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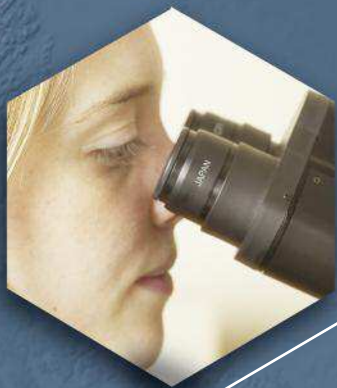
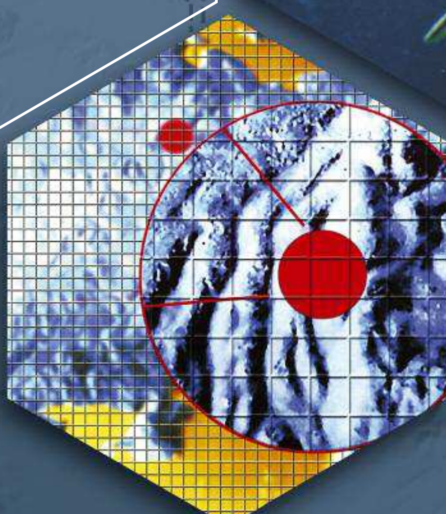
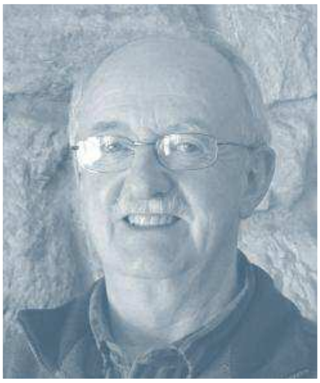
Reviews & Papers





Breaking the Ice



STEPHEN JONES

Jones provides a comprehensive review of icebreaking ships over the past 120 years.

Who should read this paper?

This review will be of interest to those designing, building, using, or modelling icebreaking ships. It will also be of interest to those living in the North who are dependent on ships for their supplies, and to the oil and mining companies that operate ships in the Arctic. The review will be of benefit to young people just starting out in the icebreaking business and will help future designers of icebreakers realise what has gone before and where we are headed.

Why is it important?

This paper is a review of the icebreaking business since its origins approximately 120 years ago. In the context of the theme for this issue, Ocean Sovereignty – Fencing the Continental Shelf, it gives a good background to Arctic sovereignty issues. It is also the first review of the subject to appear for many years.

About the author

Stephen J. Jones is a Principal Research Officer with National Research Council of Canada's Institute for Ocean Technology (IOT) in St. John's, Newfoundland, and is now semi-retired. He has earned degrees in Physics from the University of Birmingham, England (B.Sc., 1964 and Ph.D., 1967), with his Ph.D. research focusing on the mechanical properties of ice. Since, his whole career has been related to ice, first with Environment Canada's Glaciology Subdivision in Ottawa from 1967-1984, and then with the National Research Council since 1984. He has conducted laboratory research as well as Arctic and Antarctic fieldwork and, since 1984, has been concerned with research on the modelling of ships in ice using the ice tank at IOT.

A HISTORY OF ICEBREAKING SHIPS

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First Ideas on Icebreaking Ships

The first detailed description of icebreaking ships was written by Robert Runeberg, the son of Finland's Poet Laureate and writer of their national anthem, who published an extensive paper on the operation of steamers for winter navigation and icebreaking, with particular reference to the Baltic (Runeberg, 1888/89). Today, Finland can rightly claim to have built more icebreakers than any other country. He discussed both continuous icebreaking and "charging" and derived expressions for the "vertical pressure at the bow," the "thickness of ice broken," and the "total elevation at the fore-end" calculated from ship geometry for the case of continuous icebreaking. He claimed that the results agreed, "tolerably well" with the actual performance of six ships. He recognized the importance of hull-ice friction on resistance, taking, without any justification, a coefficient of friction of 0.05, as well as the role of the stem angle of the bow: "…the vertical component should be as large as possible. This is affected by making the bow very sloping at the waterline." This is still true today. His ideas were instrumental in the design of the Swedish built *Murtaja* in 1890 and shown in Fig. 1.

However icebreaking ships had been built before *Murtaja*. In 1836, the *Norwich*, an icebreaker using paddle wheels for propulsion, was introduced on the Hudson River (Ramsay, 1947), and in 1845 a totally flat icebreaking bow was proposed for the Elbe River (Prager, 1987). A barge-like ship with five circular saws to cut level ice ahead of the unit was proposed in 1867 for the Weichsel River (Prager, 1987). Two additional circular saws further aft were used to widen the channel. Somewhat surprisingly perhaps, in the UK in 1868, the Birmingham Canal Navigations Company built a narrow, wooden icebreaker boat *Samson*, 12.2 m (40 ft) in length, presumably to keep the canal open in winter. Several other similar canal icebreakers were built in the UK around the turn of the 20th century (National Register of Historic Vessels). In about 1870, a Russian merchant, Britnoff, built a small single screw tug, *Pilot*, with the express intention of icebreaking in the Port of Kronstadt. In 1871, the appropriately named *Eisbrecher I* was built in Hamburg and operated between Hamburg and Cuxhafen – a small ship of 500 tons displacement and 600 hp with a gently curving bow since referred to as "spoon shaped" – followed in 1881 by the Swedish built *Isbrytaren*, *Staefkodder* and *Bryderen* in 1883 and 1884 for Denmark.

Fig. 1. Finland´s first icebreaker *Murtaja*, built in 1890, was described as the "newest, biggest and strongest icebreaker in Europe." Its maximum horsepower was 1,600.

In 1888, the Michigan Central Railway Company ordered a large icebreaking ferry with 3,000 hp, a considerable magnitude in those days. This design was fitted with a second propeller in the bow in order to reduce friction and provide for more efficient transportation in broken ice. This proved so successful that all major Baltic icebreakers form 1898 to 1977 were fitted with bow propellers.

Runeberg (1888) can, however, claim to be the earliest published detailed paper on this subject followed closely by Tuxen (1898) and Swan (1899). Tuxen (1897) describes the six icebreaking ships then in use in Denmark built between 1883 and 1896. The newest, the *Slejpner*, had a displacement of 1,450 tons and 2,600 hp and had cost 33,300 pounds sterling to build! Swan (1899) describes the *Sampo* and the *Ermack* built in 1898 in the UK for the Finnish and Russian Governments respectively. Table 1 of Corlett and Snaith (1964) gives comprehensive details of all the icebreakers built up to 1899, and their Tables 2 and 3 cover the period up to 1954.

Icebreaking ships from 1900 to 1939

During the period 1900-1932, development continued along the lines of the *Ermack* with steam reciprocating machinery with two or three screws aft and one forward. The three large icebreakers *Leonide Krasin*, *Stephan Makarow*, and *Lenin* represented the peak of development in the UK, which then, with the exception of two ships, ceased to build for many years. Generally speaking, the vessels with bow propellers were in the majority and intended for service in the Baltic and those without bow propellers for Arctic service in the White Sea and at Archangel.

This period saw the entry of Canada as an icebreaker building country, the first vessel noted being *Mikula Selianinovitch*, built for the Archangel/White Sea service in Montreal in 1916 (Fig. 2). This considerable icebreaker of 8,000 hp was the start of the tradition of icebreaker building in Canada and was followed in 1929 by the *Saurel* of approximately half the power (3,600 hp) and intended for St. Lawrence service and Arctic escort. The *N.B. McLean* followed in 1930 for the same service and was approximately half as powerful again (6,500 hp). It is to be noted that during this period Canadian icebreakers adhered in type very closely to the European with flare in the region of 20^{o} and strong or moderate tumble home below the upper deck, this feature being introduced in *Sampo* and continued generally throughout subsequent European icebreakers.

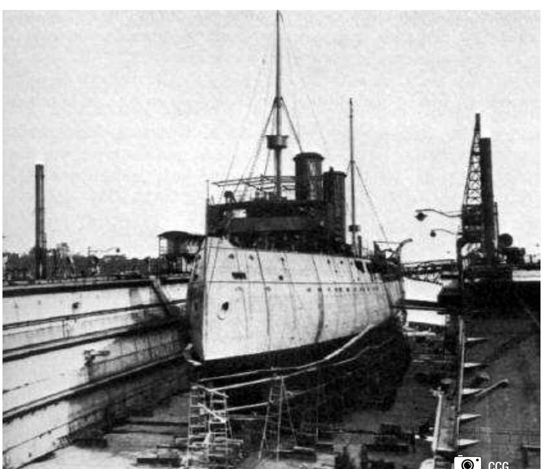
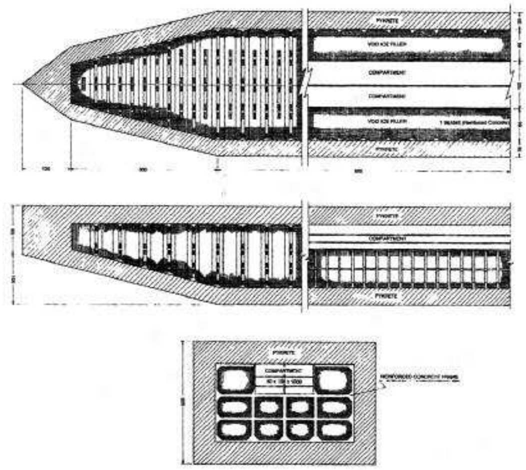


Fig. 2. The *Mikula Selianinovitch*, built in Montreal, 1916.

In 1932, a notable ship *Ymer* was constructed at Malmö for service at Stockholm. What was unusual was the installation of diesel-electric propulsion making it the forerunner of the majority of modern icebreakers whether fitted with bow propellers or not. Towards the end of the 1930s the Soviet ice breaking fleet was augmented by 7 large icebreakers of the *Stalin* and *Kirov* classes, designed for work in Arctic waters with three stern propellers, as it would have been useless to try and break the hard polar ice with fore propellers. The *Stalin* class was fitted with steam reciprocating machinery and the *Kirov* was diesel-electric. In basic type, therefore, the *Stalins* followed closely the tradition set by the modified *Ermack* and were a continuation of what was fundamentally an out-dated type of ship as diesel-electric machinery made possible a higher output per unit weight and volume, and also gave superior manoeuvrability, in comparison to steam engine machinery, allowing direct control from the bridge which was exploited in the *Kirov* class. The Finnish *Sisu* built in 1939, followed closely the design principles of the *Ymer*. The Ymer era was continued right through the Second World War, in particular in the U.S.A. where eight diesel-electric icebreakers were built, each with 10,000 propeller hp closely following *Ymer* as a pattern and with lines almost identical to *Sampo*. Seven of these vessels were sister-ships and formed the well-known *Wind* class, discussed below.

Papers on the more scientific aspects of icebreaking started to appear during this period. Kari (1921) gave, in a brief note, some empirical equations for determining the required power, displacement, length, and draught of an icebreaking ship but no derivation or justification for them was given. He also recognized the importance of low stem angle to provide a downward force.

In what appears to be the first contribution from North America, Simonson (1936) showed that the stem angle was important and derived a simple equation for stem angle as a function of thrust, vertical force, and trim angle. He concluded "the maximum thickness of ice that can be broken by a given ship without stalling depends upon the limiting angle that can be built into the bow," and he added "… the frame sections, they should show a marked flare at the waterline to relieve the crushing force of the ice." He was also the first to recognize the importance of the strength of the ice and, referring to some experiments at the University of Illinois (Beach et al. 1895), gave a tensile strength of freshwater ice as 102-256 psi (0.7-1.8 MPa) for temperatures of 19.4° to 23° F (-7° to –5° C). Simonson (1936) took the higher value as the strength of freshwater ice and the lower for sea ice, even though all the experiments seem to have been done on freshwater ice, and produced a graph in which the breaking force required for different thickness of both types of ice was calculated. His ideas were used in the design of the Wind-class American icebreakers around 1940.



INTERNATIONAL GLACIOLOGICAL SOCIETY

Fig. 3. The proposed aircraft carrier to be made of ice, from Gold (1990).

The only other pre-World War II paper was a major paper by Shimanskii (1939) who employed a semi-empirical method for investigating continuous mode icebreaking resistance. He developed several parameters for icebreakers, which he termed "conditional ice quality standards," i.e. the form of the equation was developed but certain coefficients in the equation had to be determined from full-scale data.

Icebreaking ships from 1940-1960

During the war nothing was published, of course, although icebreaking ships were being used significantly. Although not icebreaking, an interesting development was the British idea of building a ship out of ice to serve as an aircraft carrier in the Atlantic, as shown in Fig. 3. This *Habbakuk* project as it was known, has now been described in detail by Gold (1990). While a large amount of research on the strength and related properties of ice were conducted in Canada, no ship was ever built, partly because of cost and partly because aircraft became capable of crossing the Atlantic without re-fuelling.

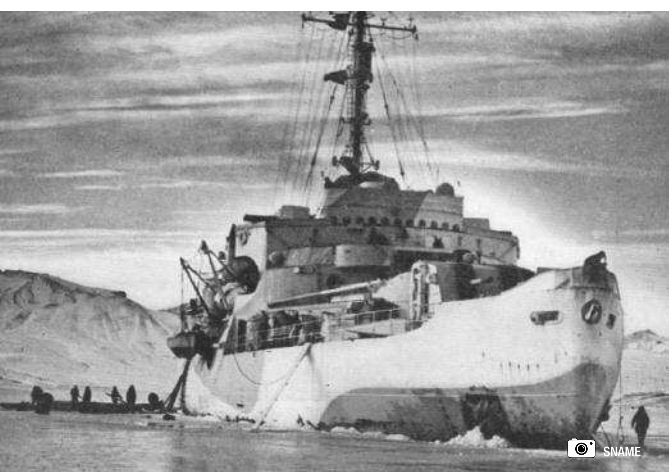


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Fig. 4. The "Northwind" class of icebreaker described by Johnson (1946) unloading supplies on ice in Greenland.

After World War II, Admiral Harvey Johnson described the U.S. Coast Guard's icebreaking vessels, in a detailed review of their work since 1936, when they were charged with "keeping open to navigation by means of icebreaking operations, channels and harbors in accordance with the reasonable demands of commerce (Johnson, 1946)." His paper details the history of American icebreaking ships up to 1946. The *Raritan* and the *Naugatuck* were the first U.S. Coast Guard vessels designed principally with ice breaking characteristics. They were single-screw, diesel-electric cutters, 110ft (33.5 m) long with 1,000 SHP and built in 1939. The Coast Guard's mandate was later extended to assist naval vessels built on the Great Lakes to reach the open ocean by way of the Mississippi waterway during winter. He described the development of the *Wind* class in detail (Fig. 4), particularly their design and strength, which was very successful around Greenland and in Russian waters during the war. Seven *Wind-class* ships were built during and after the 2nd world war, as well as the *Mackinaw*, designed for the Great Lakes with a smaller draught but larger length and breadth, all diesel-electric with one fore propeller and two stern, and closely resembling the *Ymer.* For operations in the Arctic, the fore-propeller could be removed and all the power (10,000 HP) could be split between the two stern propellers.

For the Great Lakes the USCG developed an ice plow, which was based on earlier Dutch experience with tugs and river towboats, as shown in Fig. 5. It was attached to existing ships and cleared a channel wider than the convoyed vessels, and kept the waterway from Lake Michigan to free water via the Mississippi open for movement of naval vessels during the winters of 1942-44.

Vinogradov (1946) described some of the Russian experience as well as giving an equation for the downward icebreaking force developed.

Jansson (1956[a] and 1956[b]) summarized the history of icebreaking in a major review article. He discussed in detail the history of icebreaking from what he considered the earliest true icebreaker, *Eisbrecher 1*, mentioned previously, and their bow shapes and propellers up to 1956. He described the history of the bow propellers, which originated with ships operating on the Great Lakes where pack ice was a major problem. There, vessels that got into difficulties were able to force their way through by backing into the ice. The natural consequence was that ships were built with bow propellers (Fig. 6). Thus, in 1888, the ferryboat *St. Ignace* was built, with a stern propeller driven by 2,000 hp, and fore propeller by 1,000 hp. The primary action of the fore propeller was to wash away water and broken ice from the fore end of the ship and thus reduce friction between the ice and the bow sides of the ship. Based on this American experience, the *Sampo* and the *Ermack*, built in UK, were also equipped with fore propellers but the large Russian *Ermack* was used against polar ice and the fore machinery was damaged, after which the fore propeller was removed. Developments proceeded with the building in 1926 of the Swedish *Atle* and the Finnish *Jääkarhu* equipped with oil-fired boilers rather than coal-fired, and the *Jääkarhu* was also equipped with heeling tanks which made it possible to heel the vessel a few degrees by pumping water between the tanks on either side. This had the effect of reducing friction at the sides of the ship. The wash of the fore propeller was, however, non-symmetrical, due to the direction of rotation, as a single fore propeller will always produce a side force whose varying moment makes steering and manoeuvring to one of the sides more difficult. Therefore, a major advance after the war was the first icebreakers equipped with two bow propellers. This idea originated with the *M.V. Abegweit*, a diesel electric ferry built in Canada in 1947 for operations in the Northumberland Straits (Fig. 7) where she was successfully used until 1982, then being replaced by another ship of the same name. After her retirement, the original *Abegweit* was purchased by, and now serves as, the centre of operations for the Columbia Yacht Club in Chicago, Illinois.

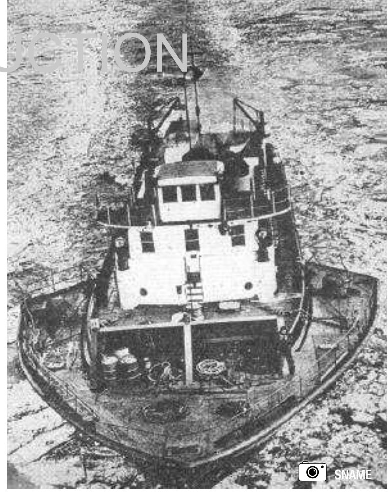

Fig. 5. An ice plow attached to a river tender type Coast Guard Cutter breaking ice on the Mississippi river system (Johnson 1946).

Fig. 6 The bow propeller of a Wind-class icebreaker.

The Finnish *Voima*, built in 1953, was the first real icebreaker to be equipped with two bow propellers and

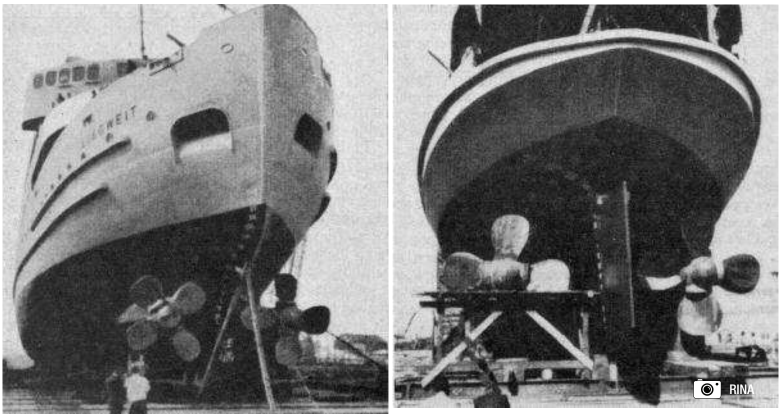

Fig. 7. The bow and stern of the *Abegweit* showing the two bow and stern propellers (Jansson 1956).

two stern. Interest in Arctic type icebreakers without bow propellers also increased in the mid-fifties, particularly in Canada.

Jansson (1956[a] and 1956[b]) also discussed the science of icebreaking. He quoted, without reference, values for the physical properties of freshwater ice, apparently at –3°C, as:-

Elastic Modulus	= 70,000 kg/cm²	(6.9 GPa)
Tensile and bending strength	= 15 kg/cm²	(1.5 MPa)
Compressive strength	= 30 kg/cm²	(2.9 MPa)
Shear strength	= 7 kg/cm²	(0.7 MPa)

and said he had failed to find any reliable values for sea ice. He said that the strength increased with lower temperatures and even followed a rule that "… ultimate strength is approximately proportional to the square root of the number of degrees below freezing point." No details were given about these experiments, which is unfortunate. He also quoted values of the coefficient of friction between ice and metal as 0.10 to 0.15 for fresh, or Baltic, ice and 0.20 for salt water and polar ice. He gave a simple formula for the total ice resistance as:-

$$R_{ice} = (C_1 h + C_2 h v^2) B \qquad (1)$$

where C_1 and C_2 are experimental constants, h is ice thickness, v is vessel speed and B is breadth of vessel at waterline. He showed that when icebreaking in "bursts", i.e. ramming, the maximum icebreaking work was proportional to the square of the change in trim and the square of the vertical force between the ship's fore stem and the ice edge. In the second part of his review, Jansson (1956[b]) discusses the open water resistance, propeller design and hull strength as well as equipment and accommodation. It is a thorough review of the state-of-the-art as it was in 1956.

In December 1957 the *Lenin* was launched in Leningrad (St. Petersburg). It was the first atomic or nuclear powered icebreaker and represented a major technological achievement (Alexandrov et al., 1959). It claimed to have a cruising speed of 2 knots in ice 2.4 m (8 ft) thick, and could remain at sea for one year. This was followed between 1971 and 1992 by five more nuclear icebreakers of the *Arktika* class, the most recent being the *Yamal*, shown in Fig. 8, as well as a lighter icebreaking container ship *Sevmorput*. The *Lenin* was laid-up in 1989 and the *Arktika* underwent life extension repairs to extend the lifetime of its nuclear installation from the original 100,000 hours to at least 175,000 hours.

At a Society of Naval Architects and Marine Engineers (SNAME) Spring Meeting held to celebrate the opening of the St. Lawrence Seaway (Fig. 9), German (1959) and Watson (1959[a][b]) both reviewed the Canadian experience and described the icebreakers then in service and those planned for the Canadian Department of Transport. Thiele (1959) described the technical aspects

Fig. 8. The *Yamal*, the youngest Russian nuclear icebreaker built in 1992.

Fig. 9. The first ship d'IBERVILLE to pass through the St. Lambert lock of the St. Lawrence Seaway, 1959.

of icebreaking operation stressing four problems including friction and Ferris (1959) discussed the proportions and forms of icebreakers. Little else was published before 1960.

Icebreaking ships from 1960-1975

The vast majority of the scientific literature on this subject has been published since 1960. The *Manhattan* voyages in 1969 and 1970, and the dramatic rise in oil prices in 1973 and again in 1979, led to a promise of extensive Arctic development. This in turn contributed to the importance of icebreaker design and to a corresponding interest in structures for use in ice-covered waters. The advent of model tests, ice tanks, analytical and numerical techniques has also meant a more scientific approach to the subject. Although model testing had started in Russia in the 1950s, the first published paper on model tests was by Corlett and Snaith (1964), who used a wax-like substance for their ice, for the *Perkun*, shown in Fig. 10, a small Baltic icebreaker.

Their paper is a complete review of the subject of icebreaking ships up to 1964, containing many references to previous work, and is essential reading for anyone interested in this subject.

Kashteljan et al. (1968) are usually credited with the first detailed attempt to analyze level ice resistance. They gave an equation for the total ice resistance, R_{TOT},

$$R_{TOT} = R_1 + R_2 + R_3 + R_4 \qquad (2)$$

where R_1 = resistance due to breaking the ice
R_2 = resistance due to forces connected with weight (i.e. submersion of broken ice, turning of broken ice, change of position of icebreaker, and dry friction resistance)
R_3 = resistance due to passage through broken ice
R_4 = water friction and wavemaking resistance

Their equation is (without R_4)

$$R_{TOT} = k_1 \mu_0 B \sigma h + k_2 \mu_0 B \rho_i h^2 + k_3 \frac{1}{\eta_2} B^{k_4} v^{k_5} \qquad (3)$$

Where σ = ice strength
B = ship beam
h = ice thickness
v = ship speed
ρ_i = density of ice

μ_0 and η_2 are related to Shimansky's ice cutting parameters and k_1, k_2, k_3, k_4, k_5, are coefficients experimentally determined (0.004, 3.6, 0.25, 1.65, and 1.0 respectively). This equation was developed from model and full-scale tests of the *Ermak*. Nearly all researchers have followed this

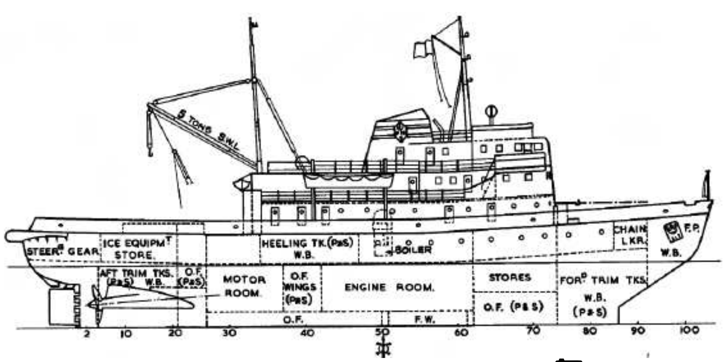

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Fig. 10. The Perkun, one of the first icebreaker to be model tested (Corlett and Snaith, 1964).

Fig. 11. Tug fitted with Alexbow icebreaking device.

approach of breaking down the total resistance into components since Kashteljan (1968).

A less than successful innovation in the mid-sixties was the upward breaking bow designed by Scott Alexander and called the Alexbow, and shown in Fig. 11 attached to a tug (Alexander, 1970). It was designed to break the ice in uplift and deposit it on the adjacent ice cover. In field trials the bow form, pushed by a 1000 kW tow, successfully broke ice up to 0.5 m thick at speeds of 2-3 knot. During the winter of 1967-68 the U.S. Coast Guard evaluated this device in ice on the Great Lakes using one of its small icebreaking tugs as the pusher vessel (Edwards, 1968). The results did not support the claims of the inventor. The tug-Alexbow combination required more power than the tug alone in both level and broken ice. The steepness of the plow often prevented the ice from being lifted onto the channel edge, and much of the broken ice found its way back into the channel. Other Alexbow craft were tested in Canada (Gilmore et al., 1967) and Europe with mixed results. The Soviets tested a similar ice plow extension on a river icebreaker and concluded that it offered no advantage over conventional designs (Kashteljan, 1972).

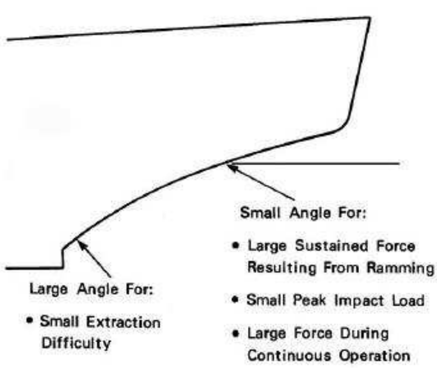

Fig. 12. The "White" bow as used on the Manhattan (White, 1969, 1970).

White (1969, 1970) made a major contribution to bow form development by giving a purely analytical method for calculating bow performance. His major contribution was to identify those qualities of a bow that would be desirable for (a) improved continuous icebreaking, (b) improved ramming and (c) improved extraction ability. He concluded that there were only three qualities that would improve all three capabilities simultaneously namely;

- decrease of spread angle complement (i.e. a blunter bow)
- decrease of the coefficient of friction
- increase of thrust.

He proposed a bow form, shown in Fig. 12, which incorporated these features. This form was used on the converted *Manhattan* for its voyages through the North-West Passage, Fig. 13. The object of these trips was to demonstrate that oil could be shipped by tanker from the Prudhoe Bay area to the oil hungry N-E United States.

Fig. 13. The icebreaking bow of the Manhattan being installed prior to her voyages through the N-W Passage in 1969 and 1970.

In addition, the *Manhattan* was strengthened generally, had added protection for its rudder, and installed a heeling device which would allow it to pump water from side to side and induce heeling up to 1.5° should the ship get stuck in ice. The *Manhattan* team had wanted to include a "Wartsila" air bubbler system but time prevented them from doing this. While the voyages were successful, the move to build a trans-Alaska pipeline took

Fig. 14. The CCGS Waban-Aki air cushion vehicle used for icebreaking in the St. Lawrence river.

hold and moving oil by tanker through the N-W Passage became less attractive.

The "White bow" came to be used on the *USCG Polar Sea/Star* built in the mid-1970s, the *MV Arctic* built in the late 1970s, and in a modified form on the Canadian *R-Class* built between 1970 and 1984.

A successful innovation in the early 1970s was the introduction of Air Cushion Vehicles (ACVs) for icebreaking, as shown in Fig. 14. They break the ice by two mechanisms depending on speed. At low speeds, a cushion of air forms under the ice and it breaks under its own weight, while at high speeds the ACV sets up a standing wave about half the craft length astern in the ice cover, which moves with the speed of the craft, and breaks the ice at the crest of the wave (Haehnel, 1998).

The Spring meeting in Montreal of the Eastern Canadian Section of SNAME in 1975 was essentially the first of the SNAME IceTech conferences, held at irregular intervals since then. Several papers were presented related directly or indirectly to the *Manhattan* voyages (Mathews, 1975; Bustard, 1975; Kloppenburg, 1975). Model-scale tests of air cushion vehicles were discussed by Lecourt and Kotras (1975), and full-scale observations over the period 1971-74 were presented by Wade et al. (1975). At this conference, Johansson et al. (1975) presented details of the new Finnish icebreaker *Atle*, one of five built by Wärtsilä for Finland and Sweden. Several designs had been model tested and the final design for Baltic service was 22,000 HP diesel-electric with two bow and two stern propellers, and two rudders.

Icebreaking ships from 1975-1985

A major development at this time was the building of the Polar class icebreakers by the Americans. Two sister ships were built, the *Polar Star* in 1975 and *Polar Sea* in 1977 capable of continuous progress through six feet (1.8 m) of ice at a speed of 3 knots, shown in Fig. 15. Their major innovations were a power train consisting of a combination of six diesel-electric engines or three gas turbines, three shafts, and three controllable pitch propellers. The diesel-electric plant could produce

Fig. 15. The Polar Star in transit in the Arctic.

18,000 shp (13 MW), and the gas turbine plant a total of 60,000 shp (45 MW). They were built to be strong ships with thick steel and closely spaced frames. Each shaft can be turned either by the diesel-electric or the gas turbine plant. Either one or two 2.24 MW (3,000 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 centre shaft. Because turbines are unidirectional engines, astern operation must be provided by the transmission and in the case of these *Polar* class ships it was provided by using controllable pitch propellers. While there were some teething problems with the propellers, the ships have proved themselves strong and capable workhorses in both the Arctic and Antarctic.

In the mid-1970s the *MV Arctic* was built in Canada as a large arctic class cargo vessel. Designed to carry both oil and ore, the vessel is not only ice strengthened but also carries a Baltic 1A Super ice rating, which means she can navigate through many ice-covered waters unescorted. She routinely services mines in the Canadian Arctic such as the Polaris and Nanisivik mines. It had a "White bow" originally but this was converted in 1986 to a bow form with considerably more flare (Baker and Nishizaki, 1986). This gave better ice breaking performance such that "in one metre of ice showed a fourfold improvement over the old bow (Luce, 1987)."

In 1981, a STAR symposium held in Ottawa published a number of model tests and some full-scale data. Narita and Yamaguchi (1981) published a very detailed account of model tests, which led to the building of the *Shirase*, an Antarctic icebreaker/research ship for Japan in 1983 (Fig. 16). First, they tested three model bows and showed that a cylindrical bow with a low stem angle of 22.5° had less resistance than the other two, because it avoided crushing at the bow. They went on to test a triple-screw ship in resistance and self-propulsion. They also showed, at model-scale, that the resistance almost doubled as the hull-ice friction coefficient doubled from 0.1 to 0.2. This *Shirase* is to be replaced in 2008 by another icebreaker/research ship of the same name.

Schwarz et al. (1981) published model tests of the Polarstern (Fig. 17), and Juurmaa and Segercrantz (1981) stressed the importance of propulsion efficiency in ice, rather than just resistance, pointing out that while different models might have the same resistance, they could have

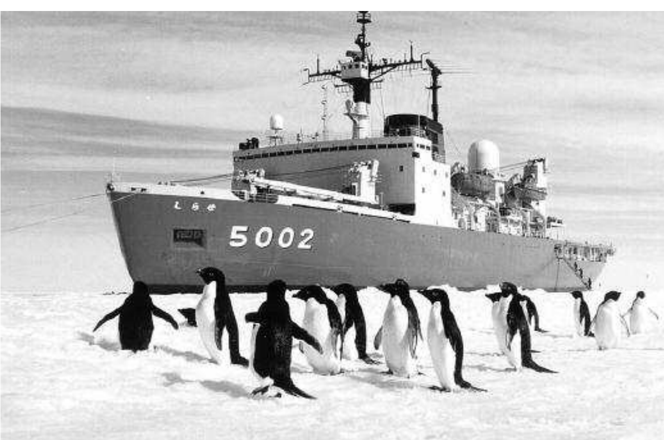

Fig. 16. The Japanese Antarctic research ship, Shirase.

Fig. 17. The German polar research ship Polarstern.

very different efficiencies due to ice/propeller interaction. They showed that a propeller with a nozzle could have very low efficiency if it became blocked with ice. Full-scale data for the Canadian "R-class" icebreakers (Fig. 18) were also presented at this conference (Edwards et al., 1981; Michailidis and Murdey, 1981), as well as a

Fig. 18. The Des Groseilliers, one of the four Canadian Coast Guard R-Class icebreakers.

set of parametric variation model tests, which examined different bow forms based on the R-Class as parent (Noble and Bulat, 1981). Resistance tests only were conducted, and these, again, showed the superiority of rounded bows with low stem angle in breaking ice, but since no self-propulsion tests were conducted it is impossible to judge the overall performance of the different ships.

The late 1970s and early 80s saw a huge interest in oil exploration in the Arctic particularly in the Beaufort Sea. This led to the design and construction of icebreakers such as the *Canmar Kigoriak* with unconventional bow forms all of which have low stem angles of approximately

Fig. 19. Canmar's Robert Lemeur icebreaker showing her hull lubrication system.

20° and are different from the classical wedge-shaped bow. These are the "spoon-shaped" bows of the *Canmar Kigoriak*, *Robert LeMeur*, and other similar designs, the *Thyssen-Waas* bow form of the modified *Max Waldeck* and the converted *Mudyuq*, and the flat bow form of the *Oden*.

The key operators in the Canadian Beaufort Sea at this time were Dome Petroleum (Canmar) and Gulf Canada. Both built their own fleets. The Gulf Canada fleet consisted on two icebreakers (*Terry Fox* and *Kalvik*) and two supply icebreakers (*Ikaluk* and *Miskaroo*). The key vessels in Dome's fleet were first the *Canmar Kigoriak* in 1979 and then the *Robert Lemeur* in 1981, shown in Fig. 19. The *Kigoriak*, designed by Aker Yards and built at St. John shipyard, pioneered the introduction of flat plate simplified hull construction, geared diesel for propulsion, CP propeller in a nozzle, and an ice reamer at the spoon shaped bow which helped its ability to turn. In addition to reamers and a spoon shaped bow, the *Robert Lemeur* introduced a hull lubrication system, a low pressure air bubbler system, and a high speed heeling system. She had two controllable pitch propellers in nozzles.

Fig. 20. MV Arctic Kalvik.

The two Gulf Canada icebreakers, *Arctic Kalvik* and *Terry Fox*, were sister ships (Fig. 20). The former is now owned by the Murmansk Shipping Company and renamed *Vladimir Ignatjuk*, and the latter is now owned by the Canadian Coast Guard. They were built in Victoria, B.C. in 1982/3. They also have two open controllable pitch propellers delivering 11,600 HP each. Their bows were of the semi-spoon type with chines and incorporating a larger ice clearing wedge than the normal spoon bow.

Fig. 21 shows these types of bow at model scale, in which the bow forms of four ships are compared: an original bow of the *Bernier* a CCG Navaids vessel, an R-

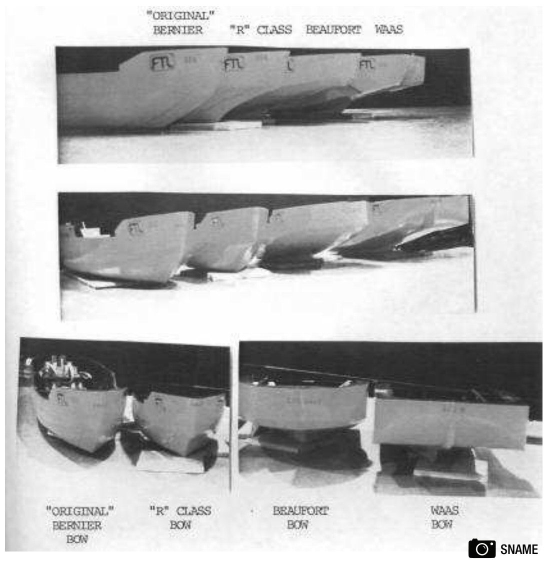

Fig. 21. Models of typical icebreaking bows showing from L-R, the original bow of a CCG Navaids tender Bernier, an R-Class bow, a Beaufort Sea type bow, and a Thyssen-Waaas bow (Glen et al. 1998).

Class bow, a Beaufort Sea bow typical of the *Kigoriak*, and a *Thyssen-Waas* type bow. The general design and operation of these ships has been published (Churcher et al., 1984; Ghonheim et al., 1984; Freitas and Nishizaki, 1986; Schwarz, 1986[a]; German, 1983; Tronin et al., 1984; Johansson and Revill, 1986) but little in the way of full-scale trials or even detailed model tests. Hellmann (1982) described model and full-scale tests with the *Max Waldeck* before and after conversion to a Thyssen-Waas bow form. He showed an approximate 25% drop in resistance model tests, and 100% increase in speed, for the same power, in propulsion tests. Full-scale data gave

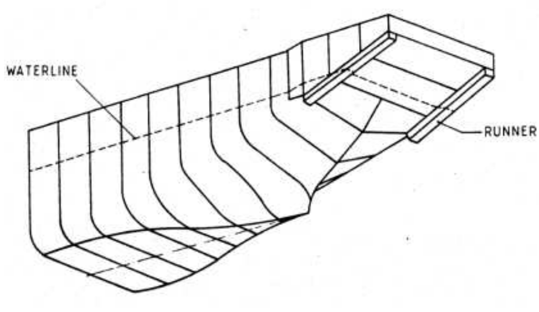

Fig. 22. The Thyssen-Waas icebreaking concept (above) and the Max Waldeck with a Waas bow (below).

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reasonable agreement. The bow form is shown in Fig. 22 and uses runners to cut the ice, which is then pushed to the sides by the shape of the bow, and underneath the existing ice sheet. It leaves a clean open channel in level ice but suffers in waves from slamming pressures.

Icebreaking Ships from 1985-2008

This modern period has seen continued development and a more scientific approach to the modeling of ships in ice with extensive model testing and, most recently, numerical methods. The most significant development has been the use of Azipods in icebreakers and in Double Acting Tankers (DAT). Other developments include the *Oden*, FPSOs in ice, and research ships such as the *Nathaniel B. Palmer*, *USCGC Healy* and *Mackinaw*, and the converted *CCGS Franklin* now called *CCGS Amundsen*. Also, the Russians completed a new nuclear icebreaker in 2007 and the Japanese will launch a new Antarctic research ship/icebreaker in 2008. It is not the intention of this paper to discuss model testing in detail, but some comments are necessary. The first model tests were done at the Arctic and Antarctic Research Institute (AARI) in Russia in 1955, but the *Manhattan* project in 1969/70 had led to the construction of the Wärtsila Arctic Research Centre (WARC) in Finland where major ice tank model testing was carried out. Since then several ice tanks have been built around the world.

Enkvist and *Mustamäki* (1986) published results of model and full-scale tests of a bow, which was derived from tests of a circular and square bow form. They showed, first of all, that ice crushing at the stem of two small ships accounted for 20-40% of the total low-speed resistance. By cutting slots in the ice ahead of the stem and removing the ice, the resistance was reduced by this amount. Their model tests compared a circular bow, a square bow, and the original *Mudyuq* bow, and showed that the circular bow had the lowest resistance. They then selected an experimental bow for further testing and analysis and after model testing, made a full-scale bow to attach to the *Protector*. Their full-scale results showed a considerable improvement in the *Protector*'s performance in level ice although they admitted that the original *Protector* was not particularly efficient. They measured full-scale friction using two panels installed on the bow of the *Protector* and obtained somewhat scattered results as shown below:-

Low pressure panel, $f = 0.16\text{-}0.26$
High pressure panel, $f = 0.05\text{-}0.13$

Similar panels were installed on the *Polarstern* (Schwarz et al., 1986), and results (Schwarz, 1986[b]; Hoffmann, 1985) also show a decrease in friction coefficient with increasing normal force. Good correlation with model data, of the performance of the new *Protector* bow, was obtained with a model friction coefficient of 0.05 as against the measured full-scale values shown above. A major disadvantage of the bow was higher slamming pressures. A similar disadvantage was noted by Freitas and Nishizaki (1986) who tested an ice class bulk carrier model with a Thyssen/Waas bow, which otherwise showed considerable improvement in icebreaking ability. This bow form was fitted to the *Mudyuq* and results showed that in snow-free ice, hull speed increased 50 to 100% without the aid of the “Jastram hull lubrication plant” (Varges, 1987, 1988). Improvements in turning circle and in clearing of ice from a broken channel were also reported, as well as agreement with model tests. A series of comparison model tests by Glen et al. (1998) on four bows, one of which was a Thyssen-Waas form, showed that while it was superior in breaking level ice, this had little real significance on the overall performance of a Navaids vessel in service with the Canadian Coast Guard, which spent a lot of its time in open water. For such a vessel a conventional R-Class type bow was superior overall. A comparison of non-traditional hull lines was made by Lerusalimsky and Tsoy (1994) who gave full-scale data from three Russian icebreakers, one with a traditional bow, one with a conical bow and one with a Thyssen-Waas bow. Their conclusions were similar to Glen et al. (1998)'s model results, namely a significant increase in performance in level ice for the non-traditional bows, but poorer performance in calm open water and in waves, with considerable slamming. They concluded that neither non-traditional bow was ideal for the Russian operations, which include long open sea voyages.

An interesting development in the mid-80s was a full-scale towed resistance trial of the *Mobile Bay* in uniform level ice (Zhan et al., 1987). In principle, this paralleled the open water trials of the *Greyhound* (Froude, 1874) and *Lucy Ashton* (Denny, 1951). While such tests are clearly difficult to perform, in theory they provide a direct measurement of full-scale resistance. They also conducted full-scale propulsion tests. They found the best fit to their towed resistance results was with the equation (one of 15 equations that they analyzed):-

$$\frac{R_i}{\rho_w g B h^2} = C_0 + C_1 \frac{v^2}{gB} {\frac{L}{h}}^{3} \qquad \text{-------------- (17)}$$

where $C_0 = 4.25$
$C_1 = 3.96 \times 10^{-5}$

Which implies a v^2 dependence of resistance on speed, as well as an h^2 dependence. From their propulsion data they determined a thrust deduction fraction as a function of ice thickness, but as I have commented in a discussion to their paper, their range of thickness (and strengths) was so small, and the normal errors associated with thrust and torque measurements so large, that such a relationship is difficult to justify. However, it is a valuable addition to the literature and, hopefully, could be repeated in the future with significantly different ice conditions, for comparison.

Fig. 23. The Swedish icebreaker Oden, delivered in 1989.

Another development around this time was the Swedish icebreaker *Oden* delivered in 1989, shown in Fig. 23. It has a number of important features. She was designed with a flat bow form at the centerline and wide turning reamers, together with a water lubrication/jet thruster system, which both reduced the friction between the bow and the ice or snow surface, and was designed so that it could provide significant side force to improve manoeuvrability. Propulsion was provided by two nozzled propellers, together with two very large rudders. When going astern in ice, these rudders could be closed against stoppers underneath the flat stern in order to protect the steering gear, and for pushing broken ice aside instead of into the propellers. A very fast heeling system was introduced on the *Oden*. It allowed 800 tonnes of water to be pumped from one side to the other in 25 seconds thus improving her progress in heavy ice. The turning reamer was located above the ice until the ship is heeled over when it helps the normal tendency of a Kigoriak-type bow to turn into the heel.

In 1993 the Finnish icebreaker *Fennica* was constructed (Lohi et al., 1994). It marked the start of multi-purpose icebreakers built by Finland, which are used in the winter for icebreaking and in the summer for other offshore duties such as laying pipes and cables, or as support vessels for oil drilling platforms. A sister ship *Nordica* was built in 1994. The most exceptional feature of the vessels was their main propulsion, which used azimuthal thrusters. They could be rotated 360°, fulfilling the requirement of extreme manoeuvrability and consisted of two nozzled, fixed pitch, 7.5 MW units driven by electric motors. The ship included

Fig. 24. A typical Azipod installation.

a heeling system but no water jet or air bubbling system to reduce friction. The foreship had a stainless steel belt at the waterline to reduce friction. Soininen et al. (1993) have described model and full-scale tests of the *Fennica*.

Since 1990, the major development has undoubtedly been that of using podded propellers with icebreakers and with double acting tankers (DAT), which has taken place principally in Finland (Juurmaa et al., 2001) and appropriate for the Baltic Sea. A podded propeller is an extension of an azimuthal thruster concept but with an electric propulsion motor inside the pod, as shown in Fig. 24. The entire pod can rotate 360° thus acting as its own rudder, as well as freeing up space inside the ship. They had been used on cruise ships but starting in 1990 with a 1.3 MW buoy tender, *MV Seili*, podded propellers have been used in conjunction with designs which allow the ship to go astern in heavy ice and forward in open water and light ice. Full power can be applied in either direction by rotating the Azipod. In 1998, Aker Yards built a multi-purpose icebreaker for the Finnish Maritime Agency, the *Botnica*, shown in Fig. 25. She was the first multi-purpose icebreaker to use Azipods for propulsion, and they consisted of two 5MW units.

Fig. 25. The Finnish icebreaker Botnica, the first to use Azipod propulsion in 1998.

The development of Azipods in ice capable ships has now progressed to a 16 MW tanker with one Azipod unit, two of which were delivered in 2003 to Fortum Shipping by Sumitomo Heavy Industries, for use in the Baltic. The idea was to design an efficient icebreaking stern for the vessel, while keeping an efficient open water bow. Fig. 26 shows one of the ships going astern in ice during its ice trials.

Fig. 26. A 106,000-dwt Masa-Yards-developed DAT crude carriers built by Sumitomo Heavy Industries in 2003.

When entering a ridge field at slow or moderate speed, a DAT vessel lets its pulling propeller chew up the ridge and slowly pull the vessel through, without any need for ramming. Whether this would work on a massive arctic ridge without damage to the propulsion unit is questionable, but the vessels are well suited to Baltic ice conditions.

Recent new icebreakers in North America are the *Nathaniel B. Palmer* (1992) and the *USCGC Healy* (2000) designed principally to be Antarctic and Arctic research/supply ships. The *Healy* is shown in Fig. 27. It has a conventional bow form with two conventional propellers. A complete set of trials in ice was conducted with this ship in 2000 with the results published in the literature (POAC 2001). The design icebreaking capability of the *Healy* was for continuous icebreaking at 3 knots through 4.5 ft (1.37 m) of ice of 100 psi (690 kPa)

Fig. 27. USCGC Healy entering St. John's, Newfoundland, harbour.

Fig. 28. The USCGC Mackinaw delivered in 2005 replacing an earlier ship of the same name.

strength. The full-scale trials were conducted in ice half this strength, but by extrapolation from model-scale tests (Jones and Moores, 2002) the ship was shown to meet this requirement.

The Americans have also built a new icebreaker for the Great Lakes, named *USCGC Mackinaw* (replacing a previous ship of the same name) and delivered in October 2005, which has two Azipod units of 3.3 MW each. The ship, shown in Fig. 28, is designed to break 32"(0.82 m) of ice at 3 knots ahead and 2 knots astern. In addition it should be very maneuverable with the Azipod units, which can turn 360^o. Full-scale trials of that ship were conducted in 2006 and 2007.

Fig 29. The new Russian "50 Year Anniversary of Victory" icebreaker launched in 2007.

The Russians have now completed a *"50 Year Anniversary of Victory"* nuclear icebreaker shown in Fig. 29. According to the press, she conducted trials in the Baltic in early 2007, and is the largest icebreaker ever built, with a length of 159.6 m., deadweight of 25,000 MT, and powered by two nuclear reactors with a total of 75,000 hp. She is designed to break through ice up to 2.8 m thick, and has a spoon-shaped bow. In open water she has a top speed of 21.4 knots. No further details have been published as yet.

A new Antarctic icebreaker/research ship, also to be called *Shirase*, will be launched in Japan in 2008. Few details are available at present (January 2008).

With the advent of the offshore oil industry in Newfoundland two FPSOs have been built for the ice-infested waters, the *Terra-Nova FPSO*, shown in Fig. 30, and the *Sea Rose*. These ships are not icebreakers as such, but are ice strengthened and can withstand pack ice forces. They are designed to disconnect if threatened by a large iceberg. Smaller icebergs are towed away by support ships.

The oil is transported to market in ice-strengthened tankers. At IOT, we have been conducting a major research program into the impact of a ship with a small iceberg, or bergy bit. The results will be published in 2008 in a special issue of Cold Regions Science and Technology. They include full-scale impact tests of the *Terry Fox* with bergy bits as shown in Fig. 31.

The last thirty years have seen advances in ship-ice modeling techniques. Jones et al. (1989) have described the different model ices in use throughout the world. A future paper will discuss model testing in detail.

Another advance in the last ten years has been in numerical methods to predict resistance in ice. Valanto

(2001) has developed a 3-D numerical model of the icebreaking process on the ship waterline, which predicts the forces on the waterline. These were compared with load panel measurements on the *MS Uisko* with good agreement.

Fig. 30. The Terra-Nova FPSO off Newfoundland.

He then calculated the resistance in ice for several ships using his numerical model, combined with a semi-empirical model of Lindqvist (1989) for the underwater components of resistance, and obtained good agreement with measured values. It will be many years, however, before this approach can replace physical model tests, but numerical methods can give useful information in conjunction with model tests.

Summary

Enormous technological progress has been made in the last 120 years from *Murtaja* to Double Acting Tankers. Ice will continue to be important factor for oil exploration and production in certain offshore areas, as well as for marine transportation. Increased tourist, as well as commercial traffic in the Arctic and Antarctic will bring demands for safer and more efficient travel in such areas. Modelling will continue to improve with emphasis on numerical simulations as well as physical modeling. Climate change may open up what are now ice-covered areas but that is many years away.

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Fig. 31. The CCGS Terry Fox deliberately impacting a bergy bit.

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