prime mover according to load demands to obtain better fuel economy. The first option has not been used in icebreakers so far.

The USCG icebreakers *Polar Sea* and *Polar Star* are the only polar vessels fitted with two types of prime movers. In these ships, there are three gas turbines (total 45 MW or 60,000 shp) and three diesel-electric propulsion systems (total 13.4 MW or 18,000 shp) for each of the three controllable-pitch propellers. Each shaft can be turned either by the diesel-electric or the gas turbine power plant. Either one or two 2.24-MW (3000-shp) diesel-electric drive units, or a single 15-MW (20,000-shp) gas turbine, can be used to drive each shaft. For example, diesel engines could supply power to the wing shafts, while a gas turbine could turn the center shaft. Gas turbines are used for heavy icebreaking, whereas the diesels are used for cruising and light icebreaking. This is a good example of combining two different systems to meet widely differing load demands for the sake of fuel economy.

AUXILIARY SYSTEMS

There have been other developments to improve the performance of polar ships besides those in propulsion systems and hull shapes, such as the use of low-friction coatings on the hull, air-bubblers to lubricate the ice/ship interface, air-bubbler–water-injection systems, and the water-deluge (or wash) system to pump a large volume of water on the ice ahead of the vessel. These improvements have also contributed to increase the icebreaking capability of polar ships beyond the limit for which they were designed. A brief account of each auxiliary system follows.

Low-friction hull coating
Depending on the age of a vessel, the coefficient of friction between ice and unpainted hull plating can be in the range of 0.2 to 0.3, which is high in comparison to the friction coefficient in the range of 0.05 to 0.17 between ice and a low-friction coating. As discussed later, the factor to account for the friction of old steel in the expression for ice resistance of an icebreaker is twice that for Inerta-coated steel plates (Keinonen et al. 1991).

Prior to the 1970s, there was no suitable coating available that could withstand interaction with ice. Only anti-fouling paint was applied to the hulls to minimize biological growth on the hull surface,

and this would wear off during first few days of icebreaking. In the early 1970s, the importance of hull–ice friction on the ice resistance was demonstrated through full-scale and laboratory tests. A measure of the force attributable to static friction acting on a hull can be obtained by gradually increasing the level of power to initiate forward motion of a ship that was stopped in ice and then measuring the steady-state velocity at that same power level. For ships having uncoated hulls, this power level corresponds to a 3-knot (1.5-m/s) speed of advance, whereas for a ship with low-friction coating, the initiating power levels are equivalent to a speed of 0.5 knots (0.26 m/s) (Voelker 1990). The power required for an icebreaker with a low-friction coating to become unstuck is much lower than that for ships without any coating.

Mäkinen et al. (1994) have given an historical account of the development of low-friction coatings in Finland, where the first effective hull coatings were developed by Wärtsilä Shipyard (now Kværner Masa-Yards). Liukkonen (1992) developed a theoretical understanding of hull–ice friction and found a functional relationship between the coefficient of friction and the normal force. This functional relationship was verified by full-scale measurements of normal and frictional forces with the help of instrumented panels installed in the bow and the sides of icebreakers.

Mäkinen et al. (1994) have listed the requirements of a good low-friction coating. A few of these are reasonable cost, high bond strength with and good corrosion protection for the base material, and resistance to all of the following: wear, high normal pressure, low temperatures and changes in temperature. Tests were conducted on many different coatings; Inerta 160 and stainless steel were selected for full-scale testing and further development. Another coating by the name of Zebron was also found to be suitable, but its use has decreased with time, perhaps because of lower resistance to wear.

Inerta 160 has been applied to hundreds of ships currently in service (Mäkinen et al. 1994). It is applied with a two-component spray gun, which has heating equipment to keep the temperature of the paint between 40 to 50°C. Two problems associated with the application of Inerta 160 were corrosion of cast iron propellers and corrosion of hull surfaces. These problems were corrected by using stainless steel propellers and cathodic corrosion protection.

An important property of a coating is to withstand the deformation of the base material. In the
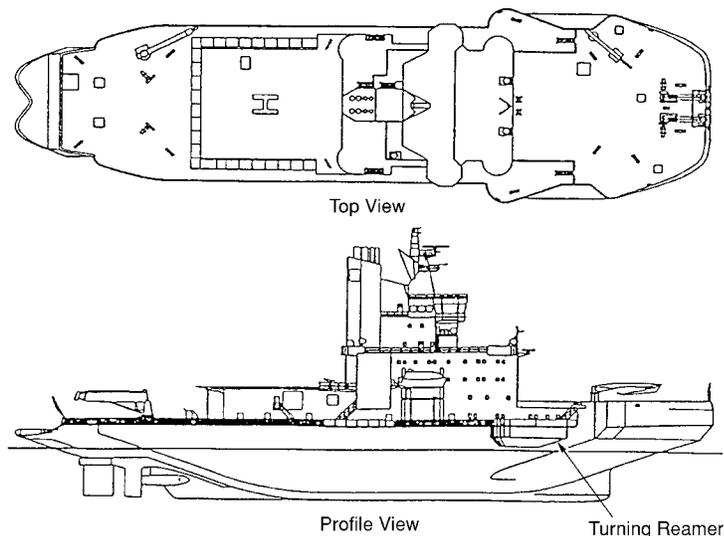
Figure 19. Outboard profile and topside deck plan of the Swedish icebreaker Oden.

case of Inerta 160, the wear-off starts at the cracks caused by the deformation of the shell plating at the edges of the ship's frames. The wear-off is intensified in heavily loaded areas, such as the ice belt in the ship's forebody, and during operations in heavy ice and especially in the presence of soil or sand mixed in ice. To correct this deficiency in Inerta 160, stainless-steel-coated surfaces, though expensive, were developed because of their high wear resistance and low-friction properties. Cathodic protection systems were developed to reduce the corrosion risks before compound steels with stainless steel claddings were installed in the ice belt regions on two *Otso*-class icebreakers for testing. Later, stainless steel compound plates were installed on the Russian icebreaker *Kapitan Nikolayev* and the Finnish icebreakers *Finnica* and *Nordica* with very favorable results.

The cost of applying Inerta 160 and installing stainless steel compound plates is, respectively, about 2 and 40 times the cost of applying conventional paint (Mäkinen et al. 1994). However, the extra cost of applying Inerta 160 may be offset by longer periods (4–5 years vs. 1 year) between reapplications of the coating, while compound steel does not require any repair or reapplication. There have been no corrosion problems with compound plate; however, the cathodic protection systems must be permanently activated, even during the summer. Investigations are currently underway to use copper-nickel compound plates as an alternative to stainless steel compound plates (Mäkinen et al. 1994).

Heeling system

In earlier times, the crews of cargo ships that were stuck in ice found that lifting a heavy weight by a crane and swinging it sideways helped to free the ship. This experience led the designers of icebreakers to install heeling tanks on each side of a ship and to provide for pumping large amounts of water back and forth between the tanks. The continuous rolling motion of a ship facilitates its progress in ice with less power.

Now most operators consider the heeling system important for improved icebreaking and maneuvering. Almost all Baltic icebreakers have heeling tanks. The Swedish icebreaker *Oden* was fitted with a fast heeling system that allows full heeling in 15 seconds (Backman 1994). This has enabled *Oden* to make continuous progress in heavy ridges. *Oden* is also fitted with turning reamers located above the ice surface on each side just aft of the bow (Fig. 19), and when the ship is heeled over, one reamer comes in contact with ice to help the ship to turn sharply into the heel (Johansson et al. 1994). Thus, a heeling system in combination with the turning reamers has improved the maneuverability of *Oden* by decreasing the turning radius. With improved maneuverability, polar ships are often able to make progress in thicker ice than they have been designed for, by finding a path of least resistance through the weaknesses in an ice cover. This is demonstrated by the successful voyage of *Oden* in 1991 with the German icebreaker *Polarstern* to the North Pole.

Air-bubbler system

An air-bubbler system releases large volumes of air through nozzles into the water below the ice in the bow and midbody portions of a ship. When the air rises to the surface, it brings water with it between the ice and the hull, thus reducing friction between them.

This system was first introduced on the Finnish icebreaking ferry *Finncarrier* in 1969 (Johansson et al. 1994). It has since been installed on vessels with conventional bows, such as the *Lunni* class of icebreaking tankers, the Canadian icebreaking cargo ship *Arctic,* and the Russian SA15's. The results of full-scale trials indicate that a bubbler system may help in reducing friction only in the low-speed range (less than 2 m/s or 4 knots). There

is no measurable benefit of an air-bubbler system on ships with unconventional bows. Captains of Bay-class Great Lakes icebreakers report that air bubblers are very useful for docking or leaving the docks under ice conditions.

To assess the effectiveness of hull lubrication by an air-bubbler system, the ratio of shaft power saved at a given speed in level ice to the power required to operate the system is computed. If this ratio is more than one, there is a net power saving in operating the system. According to the data compiled by Keinonen et al. (1991), this ratio for the air-bubbler system of hull lubrication is generally less than, or in some cases barely greater than, one. The reason for such low efficiency is that lubrication is not provided around the bow waterline, where it would be most effective.

Air-bubbler–water injection system

This system, installed on the German icebreaker *Polarstern*, injects air into the water being pumped to nozzles at the sides of the ship below the ice. Air–water jets have also been installed below the water on the Canadian icebreaker *Ikaluk* and the newly converted Russian icebreaker *Mudyug*. The ratio of power saved to the power expended is about one (Keinonen et al. 1991).

Water-deluge system

Recent developments, such as the water-deluge system and low-friction epoxy paint, have allowed the use of unconventional bows on sea-going vessels (Johansson et al. 1994). A water-deluge system throws several tons of water every second on top of the ice ahead of the bow. This not only reduces friction between the ice and the hull but also submerges the broken ice pieces to help them move down under the hull. This was first installed on the Canadian icebreaker *Canmar Kigoriak*, which was fitted with a blunt spoon-shaped bow, to solve the ice pushing problem experienced with unconventional bows in the late nineteenth century. One time, when the water-deluge system was frozen solid, the *Kigoriak* could not make good progress through a broken ice cover because of the ice-pushing problem. With the water-deluge system operating perfectly a few days later, she was able to make good progress in this same broken ice field (Johansson et al. 1994).

According to the data compiled by Keinonen et al. (1991), the power saved as a result of operating a water-deluge system is much greater than the power expended. These data were collected for the *Canmar Kigoriak* during icebreaking with a bare hull and also with an epoxy-coated hull.

On the Canadian icebreaking supply vessel *Robert Lemeur*, this system has been effective in reducing the resistance by 20–30% over the entire speed range (Dick and Laframboise 1989). On the Swedish icebreaker *Oden*, the water-deluge system has been upgraded to act as a bow thruster by directing the flow to one side of the ship. With a control system and a modified nozzle design, it is possible to obtain a side force of 0.1 MN at the forward tip of the ship.

POWER AND PERFORMANCE

As expected, installed power increases with ship size as represented by ship beam. The power-versus-beam plot of the data on existing polar ships (Fig. 20) shows a trend of increasing power as a function of beam. Except for a few data points, there appears to be a well-defined relationship between power and beam.

Using information on the performance of existing polar ships in ice, Dick and Laframboise (1989) plotted the bollard pull/beam vs. the ice thickness an icebreaker is capable of breaking at a speed of about 1 m/s or 2 knots (Fig. 21). For comparison, the data are normalized on performance for a speed of 2 knots. There appears to be a well-defined minimum performance. For a particular bollard pull/beam, the range of ice thickness above a minimum performance value represents an improvement in icebreaking capability of the hull shape. Figure 21 shows that the most recent ships have more efficient hull forms.
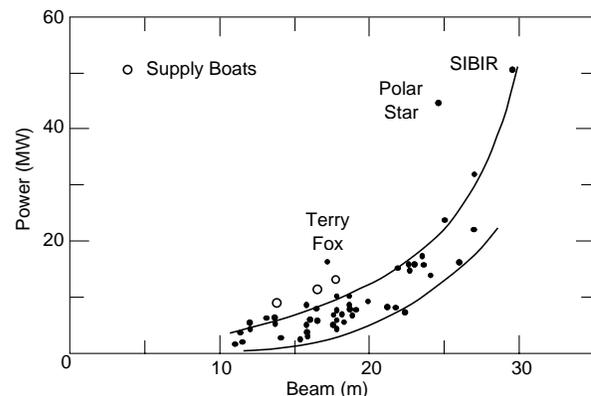
Figure 20. Power vs. beam for icebreakers (after Dick and Laframboise 1989).
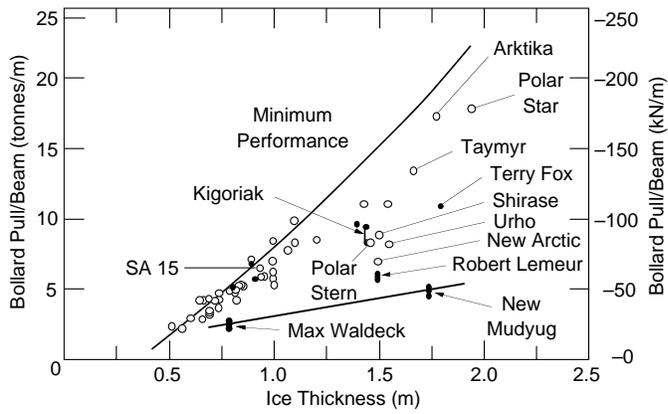
23

Figure 21. Icebreaking performance: bollard pull/ beam vs. ice thickness. Bollard pull is measured or calculated; data are adjusted for a speed of 2 knots (after Dick and Laframboise 1989).
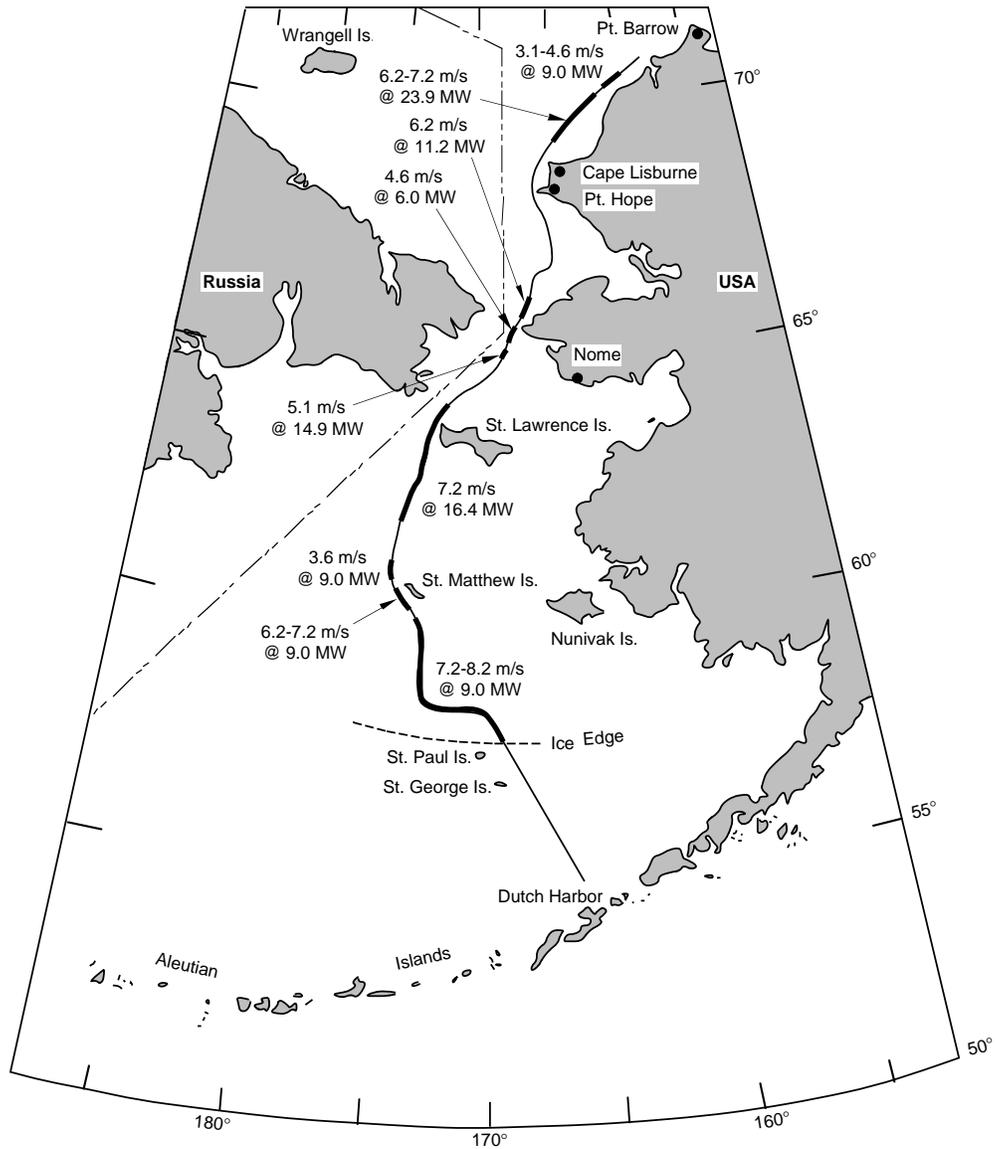

Figure 22. Speeds and power levels of U.S. icebreaker Polar Sea *during her transit from 23 March to 4 April 1983 (after Voelker 1991).*

Table 2. Estimates of daily fuel consumption for a *Polar*-class icebreaker.

	Fuel consumption rate	
Ship status	(gallons/day)	(tons/day)[*]
Stationary—systems providing only		
normal hotel services	4,000	12
Open water transit (three propulsion diesel)	14,000	42
Icebreaking (six propulsion diesel)	25,000	75
Icebreaking (diesel on wing shafts,		
gas turbine on center shaft)	35,000	105
Icebreaking (three gas turbines)	60,000	180

[*] Relation used for conversion: 1000 gallons/day ≈ 3 tons/day.

Fuel consumption rates

The fuel consumption rates of medium-speed and slow-speed diesel engines have been mentioned earlier. These rates may have been obtained for open water conditions. Data on the actual fuel consumption of icebreakers working in ice are very scarce.

Voelker (1990) has summarized the mean fuel consumption rates of 16 *Polar*-class ship deployments to the Alaskan Arctic (Table 2). The rate of fuel consumed depends on the ship's activity and the power plant being used. The *Polar Sea* and *Polar Star* can each generate up to 13.4 MW (18,000 shp) using diesel-electric propulsion systems. Alternatively, they can generate up to 45 MW (60,000 shp) by engaging their gas-turbine power plants. In Figure 22, Voelker's route map shows the sustained speeds for various power outputs during a midwinter expedition through the Bering Sea and into the Alaskan Chukchi Sea. Figure 23 identifies sections of the route where ramming of the ice was required to make headway. The number of rams and the average shaft power used are also given in Figure 23.

According to the brochures of the Murmansk Shipping Company, the rates of fuel consumption of three classes of ships (*Norilsk, Mikhail Strekalovskiy* and *Dimitriy Donskoy*) are listed in Table 3.

Performance prediction

Keinonen et al. (1991) compared the performance of 18 major icebreakers of different sizes and types to establish methods of expressing and estimating their performance in terms of ship design features and parameters. The data were obtained from full-scale trials of icebreakers in different geographical areas as well as in different ice

Table 3. Fuel consumption rates of a few Russian ships according to the information given in the brochures of the Murmansk Shipping Company.

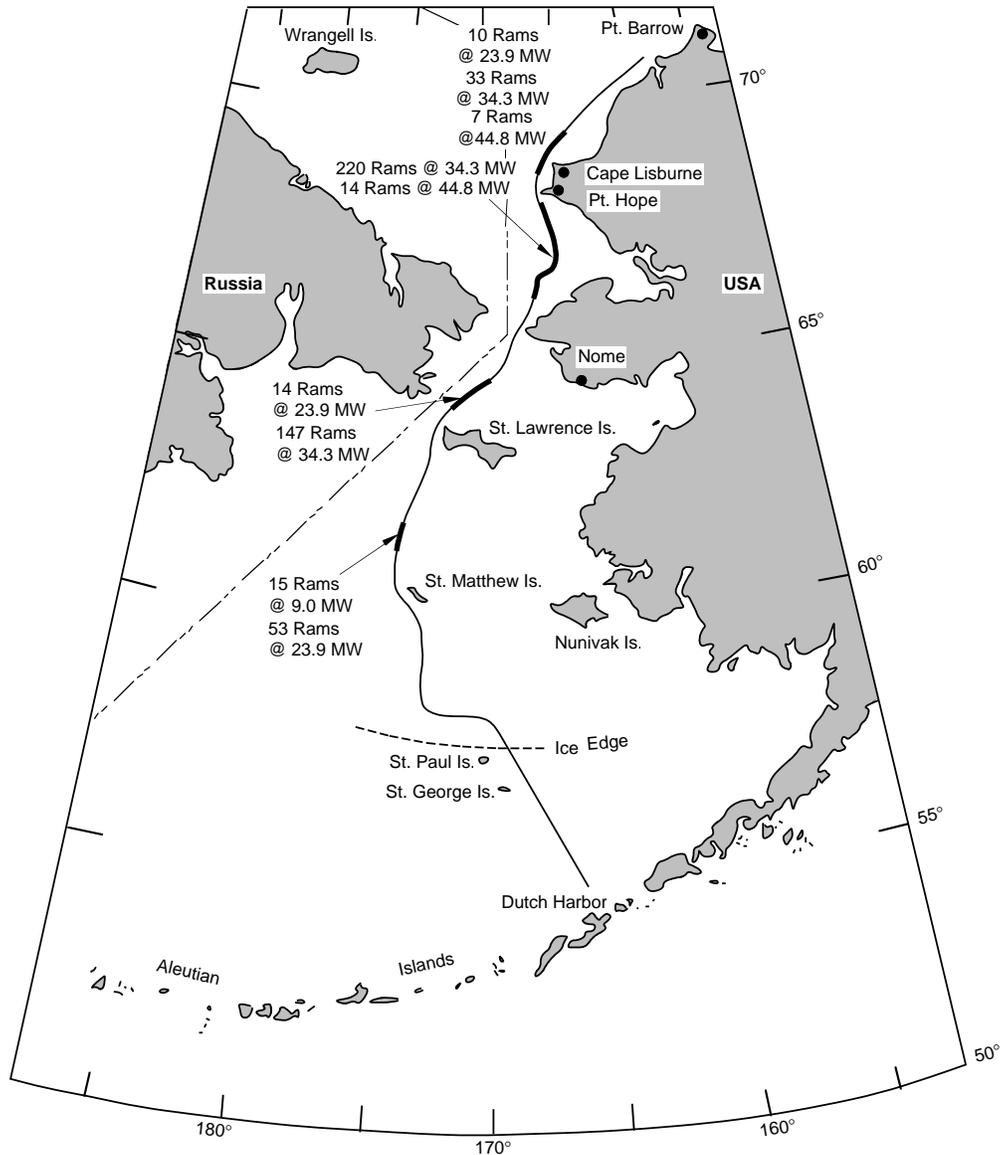|			Daily consumption rate (tons/day)		
		Storage		In port	
	Type of	capacity		Cargo	No cargo
Ship	fuel or oil	(tons)	Underway	operation	operation
SA15's	Diesel oil	783	2.0	2.0	1.0
Noril'sk	High viscosity				
Class	fuel	3743	76.0	7.0	3.0
	Lubricating oil	185	0.6	0.1	0.1
Mikhail	Diesel oil	329	5.0	2.5	2.5
Strekalovskiy	High viscosity				
Class	fuel	1348	43.1	7.3	7.3
	Lubricating oil	52	0.3	—	—
Dimitriy	Diesel oil	329	5.0	2.5	2.5
Donskoy	High viscosity				
Class	fuel	1348	43.1	7.3	7.3
	Lubricating oil	52	0.3	—	—

Figure 23. Number of ramming operations during the transit of U.S. icebreaker Polar Sea
from 23 March to 4 April 1983 (after Voelker 1991).

conditions. Though most of the hulls were coated with Inerta, a few hulls were bare steel, and one hull was fitted with a stainless-steel band at the waterline. Performance measures included in their study are level-ice hull resistance, propulsive performance, hull lubrication, ridge resistance, turning performance and open water resistance. According to Keinonen et al. (1991), these results were compiled to understand the influence of key parameters on the performance of icebreakers. The key parameters chosen for this comparison were simple and obvious to all observers. For detailed

information, readers are referred to their paper and to the reports prepared for that study. A summary of their performance predictors is given below.

Resistance in level ice
    For chined ships, an expression for ice resistance at a speed of 1 m/s is given as

$$R_1 = 0.08 + 0.0177\, C_S\, C_H\, B^{0.7}\, L^{0.2}\, T^{0.1}\, H^{1.25}$$
$$\{1 - 0.0083\,(t + 30)\}\,\{0.63 + 0.00074\,\sigma_f\}$$
$$\{1 + 0.0018\,(90 - \psi)^{1.4}\}\,\{1 + 0.004\,(\varphi - 5)^{1.5}\}$$

26

where R_1 = resistance in level ice at 1 m/s (MN)
C_S = water salinity coefficient (saline = 1, brackish = 0.85 and fresh = 0.75)
C_H = hull condition factor (Inerta = 1, new bare steel = 1.33 and old bare steel = 2)
B = ship beam (m)
L = waterline length of ship (m)
T = draft of ship (m)
H = ice thickness, taken to be ice thickness plus half the snow depth (m)
t = ice surface or air temperature (°C)
σ_f = flexural strength of ice (kPa)
ψ = average flare angle in bow region (°)
φ = average buttock angle in bow region (°).

For rounded-shoulder ships, an expression (using the same symbols) for the ice resistance at a speed of 1 m/s is given as

$$R_1 = 0.015\, C_S\, C_H\, B^{0.7}\, L^{0.2}\, T^{0.1}\, H^{1.5}$$
$$\{1 - 0.0083\,(t + 30)\}\,\{0.63 + 0.00074\,\sigma_f\}$$
$$\{1 + 0.0018\,(90 - \psi)^{1.6}\}\,\{1 + 0.003\,(\varphi - 5)^{1.5}\}.$$

Energy to penetrate an unconsolidated ridge

Based on the full-scale data, an expression for the energy to penetrate an unconsolidated ridge is given as

$$E_R = 0.25\, A_C\, A_R\, C_S\, C_H\, \{1 - 0.0083\,(t + 30)\}$$
$$\{1 + 0.012\,(90 - \psi)\}$$

where E_R = energy for ridge penetration (MJ)
A_C = largest cross-sectional area of vessel (m^2)
A_R = ridge depth × ridge profile length (rubble only) (m^2)
C_S = water salinity coefficient (saline = 1, brackish = 0.85 and fresh = 0.75)
C_H = hull condition factor (Inerta = 1, new bare steel = 1.33 and old bare steel = 2)
t = ice surface or air temperature (°C)
ψ = average flare angle in bow region (°).

Turning circle diameter

For vertical-sided chined vessels, and in level ice of thickness equal to 60% of the icebreaking capability at 1 m/s

$$D/L_{WL} = 38 \times 0.56^x$$

where D = turning diameter (m)
L_{WL} = length of waterline of ship (m)
x = reamer width relative to midbody length (%).

For rounded vessels with fully effective rudders, and in level ice of thickness equal to 60% of the icebreaking capability at 1m/s

$$D/L_{WL} = 0.022\,(PMB)^{1.75} + 3$$

where PMB is the percentage of waterline length representing a parallel midbody (%).

For rounded vessels with partially effective rudders, and in level ice of thickness equal to 60% of the icebreaking capability at 1 m/s

$$D/L_{WL} = 0.14\,(PMB)^{1.5} + 3.$$

Open water resistance

For chined vessels, open water resistance is expressed in terms of Froude number

$$R/Disp = 1.1\, F_n^{1.64}$$

where R = open water resistance (kN)
$Disp$ = ship displacement (tons)
F_n = Froude number $\left(v/\sqrt{gL}\right)$
v = ship velocity
L = ship length between perpendiculars.

For vessels of rounded shapes, open water resistance is expressed in terms of Froude number

$$R/Disp = 0.4\, F_n^{1.68}.$$

Propulsive performance

Propulsive performance is defined as the ratio of net thrust to the shaft power (or specific net thrust). Keinonen et al. (1991) compared the propulsive performance of different icebreakers at full power. The data are shown in Figure 24a for different speeds for ships having ducted propellers, whereas similar data for ships with open propellers are shown in Figure 24b. A comparison of the data for the single-screw, ducted, controllable-pitch system of *Kigoriak* and *Arctic* with that of twin-screw, open, controllable-pitch system of *Terry Fox* shows that the net propulsive performance of the ducted systems has an advantage of 27% over the open system at low speeds. However, this advantage decreases at higher speed until both systems have the same specific net thrusts.
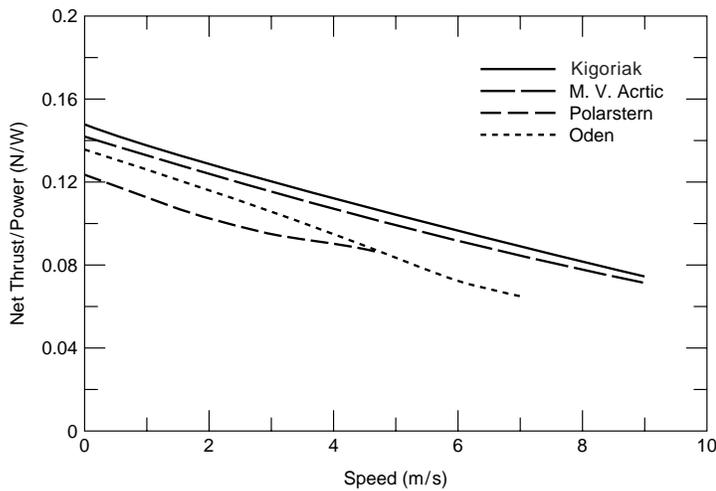
a. Propellers in nozzles.
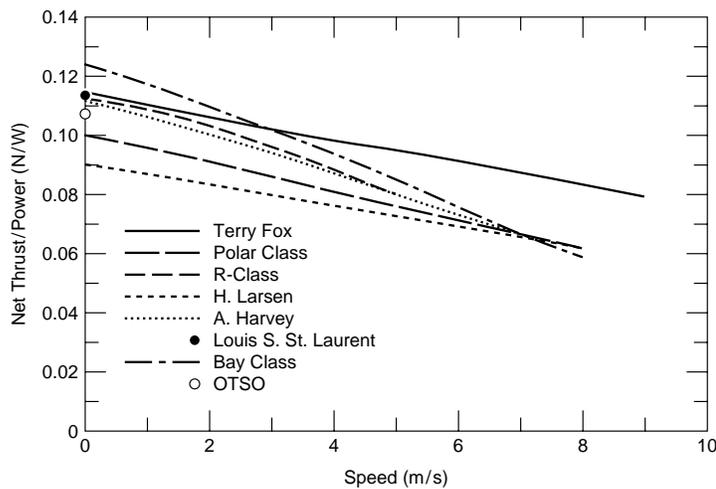
b. Open propellers.

Figure 24. Specific net thrust vs. speed at maximum shaft power, indicating propulsive performance (after Keinonen et al. 1991).

FUTURE ICEBREAKERS

At present, some of the largest icebreakers, such as the Russian *Yamal*, are capable of operating in multi-year ice without any concern for possible damage, often at speeds in the range of 15–20 knots (7.7–10.3 m/s) (Brigham 1994). The icebreakers of this class are strongly built, with a robust propulsion system. Because of nuclear power, their unlimited endurance sets this class of ships apart from the rest of the icebreakers in the world. Detailed information about the icebreaker *Yamal* by R.K. Headlands of Scott Polar Institute is given in Appendix A, which states that the maximum ice thickness *Yamal* can penetrate while navigating is estimated to be 5 m, and that *Yamal* has broken through individual ridges estimated to be 9 m thick.

The contract to build an icebreaker, named *Healy*, for the U.S. Coast Guard has been executed, with

a delivery scheduled for mid-1998.* Its displacement will be 16,303 tons, and its length, beam and maximum draft will, respectively, be 128 m, 25 m and 9.75 m. The propulsion systems will consist of 22.4 MW (30,000 hp), medium-speed diesel engines with ac–ac electrical transmission to drive two fixed-pitch propellers. Model tests indicate that it will be able to break 1.6-m-thick, level ice continuously. It will have a dynamic positioning system to support oceanographic research.

The design and model testing of a new U.S. Arctic Research Vessel has been completed (Kristensen et al. 1994), but it is not known at this time when this research vessel will be built. This vessel will support science missions in the Arctic well into

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* Personal communication, A.D. Summy, Captain, U.S. Coast Guard, 1994.

28

the next century. The ship will have an overall length of 103.6 m, waterline length of 93.9 m, maximum beam of 27.1 m, depth of 12.2 m, draft of 9.1 m and a displacement of 11,684 tons. The vessel will have a flat bow with a ridge in the middle to break ice in bending and to clear it on the side, and a double hull to comply with the CASPPR guidelines. The propulsion system will include diesel engines of 15 MW (20,000 hp) and two-ducted 4.1-m-diameter controllable-pitch propellers.

As mentioned earlier, it is well within known and proven technology and experience to design, build and operate an icebreaker year-round independently in the Arctic. Keinonen (1994) has set down the performance criteria of a proposed icebreaker for the Northwest Passage, as given in Table 4. The design parameters of the icebreaker are given in Table 5, in which the values of those parameters for *Yamal* are also given for comparison. It can be seen that the icebreaker proposed

for the Northwest Passage is slightly bigger in size and displacement than *Yamal*, but the designed installed power (from diesel engines with a mechanical transmission to two controllable-pitch propellers in nozzles) is less than that of *Yamal*, which is equipped with three propellers driven by nuclear power through an electrical transmission. Auxiliary systems for the Northwest Passage icebreaker include water wash and heeling tanks, as well as a stainless steel belt with Inerta coating elsewhere.

Figure 25 is a sketch of an "iceraker," as proposed by Johansson et al. (1994). The proposed iceraker has a vertical-sided, 50-m-wide hull that also has a submerged cantilever in front of and on each side of the vertical, wedge-shaped bow. At the edge of this cantilever, air is introduced into the water at a depth of about 15 m. Seven spurs are located on top of the cantilever at a transverse spacing of about 20 m. The spurs create a 120-m-wide channel of broken ice by deflecting a floating

Table 4. Performance criteria for a Northwest Passage icebreaker (after Keinonen 1994).

Performance	Criteria/measure	Requirements
Level ice	2 knots at continuous speed	3 m
Multi-year ice	Thickest broken ice on first ram	8 m
Backing	Thickest level ice ice broken in a continuous motion	2 m
Turning	Thickest ice below which turning circle is smaller than $10 \times L_{wl}$	2 m
Extraction	Wind speed in which able to extract (also needs to be able to extract after any ram)	15.4 m/s (30 knots)

Table 5. Comparison of design parameters of proposed Northwest Passage icebreaker (Keinonen 1994) with those of the Russian icebreaker *Yamal*.

Parameter	Unit	Proposed values for a Northwest Passage icebreaker	Values for the Russian icebreaker Yamal
Displacement	ton	30,000	23,460
Water line length	m	140	136
Length of parallel mid body	m	70	no data
Beam at water line	m	30	28
Draft	m	14	11
Hull design concept	type	four-section bow	conventional, straight wedge shaped, double
Stem/buttock angle	degrees	17	17
Flare/frame opening angle	degrees	60	—
Shaft power	MW	40	56
Propellers	number/type	2CP in nozzles	3FP
Drive system	engine/transmission	diesel/mechanical	nuclear/steam turbine/ electrical
Reamers	type—width m	two way—2 m	none
Appendages	names	stern pods, shilling rudders, bottom wedge	ice horn
Auxiliary systems	types	water wash, heeling	air bubbler
Hull coating	types	Stainless and Inerta coating with cathodic protection	polymer coating

29

Top View

Profile View

Water Line

Ramming Multi-year Floes (30 m)
Loose Pack (24 m)
Breaking Solid Ice (18 m)

0   20   40   60   80   100   120   140   160   180   200 (m)
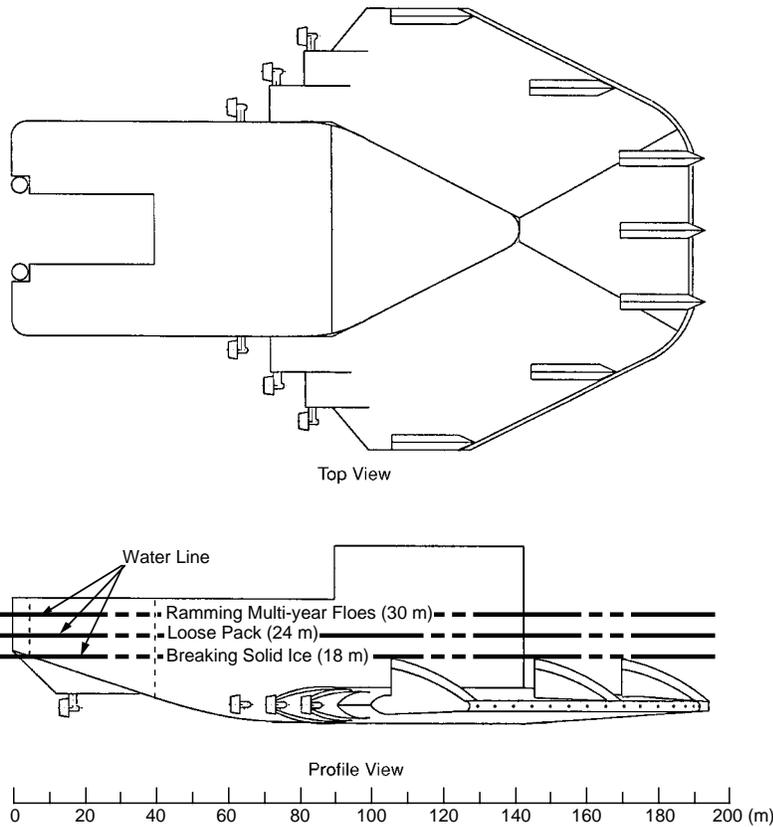
Figure 25. New "iceraking" concept, as proposed by Johansson et al. (1994).

ice sheet upward sufficiently to fracture it. The air released from the edge of the cantilever produces a current to take the broken ice pieces past the 60-m-wide main body of the iceraker. While moving through broken ice, the iceraker is submerged to a deeper level so that the spurs do not contact the ice. To break a thick (8-m) multiyear ice floe, the iceraker is submerged even deeper and allowed to strike the floe to split it in a single impact.

The proposed "iceraker" represents an innovation that may not become a reality for a long time. Enormous economic driving forces must be present to encourage building this type of vessel that is such a great departure from existing ice-breaking ships.

SUMMARY

The current status of icebreaking technology has been presented, along with a brief history. The improvements in bow designs to break level ice efficiently were suggested more than a hundred years ago. However, those designs could not be implemented in sea-going ships because of ice-pushing problems. With the help of new developments to reduce friction between the ice and the

hull of a ship, it has now become possible to build icebreakers with improved bow shapes to cope with any type of ice. The developments in marine propulsion systems were also incorporated into the icebreaking technology to obtain higher efficiency, reliability, flexibility and maneuverability. Development of auxiliary systems, such as heeling tanks, air-bubbler systems, water-deluge systems, low-friction coatings, etc., allows an icebreaker to perform effectively in ice conditions more severe than those for which they were designed.

A description of the Russian nuclear-powered icebreaker *Yamal* is given in Appendix A. An inventory of ships that are capable of navigating in at least 0.3-m-thick ice is presented in Appendix B.

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APPENDIX A: INFORMATION ABOUT THE NUCLEAR ICEBREAKER *YAMAL*

(Reproduced from an unpublished description given by R.K. Headland of
Scott Polar Institute, Cambridge University, UK)

The ship is one of three *Rossiya* class icebreakers leased to the Murmansk Shipping Company by the Russian Government (her sisters are *Rossiya* [launched in 1985] and *Sovetskiy Soyuz* [1990]).

The name is derived from a Nenets word meaning "End of the Earth," also applied to the Yamal Peninsula.

Her keel was laid on 25-V-1986 in St. Petersburg and she was launched on 28-X-1992

Registered number M 43048 and International Call Sign UPIL.

Length overall 150 m, at waterline 136 m. Breadth overall 30 m, at waterline 28 m. Draft 11.08 m.

Height, keel to mast head: 55 m on 12 decks (4 below water).

Ice knife, a 2-m-thick steel casting, is situated about 22 m aft of the prow

Displacement 23,455 tonnes; capacity 20,646 gross registered tons.

The cast steel prow is 50 cm thick at its strongest point.

The hull is double with water ballast between them. The outer hull is 48 mm thick armor steel where ice is met and 25 mm elsewhere.

Eight bulkheads allow the ship to be divided into nine watertight compartments.

Ice breaking is assisted by an air bubbling system (delivering 24 m^3/s from jets 9 m below the surface), polymer coatings, specialized hull design and capability of rapid movement of ballast water. Ice may be broken while moving ahead or astern.

An M1-2 or KA-32 helicopter is carried for observing ice conditions ahead of the ship.

The ship is equipped to undertake short tow operations when assisting other vessels through ice.

Searchlights and other high intensity illuminations are available for work during winter darkness.

Complement 131: 49 officers and 82 other ranks.

Power is supplied by two pressurized water nuclear reactors using enriched Uranium fuel rods.

Each reactor weighs 160 tonnes, both are contained in a closed compartment under reduced pressure.

Fuel consumption is approximately 200 g per day of heavy isotopes when breaking thick ice. 500 kg of Uranium isotopes are contained in each reactor when fully fueled. This allows about 4 years between changes of the reactor cores.

Shielding of the reactor is by steel, high density concrete and water. The chain reaction can be stopped in 0.6 seconds by full insertion of the safety rods.

Used cores are extracted and new ones installed in Murmansk, spent fuel is reprocessed, and waste is disposed of at a nuclear waste plant.

Ambient radiation is monitored by 86 sensors distributed throughout the vessel. In accommodation areas this is 10 to 12 μRöntgen/hr, within the reactor compartment, at 50% power, 800 μRöntgen/hr.

The primary cooling fluid is water, which passes directly to four boilers for each reactors; steam is produced at 30 kg/cm^2 (310°C).

Main propulsion system: each set of boilers drives two steam turbines that turn three dynamos (thus six dynamos may operate). 1 kV dc is delivered to three double-wound motors connected directly to the propellers.

Electricity for other purposes is provided by five steam turbines turning dynamos that develop a total of 10 MW.

There are three propellers; starboard and midships ones turn clockwise, port turns counter-clockwise. Shafts are 20 m long. Screw velocity is between 120 and 180 rpm.

Propellers are fixed, 5.7 m diameter and weigh 50 tonnes; each has four 7-tonne blades fixed by nine bolts (16 tonne torque applied); inspection wells allow them to be examined in operation.

Four spare blades are carried; diving and other equipment is aboard so a blade may be replaced at sea; each operation takes from 1 to 4 days (three such changes have been necessary on *Rossiya* icebreakers since 1985).

A propulsive effort of 480 tonnes can be delivered with 18–43 MW (25,000 shaft horsepower) from each screw (total 55.3 MW [75,000 shaft horsepower]).

Power can be controlled at a rate of 1% a second.

Maximum speed is 22 knots (40 km/hr); full speed in open water is 19.5 knots (35 km/hr); breaking ice 2–3 m thick can be done at 3 knots (5.5 km/hr) continuously.

Maximum ice thickness that can be penetrated while navigating is estimated as 5 m; individual ridges estimated at 9 m thick have been broken through.

Helm controls one rudder, which turns 35° either way, operated by four hydraulic cylinders powered by one of two pumps. It is protected by an ice-horn for moving astern.

Steering may also be provided by directing air jets of the bubbling system (comparable to use of bow-thrusters).

Auxiliary power is available from three diesel generating sets: 1 MW (1×) and 250 kW (2×).

Anchors: two 7-tonne anchors with 300 m of chain each, and four ice anchors.

Four deck cranes are aboard; the largest pair can lift 16 tonnes each.

Sea water distillation: two vacuum stills can supply 5 m^3 of fresh water an hour each (240 m^3/day).

Differential ballast tanks are suitable fore and aft, and athwart the ship; the pumps are capable of moving 1 m^3 of water a second.

Ship has 1280 compartments (cabins, storage areas, machine rooms, etc.).

Sufficient provisions and supplies can be carried to operate for 7 months.

Safety equipment includes: 1 launch, 2 fully enclosed lifeboats, and 18 inflatable life rafts.

APPENDIX B: AN INVENTORY OF EXISTING SHIPS THAT ARE CAPABLE OF NAVIGATING IN AT LEAST 0.3-m-THICK ICE COVER

(Inventory compiled by Leonid Tunik)

> [The paper version of this report includes the material listed in the Table of Contents above, but is not reproduced here. Paper copies are available through the National Technical Information Service. See the inside cover of this report for ordering information.]

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13. ABSTRACT (*Maximum 200 words*)

Since the advent of steam power, icebreakers have been built to navigate in ice-covered waters. The hull forms of early icebreakers were merely an adaptation of open water hull shapes, by sloping bow angles more to create vertical forces for breaking ice in bending. However, these bow forms were found to be unsuitable for sea-going vessels because they push broken ice ahead of them. This experience led to construction of all sea-going vessels with wedge-shaped bows from 1901 to 1979. With the introduction of low-friction coatings and the water-deluge system, it is now possible to operate ships with blunt bows efficiently in broken ice. New developments in marine propulsion technology have also been incorporated to obtain better icebreaking efficiency and performance. Both fixed-pitch and controllable-pitch propellers are in use. Nozzles surrounding the propellers are also used to increase the thrust and to reduce ice–propeller interaction. Electrical and mechanical transmission systems have been used in icebreakers to improve the characteristics of the propulsion system. Though many types of prime movers are used in icebreakers, medium-speed diesel engines are the most popular because of their overall economy and reliability. Appendix A is a description of the Russian icebreaker *Yamal*, which is one of the largest and most powerful icebreakers of the world today. Appendix B contains an inventory of existing ships that are capable of navigating in at least 0.3-m-thick ice. Some of the present icebreakers are capable of

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42

13. ABSTRACT (cont'd).

navigating almost anywhere in the ice-covered waters of the Arctic and the Antarctic, and multi-purpose icebreakers have been built to operate not only in ice during the winter but also in open water doing other tasks during the summer. With sufficient displacement, power, navigation equipment, and auxiliary systems, future icebreakers that can operate independently year-round in the Arctic and the Antarctic are well within the known technology and operational experience.