Engineering and Economic Implications of Ice-Classed Containerships

by

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Abstract

The Arctic is becoming increasingly attractive for shipping. With the potential savings in transit time and the untapped natural resources, both the shipping and offshore industries are pouring capital into research and development.

Myriad different ice-classes are described. Every classification society and country has their own system of ice-classing vessels, which leads to complexities within the system. The Polar Rules are looking to harmonize all of the different methods into one set of standards, thus simplifying the process.

Also addressed will be the effect of ice-class on vessel design. The hull shape and structure, propulsion machinery, and auxiliary systems are all affected by ice-classing a vessel.

Herein, the reader will find a presentation of the percentage increases in weight, power, fuel consumption, and cost of several different ice-classes over conventional containerships. To increase the ice-class slightly, the data is within margins of error and thus, there are no increases (especially with high speed LNG and container vessels). However, to increase the ice-class to the highest class analyzed, the weight, power, fuel consumption, and cost increase substantially.

Ice-classed containerships may become economical in the future when the ice cover diminishes due to global warming. Presently, routing containerships over the Arctic is generally not considered by the industry to be economically, politically, or environmentally feasible for continuous, reliable service. This thesis provides insight into the engineering and economic implications of ice-classed containerships.

Thesis Supervisor: Henry S. Marcus

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Definitions and Nomenclature

1. ABS – American Bureau of Shipping
2. AIRSS – Arctic Ice Regime Shipping System
3. ASSET – Advanced Surface Ship Evaluation Tool
4. Brash Ice – A fairway channel which has been cut by an icebreaker and continuously broken and re-frozen with the passage of shipping
5. CASPPR – Canadian Arctic Shipping Pollution Prevention Rules
6. CPP – Controllable Pitch Propeller
7. DAPPB – Double Acting Pusher Puller Barge system
8. DAS – Double Acting Ship concept or Double Acting Stern
9. DAT – Double Acting Tanker
10. DEICE – DNV Notation for additional ice protection
11. DNV – Det Norske Veritas
12. FE – Finite Element
13. FEM – Finite Element Modeling
14. FEU – Forty-Foot Equivalent Unit
15. FMA – Finnish Maritime Administration
16. FPP – Fixed Pitch Propeller
17. Fr – Froude Number
18. FS – Finnish-Swedish
19. FSICR – Finnish-Swedish Ice-Class Rules
20. FY Ice – First year ice up to 120 cm thick and low ice-strength properties
21. g – Universal Gravitational Constant (9.81 m/s)
22. IACS – International Association of Classification Societies
23. IM – Ice Multiplier
24. IN – Ice Numeral
25. ITTC – International Towing Tank Conference
26. JIY = LU – Russian Maritime Register Rules Notation
27. MDO – Marine Diesel Oil
28. MGO – Marine Gas Oil
29. MT – Metric Ton
30. MY Ice – Multi-year ice up to 3 m or more with high ice-strength properties (Caused by progressive leeching out of salts and minerals trapped when the ice is first formed. With the leakage of these impurities, the ice becomes much stronger).
31. NCR – Normal Continuous Rating
32. NORDREG – Arctic marine traffic system
33. NSR – Northern Sea Route
34. NWP – Northwest Passage
35. PC# – Polar Class # (ex. PC1 – Polar Class 1)

36. P_E – Effective Power
37. ρ_{SW} – Density of Salt Water at 70^0F
38. Re_N – Reynold's Number
39. RMRS – Russian Maritime Register of Shipping
40. R_R – Residuary Resistance
41. R_T – Total Resistance
42. SFC – Specific Fuel Consumption
43. SMA – Swedish Maritime Administration
44. TEU – Twenty-Foot Equivalent Unit
45. V_S – Ship Speed
46. WMO – World Maritime Organization
47. WSA – Wetted Surface Area
48. ZDS – Zone-Date System

1.0 Chapter 1: Introduction and Purpose

1.1 Overview and Background

With both intense climatic change and increased natural resource development, the Arctic is becoming a new area of development for the global economy. Climate change has powerful effects on the Arctic, where the average temperature has risen at twice the rate of the rest of the planet [13]. In combination with estimates of 25 percent of the unexploited gas and oil reserves and up to 60 percent savings in transit distance (See Figure 1.1), the Arctic is emerging as a prominent area of investigation and research. Currently, most of the development is in the natural resource sector.

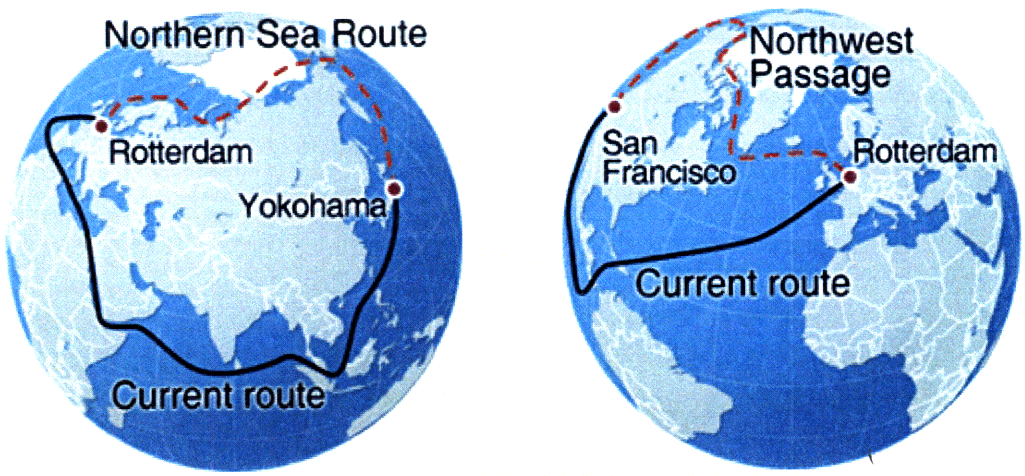

Figure 1.1: Northern Sea Route and the Northwest Passage Compared with currently used Shipping Routes [41]

One major requirement of a containership service is the stability of its schedule. It mandates a reliable, weekly service. The Arctic offers up to a 60 percent reduction in distance, thus ideally decreasing transit time. However, the Arctic has unpredictable ice conditions which can cause delays. Additionally, ice-classed containerships come with an increased capital and operating cost, plus transiting at slower speeds. Ice-classing a containership may cause a decrease in cargo space due to increased structure and closer frame spacing. The double acting concept, which will be explained in greater detail later in this thesis (Section 3.4.2), is patented. The capital cost is increased when this method is used.

Why would ice-classed containerships be utilized? Consider a future scenario, when a containership from a fleet goes into drydock, the remaining ships can then be re-routed over the Arctic to keep the same schedule with one less ship. This should be done in the summer months, ideally August to October, as seen below in Figure 1.2. The routing over the Arctic can also employ transshipment ports, thus requiring fewer ice-classed containerships.

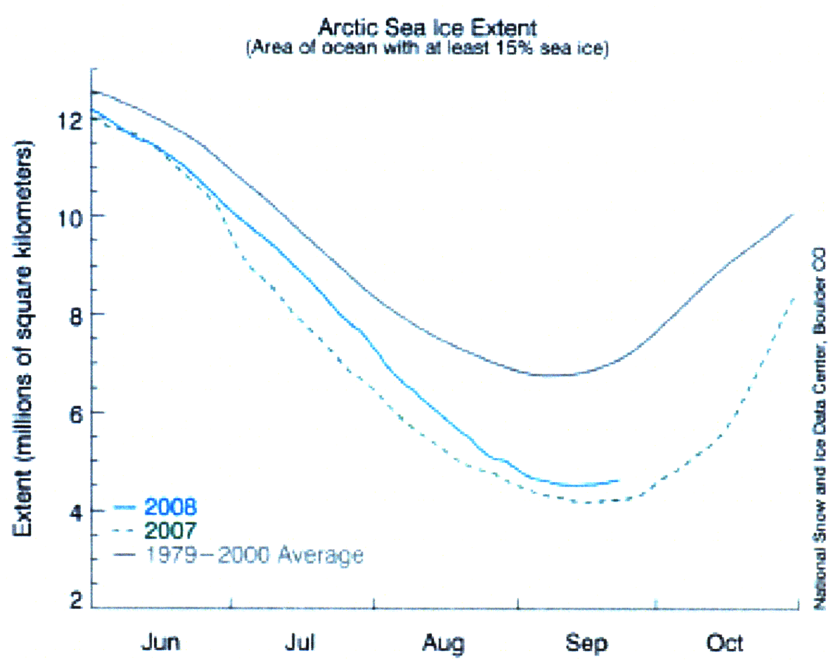

Figure 1.2: Arctic Sea Ice Extend [17]

From a transportation systems planning point of view, it's important to determine the relationship between the seasonal ice distribution conditions and the ship's capabilities, so that the economics of the relationship can be examined [40]. Figures 1.2 and 1.3 show the seasonal ice conditions in different forms. Figure 1.3 also shows the types of ships that can navigate the ice conditions safely.

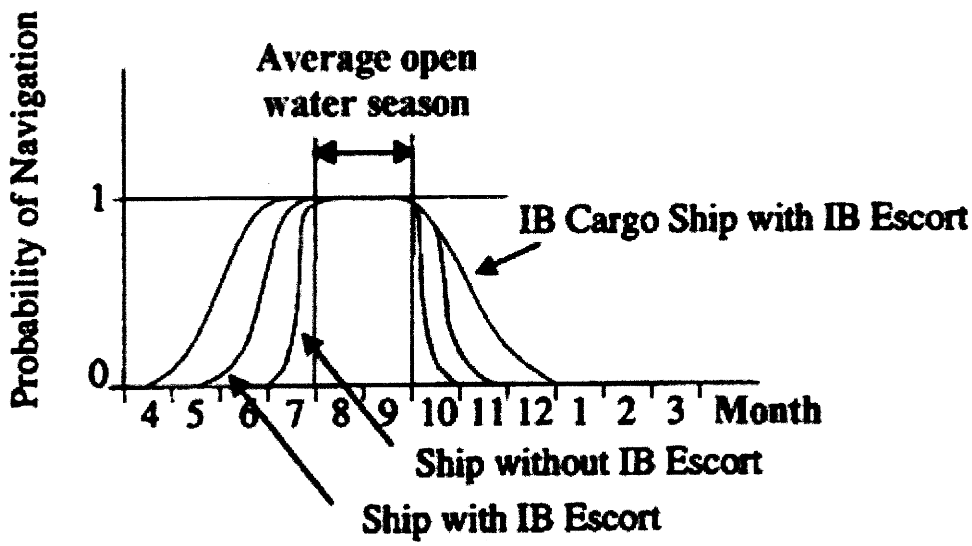

Figure 1.3: Probabilistic Shipping Seasons and Ship Capability [40]

Figure 1.4 shows the several different routes available to cross the Arctic. Not shown is the route straight over the top of the Arctic. If this route is utilized, the politics (differing classes and equivalency issues) and fees can be avoided. Presently, this route may be technically feasible, but is not yet economically feasible.

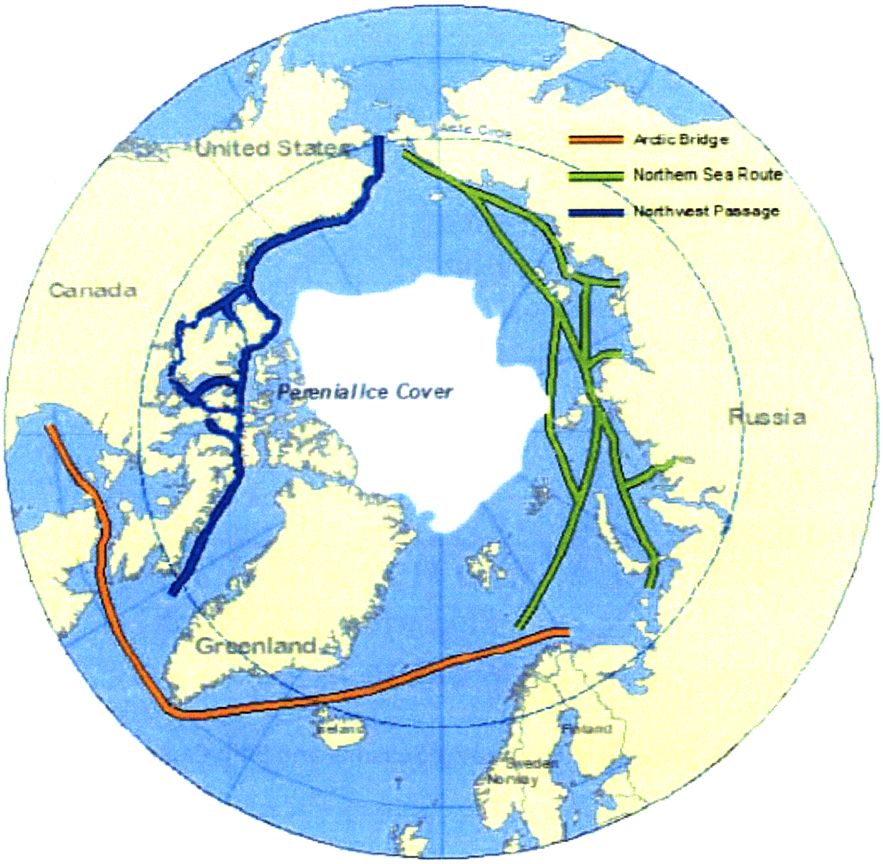

Figure 1.4: The Arctic Shipping Routes [17]

Environmental issues will have to be examined. These are not in the scope of this thesis, thus will be mentioned only briefly. Arctic areas are very sensitive to discharge of oil and other pollutants. The low temperature will preserve the pollutants, and due to the sensitive ecological balance there should be 'zero tolerance' with regard to discharge. Due to the remote location of many of the new oil fields, shore-based contingency plans and resources are limited and represent a challenge for the industry and national authorities [43]. Thus, the Arctic Ocean is a no discharge ocean. This causes several problems with ballast water management. Also, the air emissions and noise from the ships can interrupt the serene environment. However, some proponents argue that the emissions saved by cutting 2,500 miles to 3,750 miles off traditional routes will contribute to reversing the warming that is melting the polar ice in the first place [9].

1.2 Purpose

The purpose of this thesis is to determine the feasibility of ice-classed containerships. Several different sized containerships with several different ice-classes were analyzed with regards to weight, power, fuel consumption, and cost. The results of this analysis and the viability of ice-classed containerships in the future are presented.

1.3 Recent Developments

Germany's Beluga Shipping plans to deploy a ship through the Northern Sea Route this summer. As stated above, this route cuts thousands of miles off of the normal sailing route via the Suez Canal. From Bremen to Shanghai, 3,200 nautical miles can be saved. Beluga would have used the NSR last summer if the necessary permits had been obtained from the Russian authorities. The ships will operate independently of icebreaker assistance since the economic benefits would be lost. The route is only available six to ten weeks and must be at least 90% ice-free because of the dangers posed by drifts. Beluga will be the first Western Europe shipping company to attempt the passage without assistance. Aker Arctic Technology is carrying out an NSR feasibility study determining what type of ship should be used and the viability of the passage. The main obstacle to using the NSR remains psychological. If you are stuck in ice in Russian waters, what is the reliability and cost of the Russian icebreaker service? It is almost two decades old; the service is the same that has been around since the early 1990s when the route was first opened [27].

2.0 Chapter 2: Class

2.1 Introduction

Currently, there are many different ice-classes in use. The countries bordering the Arctic include Russia, Canada, Finland, Sweden, and the USA, and their classification societies each have a different set of ice-classes. The requirements span the spectrum from hull strengthening to power requirements. The purpose of ice-classes is to permit the safe operation of ships in ice-covered sea areas [42]. There are three main regions where ice-classes are applicable; the Baltic Sea, the Arctic Ocean, and the Okhotsk Sea (see Figures 2.1-2.3). Also, inland lakes such as the Great Lakes have supplemental regulations regarding operation during winter months.

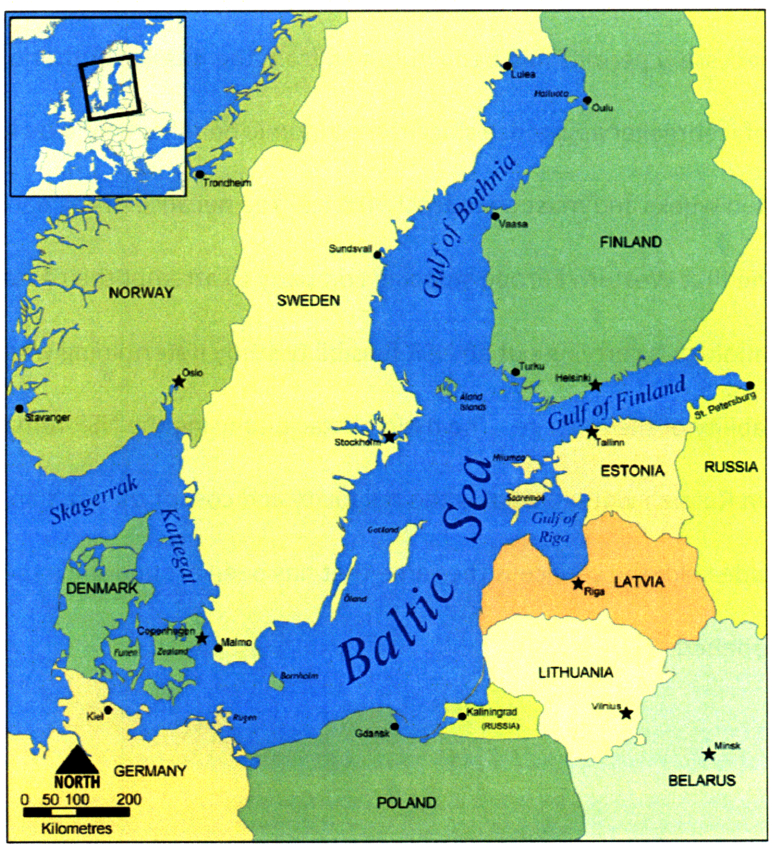

Figure 2.1: Map of the Baltic Sea

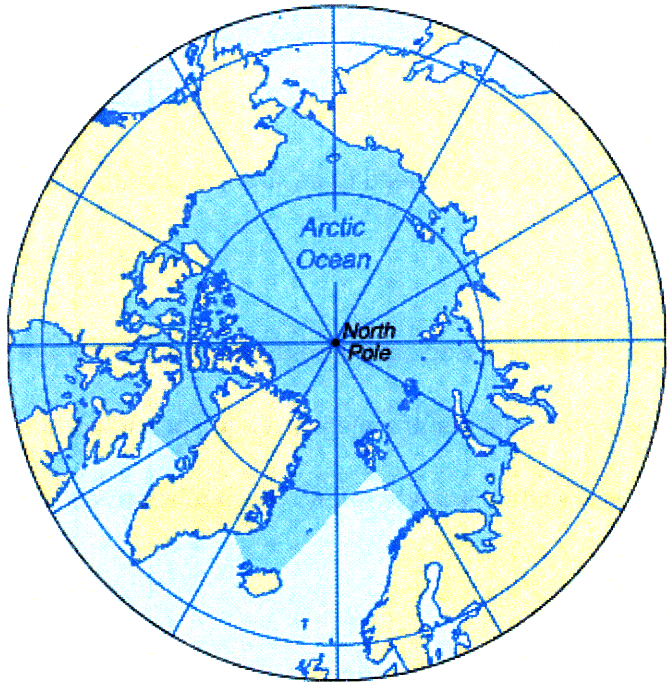

Figure 2.2: Map of the Arctic Ocean

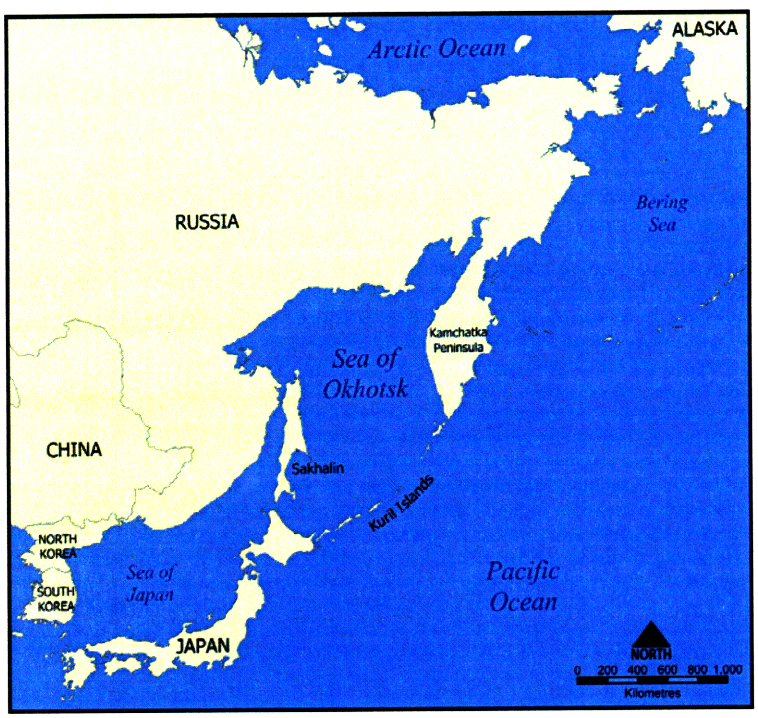

Figure 2.3: Map of the Okhotsk Sea

The ice-classes endeavor to ensure the safety of the hull and essential propulsion machinery. Additionally, sufficient power for safe operations in ice covered waters must be demonstrated. The hull structure, propeller, and propeller shaft need to be strengthened to withstand loading with ice interactions.

Classification ice rules are based on the ice thickness the ship is intended to navigate in. The thicker the ice, the greater the hull reinforcement strength, propeller thickness, and steering gear strengthening the ship will need to navigate safely. The regulations also take into account independent or escorted operations [20].

2.2 Finnish-Swedish Ice-Class Rules

The Finnish Maritime Administration (FMA) and the Swedish Maritime Administration (SMA) created the Finnish-Swedish Ice-Class Rules (FSICR) with consultation from various classification societies [20]. A description of each Finnish Swedish Ice-Class is shown in Table 2.1 below.

The Finnish-Swedish Ice-Class Rules apply only to first-year ice conditions in the Northern Baltic. The Baltic has a relatively low salt content, so the ice that is formed is stronger.

Table 2.1: Finnish-Swedish Ice-Class Rules [20, 32]

Ice Class	Ice Description	For Navigation in
IA Super	First year ice thickness 1.0m. Special ice class IA Super, ships whose structural strength in essential areas affecting their ability to navigate in ice essentially exceeds the requirements of ice class IA and which as regards hull form and engine output are capable of navigation under difficult ice conditions without the assistance of ice breakers. Engine output will not be less than 2800kW. Escorted operation in all Baltic ice conditions.	Extremely difficult ice conditions
IA	First year ice thickness 0.8m. Ships with such structure, engine output and other properties that they are capable of navigating in difficult ice conditions, with the assistance of icebreakers when necessary. Escorted operation medium (smaller vessels) and severe Baltic ice conditions. Engine output will not be less than 1000kW.	Difficult ice conditions
IB	First year ice thickness 0.6m. Ships with such structure, engine output and other properties that they are capable of navigating in moderate ice conditions. Escorted operation in medium ice conditions.	Moderately difficult ice conditions
IC	First year ice thickness 0.4m. Ships with such structure, engine output and other properties that they are capable of navigating in light ice conditions. Escorted operation in light ice conditions.	Easy ice conditions
II	Ships that have a steel hull and that are structurally fit for navigation in the open sea and that, despite not being strengthened for navigation in ice, are capable of navigating in very light ice conditions with their own propulsion machinery.	Very easy ice conditions
III	Ships that do not belong to ice classes mentioned above.	

The ice-class and tonnage requirements may vary depending on the severity of the winter season. The two administrations (Finland and Sweden) provide icebreaker assistance, when needed, to ships during the winter. Additionally, they provide navigational limitations on a weekly basis depending on ice conditions. The FSICR criteria are driven by the maintenance of ship speed in ice, ensuring the continuity of trade in the winter. Thus in more severe winters, smaller ports without their own icebreakers may be closed temporarily. These traffic restrictions can also be accompanied with loading restrictions (ie. 1000 MT of loaded/unloaded goods per port). Also, if a vessel is damaged, its ice-class notation can be withdrawn and it may be issued a new, lower ice-class notation [20, 32].

The various ice-classes have different meanings depending on one's perspective. For example, an ice class of Finnish-Swedish 1A may represent several connotations. Technically, the hull steel structure and rudder are designed for pressures from 0.8 m thick first-year ice. Also, the propeller and shafting are designed for impact loads from ice pieces. The power requirement is given by a minimum maintainable ahead speed of 5 knots in 1.0 m thick brash ice. Commercially, this vessel is then suitable for assisted navigation in first-year ice in the northern Baltic.

2.3 Russian Maritime Register of Shipping (RMRS) Ice-Class Rules

The Russian Maritime Register Rules apply to both first- and multi-year ice. The Russians also have stability (intact and damaged) requirements in their ice-class rules. The Russian's set of rules are the only set that aren't based on the FSICR guidelines. Table 2.2 provides the descriptions of the Russian Maritime Register of Shipping Ice-Class Rules.

The Russian's have several guidelines that must be followed to navigate the NSR. The Captain of a ship sailing through the Northern Sea Route is required to submit a notification and request of passage to the Russian Administration (lead time of four months) and also guarantee payment of the icebreaking dues. While transiting the NSR, the ship must report twice a day and must maintain the pre-determined route unless under control of a state ice pilot. Two ice pilots are required and the Captain must have fifteen days of NSR ice experience. However, the Captain maintains ultimate control despite the ice pilots and directions from shore command. And prior to the use of the NSR, the ship must undergo a mandatory inspection and is subject to spot inspections at any time. Also, compulsory icebreaker assisted pilotage is required at certain choke points including the Vil'kitskogo Strait, Shokal'skogo Strait, Dmitriya Lapteva Strait, and Sannikova Strait. Russian legislation defines the NSR as a national transportation line, thus allowing them legal jurisdiction [17, 20].

Table 2.2: RMRS Ice Strengthening Notations [20]

Notation	Ice Description
UL	Independent navigation in the Arctic in summer and autumn in light ice conditions and in the non-arctic freezing seas all the year round.
L1	Independent navigation in the Arctic in summer in broken open ice and in the non - arctic freezing seas all year round in light conditions.
L2	Independent navigation in the non-arctic seas in small open ice. (≈ FSICR IB)
L3	Independent navigation in the non-arctic seas in small open ice. (≈ FSICR IC)
L4	Independent navigation in the non-arctic seas in small open ice, short period.
LU1	Independent navigation in small open ice in the non-arctic seas, short period and in compact ice up to 0.4m thick in a navigable passage astern an icebreaker.
LU2	Independent navigation in small open ice in the non-arctic seas, and in compact ice up to 0.55m thick in a navigable passage astern an icebreaker.
LU3	Independent navigation in small open ice in the non-arctic seas, and in compact ice up to 0.70m thick in a navigable passage astern an icebreaker.
LU4	Independent navigation in young open arctic ice up to 0.6m thick in winter and spring, and up to 0.8m thick in summer and autumn. Navigation in a navigable passage astern an ice breaker in young arctic ice up to 0.7m thick in winter and spring and up to 1.0m thick in summer and autumn.
LU5	Independent navigation in young open arctic ice up to 0.8m thick in winter and spring, and up to 1.0m thick in summer and autumn. Navigation in navigable

	passage astern an icebreaker in young arctic ice up to 0.9m thick in winter and spring and up to 1.2m thick in summer and autumn.
LU6	Independent navigation in young open arctic ice up to 1.1m thick in winter and spring, and up to 1.3m thick in summer and autumn. Navigation in navigable passage astern an icebreaker in young arctic ice up to 1.2m thick in winter and spring and up to 1.7m thick in summer and autumn.
LU7	Independent navigation in young open arctic ice up to 1.1m thick in winter and spring, and up to 1.3m thick in summer and autumn. Navigation in navigable passage astern an icebreaker in young arctic ice up to 1.2m thick in winter and spring and up to 1.7m thick in summer and autumn.
LU8	Independent navigation in close young and biennial arctic ice up to 2.1m thick in winter and spring and up to 3.1m thick in summer and autumn. Ramming rammer of ice ridges. Navigation in a navigable passages astern an ice breaker in biennial arctic ice up to 3.4m thick in winter and spring and in perennial ice in summer and autumn with no restrictions.
LU9	Independent navigation in close perennial arctic ice up to 3.5m thick in winter and spring, and up to 4.0m thick in summer and autumn. Ramming rammer of ice ridges. Short ramming rammer of the young and biennial close ice segments.

2.4 Canadian Arctic Shipping Pollution Prevention Rules (CASPPR)

The Canadian criteria are driven by a need to limit the potential risks of hull and machinery damage coupled with the prevention of pollution due to ship damage.

There have been changes to the Arctic Waters Pollution Prevention Act. Under the proposed changes, their jurisdiction will be extended to 200 nautical miles (increased from 100 nautical miles) to guard against pollution of the region's marine and coastal environments. In addition, the Prime Minister announced new regulations under the Canada Shipping Act that will require mandatory reporting from all ships destined for Arctic waters within the same 200 nautical mile limit [16].

An increase in international shipping throughout the Arctic raises the potential for accidents, smuggling, illegal immigration, and even threats to national security. Canada claims the entire

Northwest Passage, a link between the Pacific and Atlantic oceans, but other countries including the United States dispute Canada's claim over the waterway [19]. The United States may challenge Canada's right to require notification if a ship is entering the Northwest Passage, a route it considers an international waterway. The US would most likely lodge a quiet diplomatic protest as a first step. Other foreign vessels have an incentive to register because Canadian authorities will share vital information with them, such as satellite imagery [15].

The Canadian Arctic is regulated by the Zone-Date System (ZDS) and outside its permissible dates by the Arctic Ice Regime Shipping System (AIRSS), which is used with certain conditions. The Zone-Date System is based on historical data of ice conditions. It includes sixteen geographic regions, Shipping Safety Control Zones, which start north of 60^0N latitude (See Figure 2.4). There is an associated table which indicates the allowable dates for passage. This system does not take into account the actual ice conditions present in the Zone while the ship is proceeding through it [39, 61].

The Arctic Ice Regime Shipping System reflects actual ice conditions. An Ice Numeral (IN) is calculated based on ice type, thickness, and concentration. It is the sum of the ice types and ice multipliers (IM) specific for each ship class. The ice multiplier indicates the risk of damage to a ship by different ice types. If the ice numeral is greater than or equal to zero, the ship may proceed. Currently, this system is only used outside of the Zone-Date System [39].

In addition to mandatory registration for use of the NWP (4 months to one year lead time), ships must report to NORDREG (the Arctic marine traffic system) on entry to each Zone giving 96-hour advance notice and once a day. Also, the vessels are subject to spot inspections at any time. There are no fees to use the NWP, and routing and icebreaker assistance are available via NORDREG. A certified ice navigator may be required as detailed in Schedule VIII of the CASPPRs. The ice navigator must be a qualified master with at least 50 days of experience, with at least 30 days in Arctic waters. Similar to the

Russian rules, the Captain maintains ultimate control despite ice pilots and directions from shore command [17].

Figure 2.4: Canadian Shipping Safety Control Zones [17]

2.5 DNV Class Rules

Det Norske Veritas (DNV) ice-class rules are summarized in Table 2.3. DNV has had ice strengthening requirements since 1881, mandating that the frames had to be placed closer together in the bow section in addition to other internal strengthening. Then, in 1932, a special set of standards were released including increased scantlings of frames, plates and stringers specified as a percentage increase (15–25%) above standard class rules [43].

Table 2.3: DNV Ice-Class Notations and Descriptions

DNV Ice-Class Notations	
Ice-Class	Description
ICEBREAKER	Similar to POLAR-30, but the vessel's mission is icebreaking
POLAR-30	Vessels operating unassisted in ice-infested waters with pressure ridges, multi-year ice-floes and glacial ice inclusions and a nominal ice thickness of up to 3.0 m
POLAR-20	Vessels breaking ice of 2.0 m level thickness in polar areas
POLAR-10	Vessels breaking ice of 1.0 m level thickness in polar areas
ICE-15	Vessels breaking ice of 1.5 m level thickness
ICE-10	Vessels breaking ice of 1.0 m level thickness
ICE-05	Vessels breaking ice of 0.5 m level thickness
ICE-1A*F	Operating regular services in ice conditions with ice floes of 1.0 m level ice thickness
ICE-1A*	Operating in ice conditions with ice floes of 1.0 m level ice thickness
ICE-1A	Operating in ice conditions with ice floes of 0.8 m level ice thickness
ICE-1B	Operating in ice conditions with ice floes of 0.6 m level ice thickness
ICE-1C	Operating in ice conditions with ice floes of 0.4 m level ice thickness
ICE-C	Operating in light ice conditions
ICE-E	Ice strengthening for light localized drift ice in mouths of rivers and coastal areas

Recently, DNV has increased its Arctic-related class activities. They are researching contingency planning and preparedness standards, vessel routing measures, reporting systems, and traffic services. Approximately 1,900 vessels carry DNV ice-class notations with one-third of all the DNV-classed tankers on order specified with ice strengthening. DNV covers the entire spectrum from icing in open water to icebreaking capabilities in temperatures as low as -55^{o}C. In addition, optional notations are available, such as winterization and DEICE (described in more detail in Section 3.5.4.1) [55].

Higher requirements for redundancy and reliability are required for vessels operating alone in such remote areas. Furthermore, as the traffic increases, there will be less icebreaker support available unless local governments are increasing icebreaker support by rearranging the existing fleet or by ordering additional icebreakers.

Also, the increased size of the ships becomes a concern when the width of the vessel is larger than the width of the icebreaker. Either two icebreakers acting together are required or the vessel will have to be designed for independent icebreaking. Double-acting vessels may be a solution (described in more detail in Section 3.4.2) [43].

DNV also researched an ice load monitoring system that provides bridge personnel with real-time information about the actual ice loads on the ship's hull and shows satellite information about the ice in the vicinity of the vessel. This system includes fiber optic sensors that measure shear strain on the vessel's hull and electromagnetic equipment which measures the thickness of the ice at the bow. This information is analyzed and displayed on the bridge. Additionally, meteorological and satellite data about the ice is integrated into electronic charts allowing for optimum route selection. The project is the first to monitor the actual ice loads and present them in real time at the bridge as a part of a decision support system. The system is ready to be installed for both new and in-service ships [56].

2.6 ABS Class Rules

The American Bureau of Shipping has a system of ice classes which includes classes A5 through A0; B0, C0, and D0. A5 class is the strongest built of the classes, with D0 being the weakest. The Ice Class Rules are separated into three Chapters.

Chapter 1 provides a procedure for ice strengthening of side structures using nonlinear finite element modeling (FEM), including both side longitudinals and side shell plating. The ice strengthening procedure involves four steps for alternative design of the side structure under ice load. Table 2.4 summarizes their four steps.

Table 2.4: Steps in Ice Strengthening of Side Structures [2]

Step	*Design*	*Notes*
1	FSICR design, baseline design	Design fully complies with FSICR (Ice strengthened longitudinal spacing, less than 450 mm)
2	FMA interim design	Design complies with the FMA Guidelines, item 2 (Longitudinal spacing is wider than that specified by FSICR)
3	Alternative design for side longitudinals	Side longitudinals without brackets are determined using nonlinear FEM.
4	Alternative design for side shell	Side shell thickness is determined using nonlinear FEM for extreme ice loads.

The initial design of the side structures should fully comply with FSICR. FSICR require that the maximum frame spacing of longitudinal frames "shall not exceed 0.35 meter for ice class IA Super and IA and shall in no case exceed 0.45 meter". Brackets are required to connect longitudinals and webs. A more sophisticated method may be substituted to determine the hull scantlings. The reasons a non-linear FE model approach would be used are to lower the production costs and to reduce the weight. The weight of the structure according to direct calculation is normally lower than that required by FSICR [2].

Chapter 2 provides a procedure for calculating the power requirement for ice-class ships. The minimum required engine output power is calculated utilizing the following formula:

$$P = K_C \frac{(R_{ch}/1000)^{3/2}}{D_p} \; kW$$

where

K_C – efficiency of propeller

R_{ch} - resistance of the vessesl

D_p - diameter of the propeller

This power requirement is meant to provide the vessel with a minimum speed of 5 knots in the following ice conditions shown in Table 2.5 [2].

Table 2.5: Performance Requirements [2]

Performance Requirement			
Class	*Speed (knots)*	*Channel Thickness (m)*	*Consolidated Layer (m)*
IA Super	5	1	0.1
IA	5	1	0
IB	5	0.8	0
IC	5	0.6	0

Note: FSICR Notation
Channel thickness = Ice Thickness
Consolidated Layer = Thickness of Snow on Top of Ice

Chapter 3 provides a procedure for the strength analysis of propellers for ice class vessels. In propeller strength assessment, the updated Finnish-Swedish Ice Class Rules requests that all IA Super class propellers and highly skewed propellers in IA, IB, and IC classes be subjected to detailed FEM-based stress analysis. Technical details regarding the performance of fatigue and plastic failure analysis in the blade strength assessment procedure are provided [2].

There are two types of interactions between ice and propellers, namely 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 occur more frequently [2].

The material used for the propeller blades of ice class vessels must have high stress and impact resistance qualities. Stainless steel and bronze are commonly used for ice-strengthened propeller blades [2].

2.7 Polar Class Rules

There have been efforts to harmonize all of the different ice-classes into one unified set. The introduction of the International Association of Classification Societies (IACS) Polar Class Rules is a significant step in the rule harmonization process. The rules will then have to be adopted by all IACS members. These rules may be the standard in years to come.

2.7.1 Polar Class Description and Application

The Polar Class Rules consider limited icebreaker assistance and, thus, glancing impact with an ice floe. These rules are mainly applicable to navigation in multi-year ice, with the PC1 class capable of independent operation without limitation. Table 2.6 describes the different Polar Ice Classes.

Table 2.6: Polar Class Descriptions [54]

Polar Class	Ice Description (based on WMO Sea Ice Nomenclature).
PC1	Year-round operation in all Polar waters.
PC2	Year-round operation in moderate multi-year ice conditions.
PC3	Year-round operation in second-year ice which may include multi-year ice inclusions.
PC4	Year-round operation in thick first-year ice which may include old ice inclusions.
PC5	Year-round operation in medium first-year ice which may include old ice inclusions.
PC6	Summer/autumn operation in medium first-year ice which may include old ice inclusions.
PC7	Summer/autumn operation in thin first-year ice which may include old ice inclusions.

2.7.2 Structural Requirements for Polar Class Ships

This section of the Polar Class Rules provides structural requirements to enable ships operating in the Arctic to withstand the effect of ice load and temperature. For ships of all Polar Classes, a glancing impact on the bow is the design scenario for determining the scantlings required to resist ice loads. Additionally, global hull girder longitudinal strength analysis is made based on an ice-ramming scenario.

This section also contains material requirements, framing method, corrosion/abrasion allowances, direct calculations, and welding requirements [20, 54].

2.7.3 Machinery Requirements for Polar Class Ships

This section of the Polar Class Rules includes technical requirements for the main propulsion, steering gear, emergency and other auxiliary systems essential for the safety of the ship and the survivability of the crew. It considers the results of research and development on propeller damages, propeller and shaft load measurements, and propeller-ice interactions to base its Rules [20, 54].

2.8 Equivalencies

The comparison of the different ice-classes' rules is a multi-parametric problem. To make it a one-parameter problem, two methods are used: weakest element criterion and averaged correspondence criterion [8]. The average method is used below since it obtains more objective results. There are also three different ways to compare ice-classes: hull structure strength and metal consumption, power requirements, or both. Figure 2.5 shows the ice-class equivalencies based on power requirements while Figure 2.6 shows ice-class equivalencies based on hull structure strength and metal consumption.

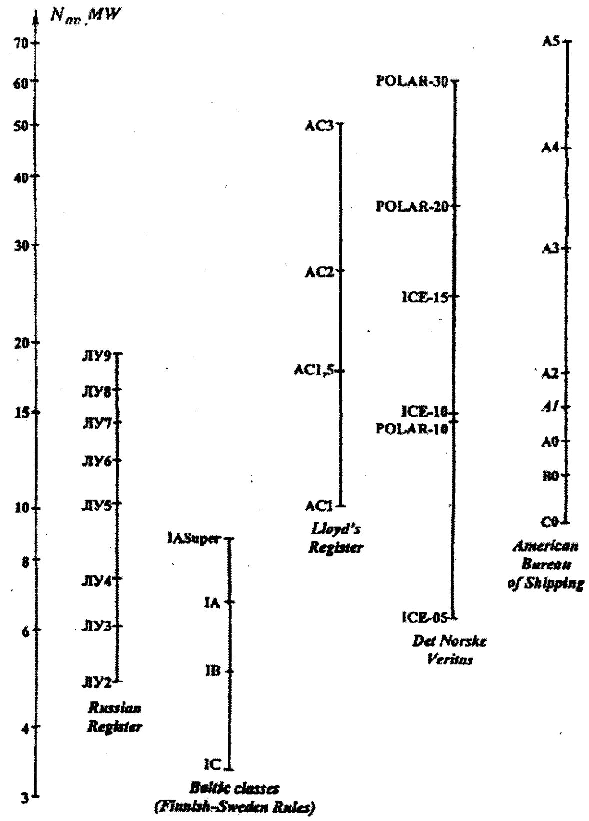

Figure 2.5: Ice-Class Equivalency by Power Requirements [8]

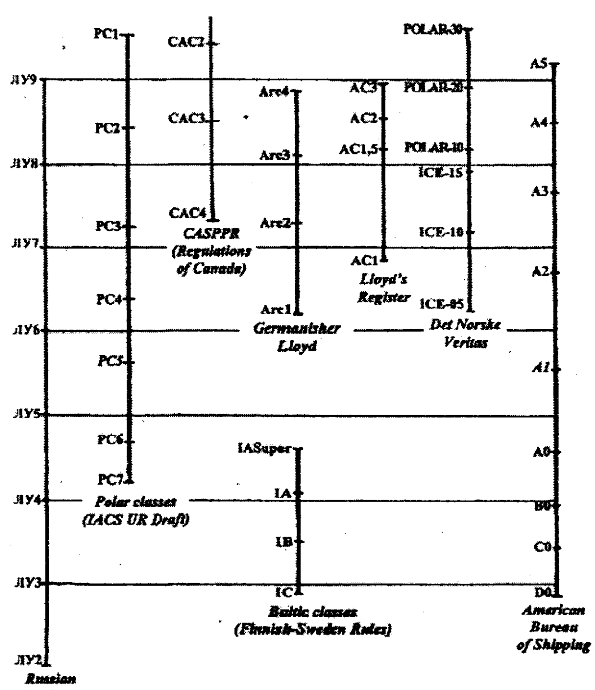

Figure 2.6: Ice-Class Equivalency by Strength and Metal Consumption Condition [8]

Figure 2.7 shows ice-class equivalency combining the strength and power requirements.

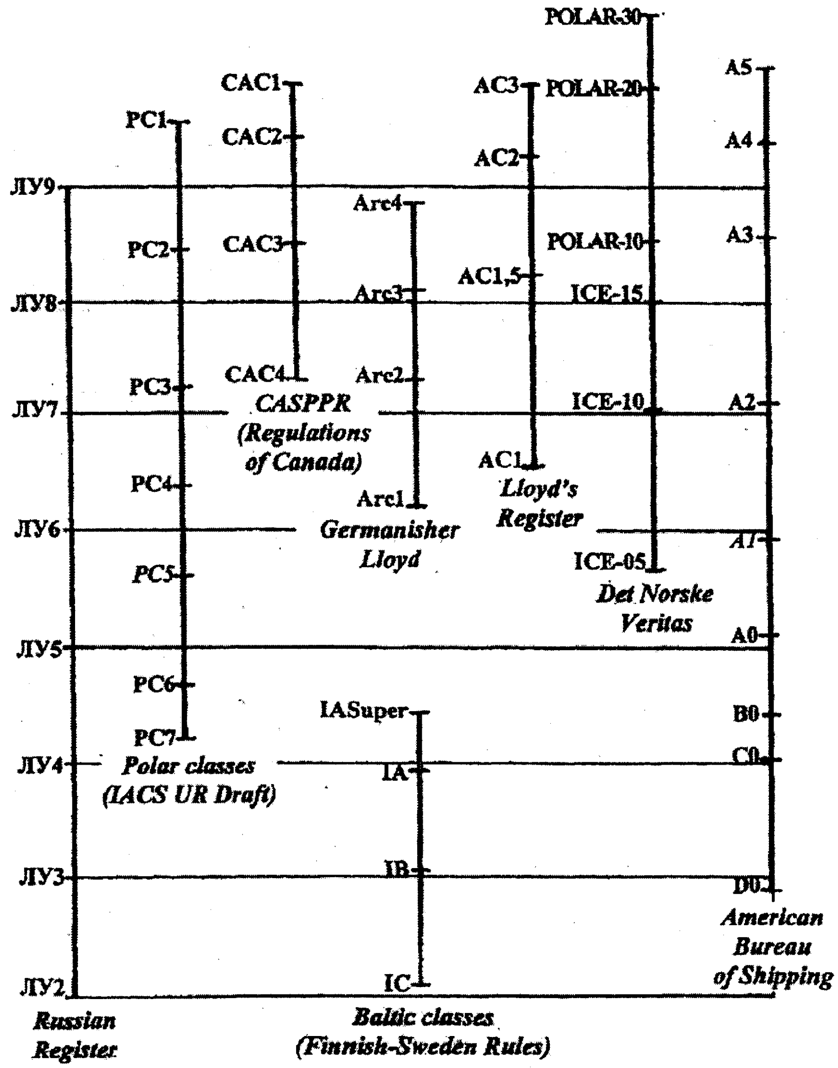

Figure 2.7: Ice-Class Equivalencies by Combining Strength and Power Requirements [8]

The feasibility of the equivalency tables comes into question. Will governments adopt other ice-classes? Or, will governments require the vessel to be classed within their current operating jurisdiction? Also, several different methods and charts of equivalencies are available. There can be differences of ±20% between the ice-class equivalencies.

Figure 2.8 shows another set of ice-class equivalencies obtained from industry sources.

ABS	Canadian	Baltic	DNV		Russian*		Russian old rules		Proposed IACS	Ice conditions regularly recorded in the area of operation	Minimum Icebreaking Capability of the Escort Icebreaker at 4 knots, m	Minimum Icebreaking Capability at 4 knots, m
			Vessel	Icebreaker	Vessel	Icebreaker	Vessel	Icebreaker				
A5	CAC1								PC1	Multi-year ice of more than 3.5m	3.25	3.00
A4	CAC2			POLAR-30		LL9		LL1	PC2	Multi-year ice of 3-3.5m	3.00	2.25
A3	CAC3			POLAR-20	LU9	LL8		LL2	PC3	Second year ice of 2-3 m	2.50	1.50
A2	CAC4			ICE-15/POLAR-10	LU7/8	LL7	ULA	LL3	PC4-PC5	First-year medium/thick ice of 0.7-2 m	1.50	1.00
A1	Type A	IAS	ICE-IA*-1A*F	ICE-10	LU6/LU5	LL6	ULA-UL	LL4	PC6	First-year medium ice of 0.6-1.2 m	1.20	0.70
A0	Type B	IA	ICE-IA	ICE-05	LU4		UL	UL	PC7	First-year thin ice of 0.5-0.9 m	1.00	0.70
B0	Type C	IB	ICE-1B		LU3		L1	L1		First-year thin ice of 0.3-0.6 m	0.70	0.45
C0	Type D	IC	ICE-1C		LU2		L2	L2		First-year thin ice of 0.3-0.4 m	0.50	0.35
D0	Type E				LU1		L3	L3		First-year thin ice of 0.2-0.3 m	0.5	0.25

* Current rules

Figure 2.8: Ice-Class Equivalencies from Industry

Table 2.7 shows yet another set of ice-class equivalencies.

Table 2.7: Approximate Equivalence of Class Symbols for Ice Strengthening Between Classification Societies [20]

Classification Society					
Finnish Swedish Ice Class Rules	IA Super	IA	IB	IC	II
Russian Maritime Register of Shipping (Rules 1995)	UL	L1	L2	L3	L4
Russian Maritime Register of Shipping (Rules 1999)	LU5	LU4	LU3	LU2	LU1
American Bureau of Shipping.	A1	A0	B0	C0	D0
Bureau Veritas	IA Super	IA	IB	IC	ID
CASPPR, 1972.	A	B	C	D	E
China Classification Society.	B1*	B1	B2	B3	B
Det Norske Veritas	ICE-1A*	ICE-1A	ICE-1B	ICE-1C	ICE-C
Germanischer Lloyd	E4	E3	E2	E1	E
Korean Register of Shipping.	ISS	IS1	IS2	IS3	IS4
Lloyd's Register of Shipping.	1AS	1A	1B	1C	1D
Nippon Kaiji Kyokai.	IA Super	IA	IB	IC	ID
Registro Italiano Navale	IAS	IA	IB	IC	ID

Figures 2.9 and 2.10 show another set of ice-class equivalencies.

Ice-Class Equivalents			
Lloyds	DNV	Russian 1999	Finnish-Swedish
Ice Class 1AS	ICE-1A*	JIY6	1A Super
Ice Class 1A	ICE-1A	JIY4	1A
Ice Class 1B	ICE-1B	JIY3	1B
Ice Class 1C	ICE-1C	JIY2	1C
Ice Class 1D		JIY1	II
100 A1		JIY1	II

Figure 2.9: DNV Ice-Class Equivalencies

Classification Society/National Administration	*Approximate class equivalents*								
Canadian Arctic Shipping Pollution Prevention Regulations		CAC 1	CAC 2	CAC 3	CAC 4	Type A	Type B	Type C	Type D
Russian Maritime Register of Shipping	LL1	LL2	LL 3	LL 4	ULA	UL	L1	L2	L3
Det Norske Veritas	P30	P20	P10 I15	I10	I05	1A*	1A	1B	1C
Lloyd's Register of Shipping	LR 3	LR 2	LR 2 LR 1.5	LR 1.5	LR 1	1A 1AS	1B	1B 1C	1C
Finnish-Swedish Maritime Administrations						1AS 1A	1B	1B 1C	1C
Germanischer Lloyd						E4	E3	E2	E1
Bureau Veritas						1AS	1A	1B	1C
American Bureau of Shipping						1AA	1A	1B	1C

Figure 2.10: Approximate Equivalencies between Classes [40]

Figure 2.11 shows another equivalency table between FSICR and IACS Polar Class rules.

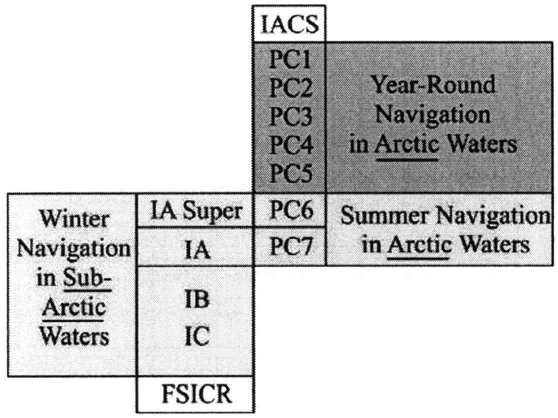

Figure 2.11: Ice-Class Equivalencies between FSICR and IACS [17]

Several of these ice-class notations are used in the analysis and discussion of ice-classing impacts for containerships in Section 3.5.

3.0 Chapter 3: Arctic Containerships

3.1 Introduction

Arctic containerships are significantly different than their conventional (or open water) counterparts. The design implications of an ice-classed containership are described as well as a survey of the current ice-classed containership fleet. This survey shows the profile of the different ice-classes, with the lowest ice-classes being the most prevalent. The implications of an ice-classed design are far-reaching, from the hull form and structure to the power and auxiliary systems. Then, the Aker study is examined to obtain baseline sizes for the containerships that are analyzed [6]. The analysis of the different sized containerships begins in Section 3.5.

3.2 Fleet Survey

Three classification societies' fleets were analyzed to determine the allocation of the different ice-classes. Lloyd's Registers' database of ice-classed containerships was examined and the distribution of the different classes was determined. Figure 3.1 shows the majority (76%) of the containerships classed as ice-class were the lowest Finnish-Swedish Ice-Class available (FSII). This class is defined as "ships that have a steel hull and that are structurally fit for navigation in the open sea and that, despite not being strengthened for navigation in ice, are capable of navigating in very light ice conditions with their own propulsion machinery" [26].

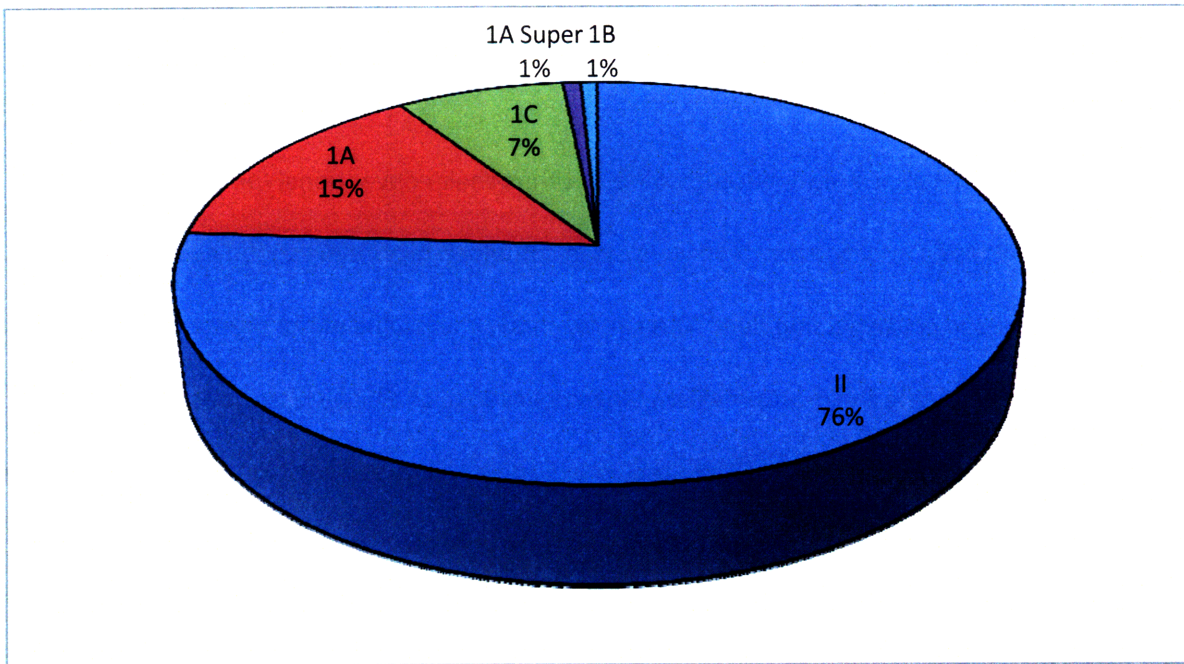

Figure 3.1: Lloyd's Register Ice-Class Fleet (1,350 Containerships)

The Germanischer Lloyd's ice-class fleet was also analyzed. Approximately one-third of their ice fleet consists of containerships (2,631 Ice-Class Vessels in Fleet). The profile of the fleet of containerships was examined in Figure 3.2. More than half of the fleet was classed at the two lowest classes (1C and 1B). Approximately 97% were classed at the 1A, 1B, and 1C ice-classes.

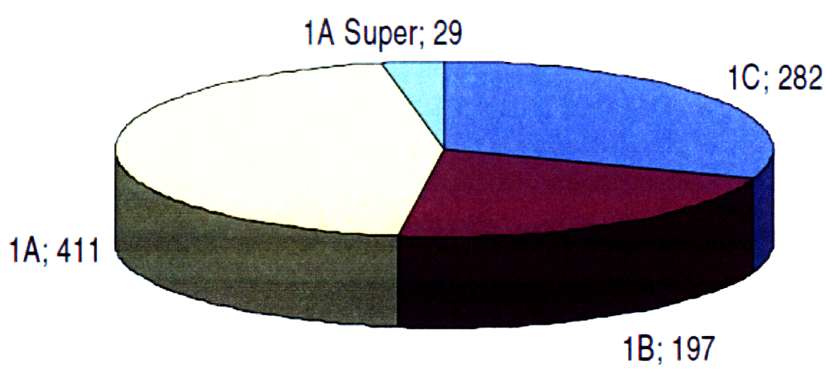

Figure 3.2: Germanischer Lloyd's Baltic Ice-Class Fleet (919 Containerships) [28]

Finally, DNV's fleet was studied. Their fleet of containerships was considerably smaller in size (DNV mostly classes tankers), but similar trends were seen. Figure 3.3 shows the distribution of ice-classes. More than 80% of the containerships were classed at the two lowest classes (1C and 1B).

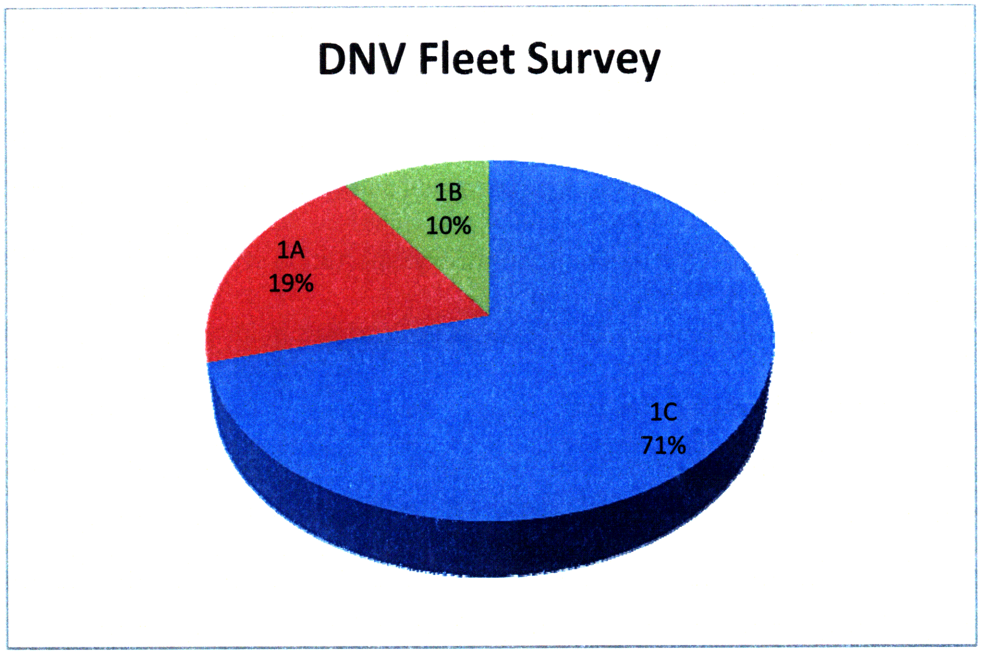

Figure 3.3: DNV's Containership Fleet Survey (31 Containerships)

3.3 Impact of Ice-Class on Vessel Design

Ships whose missions take them into ice-covered waters must be designed to operate effectively in an environment distinguished by cold temperatures, remote locations, and the presence of sea ice. Sea ice can be from a few centimeters to several meters thick, take on a variety of morphological forms, and change on daily, seasonal, and annual bases [40].

The choice of ice capabilities of the vessel depends on the amount of time spent in ice-covered water relative to open water, the ice conditions on the transportation service route, and on the availability and costs of icebreaker escort services on specific routes. Additionally, operational flexibility and the second hand market could be factors.

Usually an icebreaker would be expected to achieve about 10 to 12 knots in ice conditions considered normal in its operating area. In heavier ice conditions, a lower speed, about 6 knots, is acceptable. The ability to break a given thickness of ice at a minimum continuous speed of about 2 knots is the usual measure of performance [40].

For most commercial ships, the effects of ice-classing are incremental: increasing scantlings and propulsion power leads to a higher capital cost and loss of cargo capacity. But for ships with icebreaking as their primary mission, ice has a more fundamental impact on design.

3.3.1 Hull Form

3.3.1.1 General Arrangements

The general arrangements of ice-going vessels can vary widely due to their diverse missions. Since the ports in the Arctic are usually remote, vessels may carry their own cargo handling gear. Also, endurance is a factor, so tank capacities and storage for spares and provisions are more important than for a conventional vessel. The extreme cold and darkness call for several other amenities not commonly found on ships: more interior access ways and equipment operating spaces, adequate heating, insulation, air conditioning, and extra lighting. Additionally, the noise and vibration from icebreaking should be kept in mind when designing accommodation spaces.

Escort icebreakers typically have a clear deck aft to accommodate towing operations. This can include a stern notch. Also, helicopters are usually carried on-board icebreakers, so a helicopter deck is needed. Most importantly, the bridge needs to have excellent visibility in all directions.

The *Oden* is a Baltic escort icebreaker with Arctic icebreaking capabilities shown in Figure 3.4. Several features shown are the stern notch, helicopter deck, and clear decks forward and aft. Some noteworthy hull form features include a wide forward form incorporating reamers (discussed more in Section 3.3.1.2), an ice clearing wedge at bottom, a shallow icebreaking stern, and a rugged arrangement of twin rudders and propellers in nozzles [40].

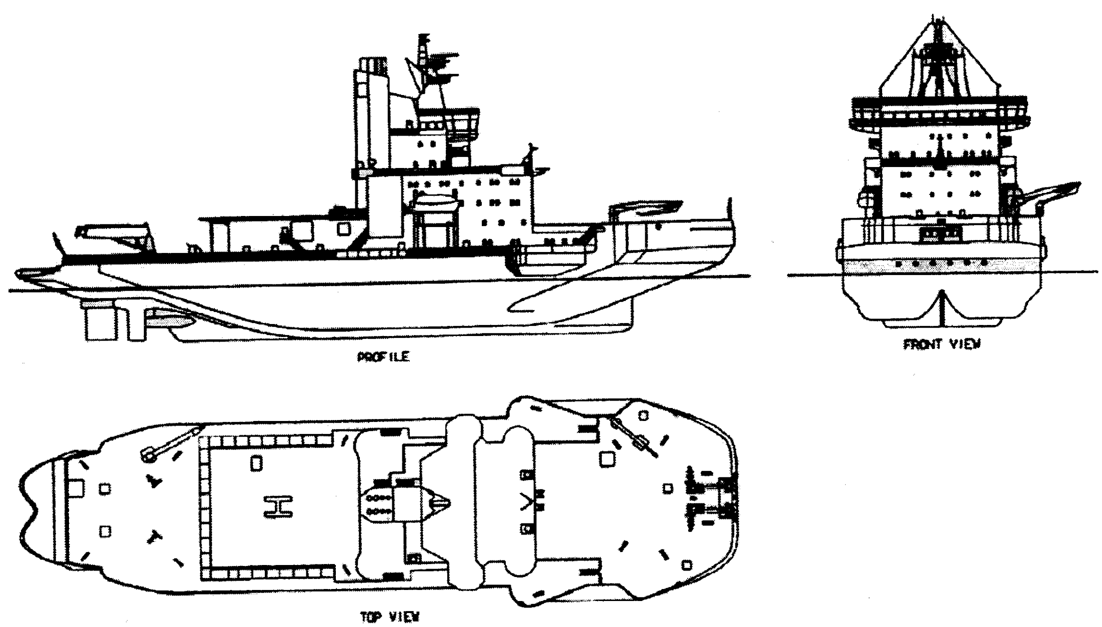

Figure 3.4: General Arrangements of the *Oden* [40]

3.3.1.2 Shape

The design of the hull form for an icebreaking vessel is a compromise between icebreaking and open water performance. The appropriate balance is determined specifically for each ship's mission. Improved icebreaking performance usually comes at the expense of open water resistance and seakeeping.

To break level ice effectively, the bow form should promote flexural failure instead of crushing. This means a shallow stem, buttock, and flare angles. This form also eases the submergence of the ice. To promote good ice clearance, shallow waterlines and a fine fore body should be utilized. However it is difficult to reconcile a good icebreaking form with superior ice clearing. The progress of all vessels is impeded in ice-clogged channels, but those with shallow bow angles and relatively blunt fore bodies tend to suffer the most. Shallow refers to small buttock and flare angles. Figure 3.5 shows these bow form characteristics.

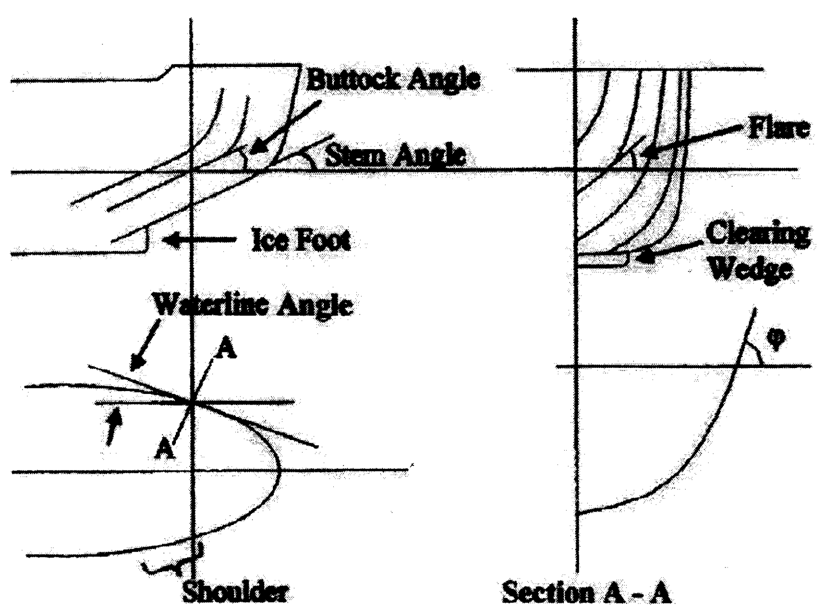

Figure 3.5: Bow Form Characteristics [40]

A bulbous bow is probably not appropriate for icebreaking. A bulb is not effective in breaking ice, has poor clearing attributes, and presents difficulties for some towing arrangements.

Clearing is particularly important when navigating in very close thick pack ice or in brash ice-clogged channels. Submerged ice can accumulate at the bow and impede or stop progress. Additionally, these ice pieces can slide along the entire length and reemerge along the buttocks leading to the propeller. Propeller-ice interactions can severely hinder propulsion performance. To deal with this, a clearing wedge can be incorporated into the hull to promote clearing to the sides. This feature can be seen in Figures 3.4, 3.5, and 3.6.

To prevent the vessel from becoming beached during aggressive ramming of ridges and thick ice floes, an ice skeg (or foot) can be fit to the bow to limit the extent to which the vessel can ride up on the ice feature (See Figures 3.4, 3.5, and 3.6). Figure 3.6 shows several examples of icebreaking hull shapes.

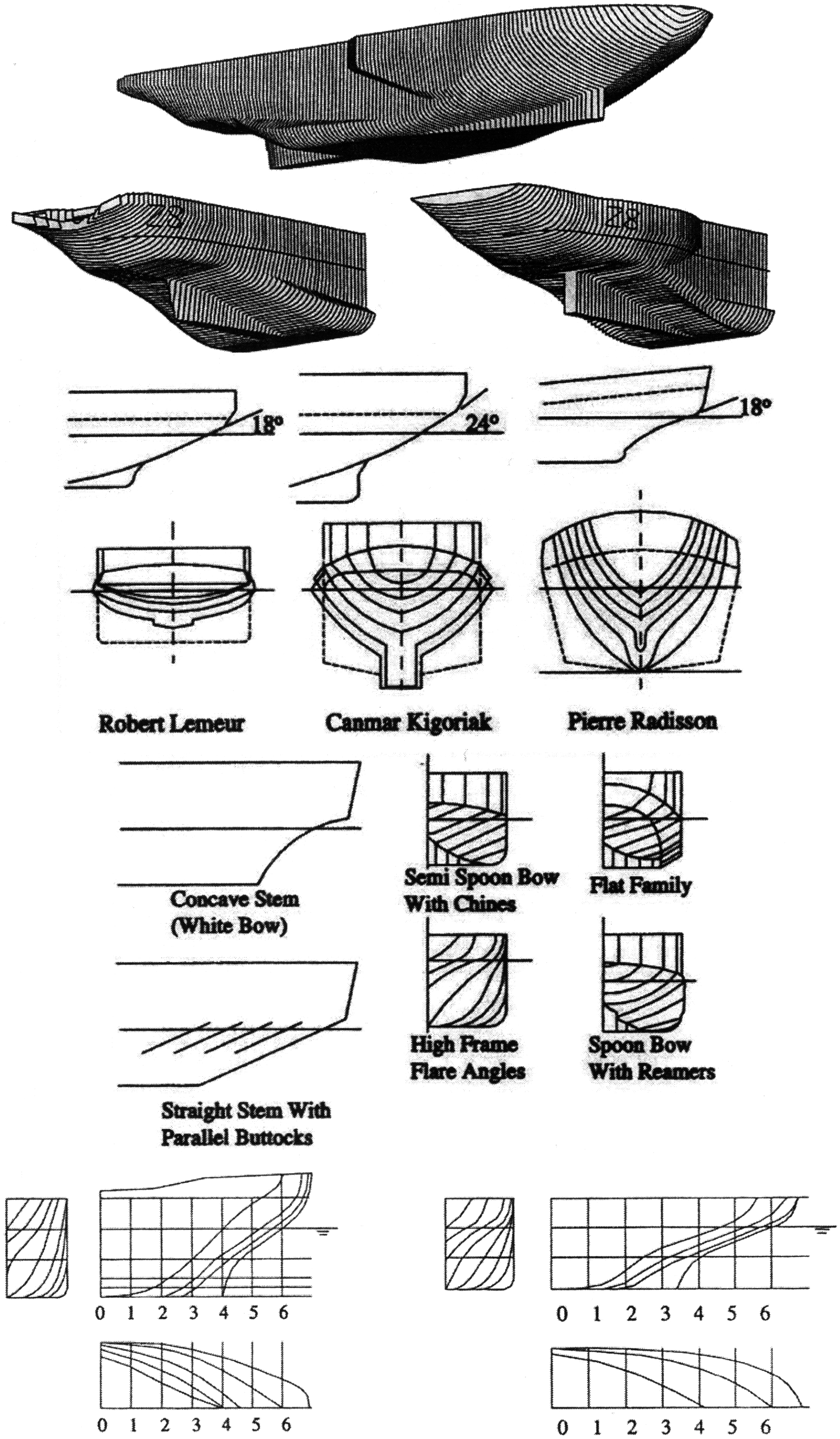

Figure 3.6: Icebreaker Hull Forms [40]

For conventional icebreakers, a gradual transition from the bow to the midbody is usually employed. This avoids excessive crushing at the shoulders during forward icebreaking and maneuvering. Some icebreakers have sloped sides (about 8^0 from vertical) along the midbody to provide some force for the ice to fail in bending rather than crushing. This can improve maneuvering where the midbody comes into contact with the ice, but can complicate the internal structure [40].

Frictional resistance (from both water and ice) can be kept to a minimum with a good bow form, which breaks a channel wide enough for the rest of the vessel to pass through. Some icebreakers have bows that include reamers, so that the bow is wider than the midbody (See Figure 3.4).

The design of an icebreaker's stern is driven by the required icebreaking capabilities, the propulsion system (conventional shafting vs. Z-drives or Azipods, single, twin, or triple screw, and open or ducted propellers), and the protection of the propulsion gear. The stern also has shallow buttocks at the waterline for reverse icebreaking. Reamers in the bow are a disadvantage when operating in reverse and some auxiliary systems, such as a water wash (described in Section 3.3.3) system, can be used to mitigate this disadvantage [40].

Several methods have been used to protect rudders and propellers from ice. Ice knives aft of the rudders are intended to deflect and split ice floes when operating in reverse. They are also used to prevent the ship from excessive ride up on an ice feature, like the ice skeg on the bow.

The importance of bow shape can be seen by analyzing the characteristics of three different bow shapes for two different ice-classes as shown in Table 3.1. The table compares two ice-classes to the open water variant. For each ice-class, three different bow shapes were analyzed. Most of the additional weight was added in the forward section of the hull (50% to 60% of the extra hull steel). The effect on power is tremendous. For the 1A Super class, the power ranges from 15MW to 40MW; that's almost three times as much power for a change in bow shape.

Table 3.1: Effect of Bow Shape on Power [48]

Ice-Class	P_B (MW)	P_B (hp)	Aft (t)	Midship (t)	Forward (t)	Total (t)	Δ Increase	Δ_{NEW} (t)
IA	15.0	20,115	61	261	529	851	4.4%	20,251
	22.5	30,173	79	299	583	961	5.0%	20,361
	30.0	40,231	93	330	628	1,051	5.4%	20,451
IA Super	15.0	20,115	142	453	605	1,200	6.2%	20,600
	27.5	36,878	176	528	698	1,402	7.2%	20,802
	40.0	53,641	202	586	770	1,558	8.0%	20,958
Open Water Hull Steel Weight =					19,400 t			

3.3.1.2 Structure

The structure of an ice-capable ship is designed to resist local loads due to ice contact and global loads associated with ramming-type operations. Vibration, caused by icebreaking and high installed power, is also a consideration. Special steel grades with adequate fracture toughness are used because of the very low temperatures encountered. To reduce the steel weight, usually higher strength steels are used, which can complicate the fabrication, especially the welding [40].

Ice loads are very difficult to quantify. Efforts are underway to better predict these loads. Several full-scale measurement programs have shed new light on this area of research recently. Using this data, a nominal uniform average pressure and corresponding load area could be deduced for future designs [40].

For the speeds used in icebreaking, the ice at the interface fails in a brittle manner and the contact pressure over a nominal contact area tends to be highly concentrated in relatively small regions distributed within that area. This causes local ice failure and rapid changes in the locations of the concentrated high contact pressure. Additionally, the variability of the mechanical properties of ice (which affect failure) complicates the contact loading phenomena further. There are also interaction effects like global body motions due to contact loads and local structural deflection, that influence the ice loads [40].

An ice load model must capture the magnitudes of the design loads corresponding to full-scale experience and the contact areas and pressures reflecting the pressure-area relationship (the design pressure is higher for local structural members than for larger structural assemblies).

Lately, a move from using the first yield (elastic limit) as a design criterion to using the large strength reserve in ductile steel plate due to its plasticity is being incorporated into the design criterion. Using plastic design criteria, permanent set is acceptable, but rupture is still avoided [40].

Structural failure of the support structure can take the form of bending, shear failure, fracture, and local buckling and tripping instability. To prevent these failure types, each member must have an adequate section modulus, shear area, and fracture toughness. When aggressive ramming is part of a ship's mission, the deck and bottom stresses due to global bending are kept within permissible limits by ensuring adequate hull girder section modulus.

Another consideration for a vessel's structure is brittle fracture. Ice-capable ships are especially prone to this condition due to their operating environment (air temperatures of -20^{0}C to -50^{0}C and water temperatures of 0^{0}C), their mission (causes high local stresses and intermediate strain), and their thick plating (increases the number of flaws that can propagate). This has caused the use of high-strength steels to become a requirement for most classification societies. The most likely sources of defects are the weld metal and heat-affected zone of the base metal [40].

The use of high strength steels is becoming more prevalent in the design of icebreakers. Using higher strength steel reduces weight and provides flexibility to the designer. In the *Oden* design (Figure 3.4), high strength and extra high strength steel were extensively used ($\sigma_Y \approx 355$ Mpa and $\sigma_Y \approx 500$ Mpa), which offered shell weight savings of about 18% and 30%, respectively, over conventional steel ($\sigma_Y \approx 245$ Mpa) [40].

The hull can be separated into various sections, depending on the frequency and the severity of the ice loads. Figure 3.7 shows these respective areas.

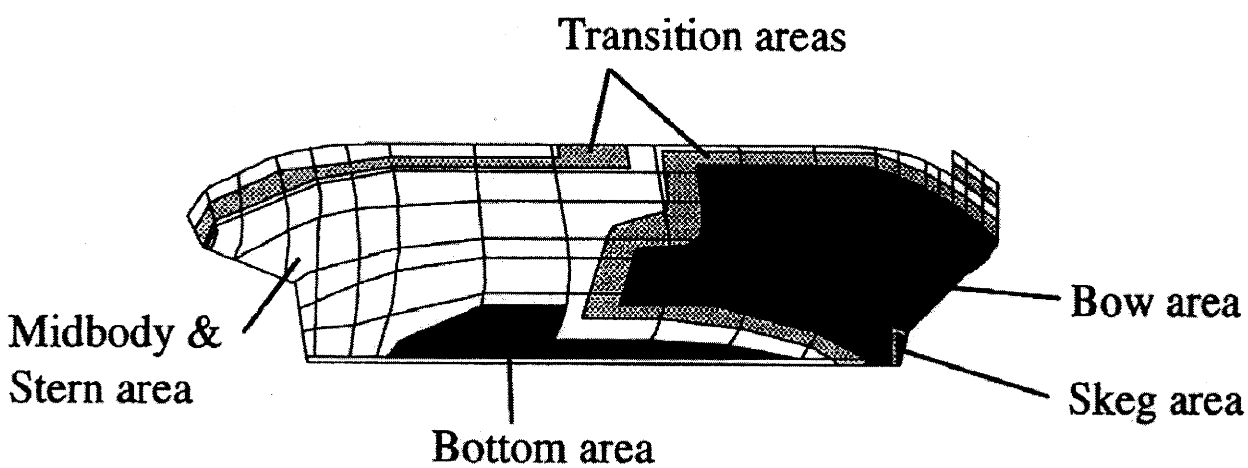

Figure 3.7: Ice-Strengthened Hull Areas [40]

The classification societies usually state maximum design loads that are based on ship-ice interaction models that are calibrated with full-scale measurements. The design loads depend on displacement and power and are applied to different structural members according to a pressure-area relationship. Scantlings are determined using elasto-plastic design criteria that permit stresses in excess of yield so that some permanent deformation is acceptable. This leads to thinner plate, bigger frames, and larger frame spacing over traditional ship structural design methods [40].

3.3.2 Propulsion

The propulsion system for an icebreaker is selected similarly to that of conventional ships. The selection is based on capital and operating costs, reliability, power to weight ratio, and efficiency. Additionally, icebreakers need systems that are highly responsive for maneuvering and that can operate effectively even while subjected to repeated, intermittent, high torque loading due to propeller impacts with ice.

The medium speed diesel engine is the most common type of prime mover used on icebreakers. They have relatively good power to weight ratios and fuel consumption, with relatively inexpensive fuel, and are compact and reliable. One drawback is their relatively poor overtorque capability. The transmission used deals with this deficiency [40].

The determination of the required power is based on the resistance and propulsion in ice. Decisions on the necessary power are increasingly being made on the basis of model testing. Figure 3.8 shows typical ice and open water resistance curves. The rate of increase of the ice curve is comparable to a quadratic while a cubic is fitted to the open water curve [43, 63].

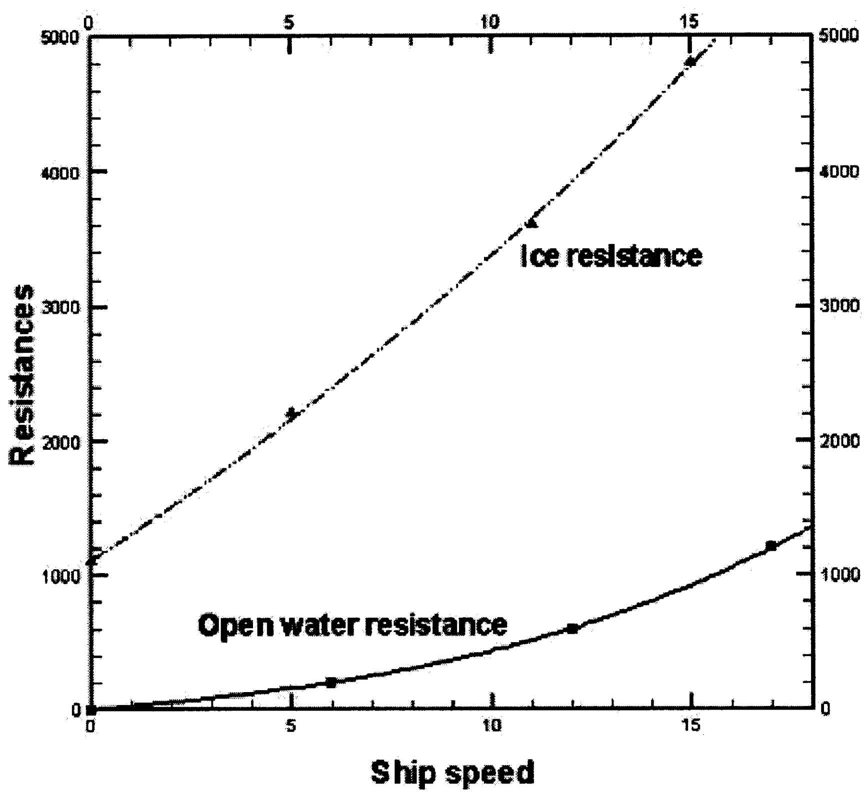

Figure 3.8: Typical Ice and Open Water Resistance Curves [63]

The transmission type is either a geared diesel or a diesel-electric system. Geared diesels have a higher efficiency and are lighter, more compact, less costly, and simpler although the ice loads pose some complications. The high transient ice torque loads necessitate a large flywheel to ensure that the shaft continues to rotate without a sudden loss of speed when the propeller mills ice. Also, controllable pitch propellers with a rapid pitch control capability can be used to accommodate high ice torque loads. Diesel-electric systems cope better with the ice torque loads by decreasing shaft speed. Diesel-electric systems have excellent speed-torque characteristics and flexibility, in both power output and arrangement [40].

A single centerline screw on a horizontal shaft is the most common arrangement used on ice strengthened cargo ships. Most icebreakers have two or three propellers. Multiple propellers offer redundancy in case of damage, flexible use of power, and enhanced maneuverability. Azimuthing propellers are becoming popular as they eliminate the need for rudders, shafting, and brackets so the flow into the propeller is more uniform [40].

The propeller also has to be strengthened for the ice. The extra strength requirements and high thrust loading results in high strength material, thick blade sections, large blade areas, large hubs, and little or no rake. Some propellers have the individual blades bolted to the hub, which makes for easier replacement if one blade is damaged [40]. There are advantages and disadvantages to either fixed pitch (FPP) or controllable pitch (CPP) propellers. They are related to the machinery commonly used with each: diesel-electric for FPP and geared diesel for CPP. To ensure the pitch control for the CPP is adequately strong and protected, the hub is large (35 to 40% of the propeller diameter). This causes a loss of efficiency and CPPs are relatively expensive. However, CPPs are good for a vessel that operates over a wide range of loading conditions and eliminates the need for shaft reversals, thus avoiding low speed and stopped propeller conditions under which a propeller is particularly vulnerable to ice damage. However, FPPs reverse performance is superior to that of the CPPs.

There are several methods to protect a propeller from ice damage: use a duct, locate the propeller as close to centerline as possible, reduce the propeller diameter in order to limit torque loads, use ice deflecting devices, use ice horns and rudders for reverse operation, and for forward operations use a large skeg or ice wedge. However, all of these devices have drawbacks [40].

3.3.3 Auxiliary Systems

There are a variety of auxiliary systems that are employed to aid the icebreaking process, reduce resistance, or improve propulsive performance. Low friction paint is one of the simplest. Another method is an air bubbler system that pumps compressed air at the midbody and bow to reduce frictional resistance. This system works best at low speeds. A water deluge, or water wash, system sprays large volumes of water under low pressure on the ice from above the waterline at the bow. This reduces friction, overburdens the ice, and promotes submergence of ice pieces. Also, heeling tanks are used to aid in icebreaking and increase maneuverability. By transferring water between the tanks in rapid succession, the ship can proceed through heavy ice conditions in a 'duck walk' (rocking/swaying motion). All of these systems require power that could be incorporated into the propulsion plant [40].

3.3.4 Operation in Ice

Successful passage through ice-choked waters depends on the freedom to maneuver. The safety of the vessel is dependent primarily on the operational aspects (mainly speed) and the structural capability of the vessel. There are three basic ship handling rules when encountering ice:

- Keep moving, even if very slowly.
- Work with the ice movement and not against it.
- Excessive speed leads to ice damage.

Additionally, the severe cold could cause a reduction in the standard operating procedures for radio and navigational equipment.

The crew will be exposed to continuous freezing temperatures and darkness, which will deteriorate their performance, thus reducing the safety of the vessel. Each crew member should be familiar with the signs and treatments of hypothermia. Furthermore, an Ice Navigator should be on board vessels operating in Arctic ice-covered waters [20].

3.3.5 Other Requirements

3.3.5.1 Stability

Icebreakers have special stability requirements due to the potential for icing (discussed in Section 3.5.4.1). Damage stability requirements are also more stringent. In order to ensure safe passage, there are additional minimum navigation and equipment requirements.

3.3.5.2 Pollution Prevention Provisions

Each classification society and country has a different set of environmental rules. Russia requires a wastewater treatment facility with a thirty day holding tank. Also, a bilge water separator is mandated and there are bilge water and garbage discharge restrictions. The vessel must have a double bottom with no storage of petroleum products. Canada implements a zero-discharge of water policy (with minor exceptions). Similarly, there are bilge water discharge restrictions and no pollutants can be stored on the ship side or bottom [17].

3.4 Aker Study Comparison [6]

3.4.1 Overview

Aker Arctic Technology performed the study, "Arctic Shuttle Container Link from Alaska US to Europe," in March 2006. In this paper, two containerships were considered: a 750 TEU vessel and a 5000 TEU vessel. One major difference between the 750 TEU and 5000 TEU containerships is the draft. The larger vessel cannot sail on the coastal route; therefore, it must navigate the Arctic polar pack ice on the more northern route [6]. Accordingly, the ice conditions are more difficult, increasing her ice strengthening and power requirements.

3.4.2 Aker's Double Acting Operation

The double acting concept is patented by Aker. A vessel operates bow first in open water and light ice conditions and stern first in heavy ice conditions. This allows the bow to be designed to be efficient in open water, which usually includes a bulb. Also, electric propulsion and azimuthing thrusters must be adopted. The DAS, 'Double Acting Stern,' has no rudder in front of the propellers to impede its progress. The azimuthing movement of the thrusters makes the reversing steerable, and the ice crushing effect of the propellers is seen over a wider range, simultaneously enlarging the flushing effect on the hull surfaces [6].

3.4.3 750 TEU Arctic Containership

The 750 TEU Arctic containership is an improved design of the *Norilskiy Nickel*. The *Norilskiy Nickel* is an operating 650 TEU containership with an ice-class of LU-7 in the Russian Maritime Register. The *Norilskiy Nickel* exceeded all performance predictions and has even been known to lead actual icebreakers in heavy ice conditions. The design of the 750 TEU containership is shown below in Figure 3.9. This vessel is expected to operate in more difficult ice conditions than the *Norilskiy Nickel*. However, its ice-class will not include independent operations on the Northern Sea Route year round.

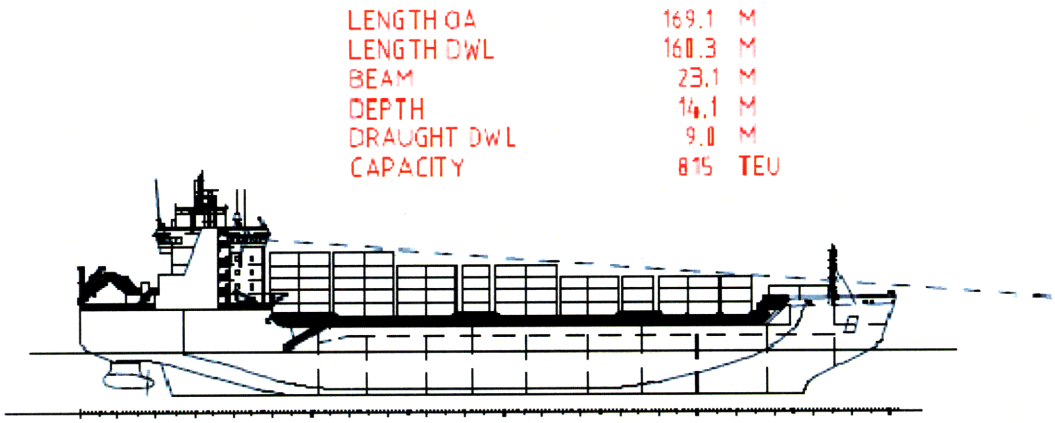

Figure 3.9: 750 TEU Arctic Containership [6]

3.4.4 5000 TEU Arctic Containership

The 5000 TEU containership is a scaled up (1.5:1) version of the 750 TEU containership with one hold of parallel mid-body added to achieve capacity. The stern is also modified to allow for a twin pod arrangement. It will be designed for an ice-class of either LU-8 or LU-9, the two highest Russian Register ice-classes. Presently, there are no ships designed or constructed meeting these classes. This vessel will be able to operate year round, even during a 'severe' ice winter. The inboard profile of the 5000 TEU containership is shown below in Figure 3.10.

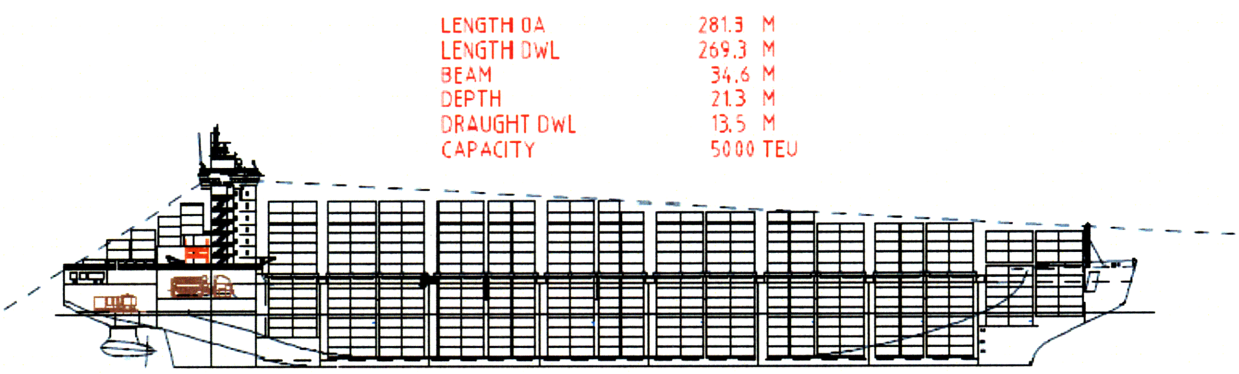

Figure 3.10: 5000 TEU Arctic Containership [6]

The powering of this vessel may be only 70 to 80 percent of its open water counterparts. This is because open water containerships of this design travel at 22 to 26 knots while the ice-classed containership is estimated to achieve 19 knots in open water.

The principal characteristics of the *Norilskiy Nickel,* the 750 TEU containership, and the 5000 TEU containership are shown in Table 3.2.

Table 3.2: Principal Characteristics [6]

	SI Units - (m, t, kW, knots)		
	Norilskiy Nickel	750 TEU	5000 TEU
L_{OA}	169	169	281
L_{PP}	160	160	269
B	23.1	23.1	34.6
D	14.2	14.2	21.3
T	9	9	13.5
Deadweight @ T = 9m	14,500	14,500	68,000
Cargo	12,700	11,200	61,500
Containers	650	815	5,000
Fuel	1,500	3,000	6,000
Shaft Power	13,000	13,000	36,000
Speed	17	17	19
Displacement			100,000
Lightship			32,000

3.5 Open Water, Ice-Strengthened, and Ice-Breaking Containerships

A conventional (or open water) containership, two classes of ice-strengthened containerships, and an ice-breaking containership will be examined in this section.

Detailed industry analyses were reviewed to determine which ice-class should be used for the ice-strengthened containership in this analysis. Although the analysis was not performed specifically for containerships, comparable sizes and ice-classes were found and deemed reasonable.

The first ice-strengthened ship chosen was a compromise between Arctic conditions and open water. This was to allow greater flexibility of operational area, thus as to not restrict the containership to only icy waters or to only open water.

This leads to a containership ice-classed at the ABS A1 or FS 1A-Super level. These classes have the ability to operate in first-year medium ice of 0.6 - 1.2 meters. To meet these requirements an increase in the lightship of 2% was seen with no additional power being necessary. The increase in lightship should have a minimal effect on the ship's operations. Also examined were containerships ice-classed at the ABS A3 level (higher ice-strengthened) and ABS A5 level (independent icebreaker).

The three different ice-classes will be compared to the open water variant in several areas relating to cost. First, the increase in weight is analyzed and the effect on the capital cost is found. Then, the power and fuel consumption are examined and their effect on the operating costs are determined.

3.5.1 Capital Cost

The capital cost of an ice-classed containership will be higher than a conventional containership. The hull steel weight will be higher for an ice-classed vessel, increasing construction costs. Additionally, several auxiliary systems must be installed on the vessel to enable safe operating in Arctic waters (described in Section 3.3.3). The additional costs for the auxiliary systems were not included in the analysis of the construction costs.

3.5.1.1 Hull Steel and Lightship Weight

Several methods were used to calculate the lightship and hull steel weight. Data provided by industry contacts and a proprietary HEC-ABS report were all used and compared to determine these values. This data is summarized in Appendix A. The increase in weight derives primarily from thicker shell plating, especially in the ice belt, and closer framing. This is the hull steel weight, a component of the lightship weight.

Using data provided by industry and the calculations made using the HEC-ABS model, Figures 3.11 and 3.12 show the trend for increasing hull steel weight and lightship weight, respectively, as the ice-class increases (plotted in terms of the Russian LU system).

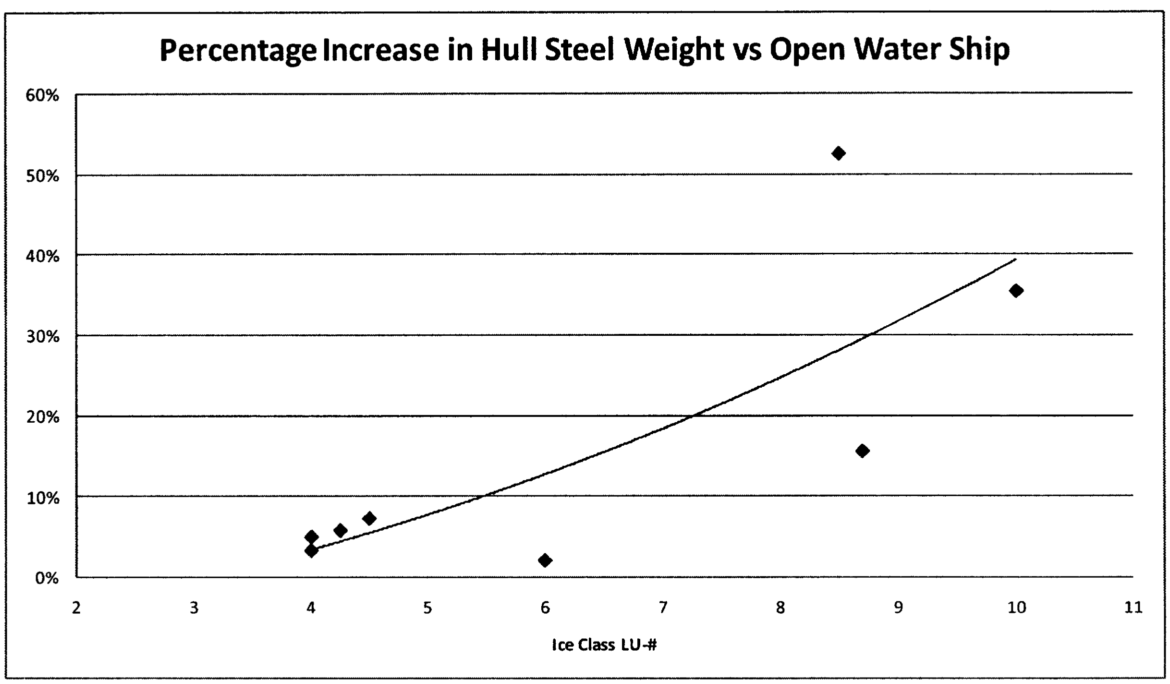

Figure 3.11: Increase in Hull Steel due to Ice-Class

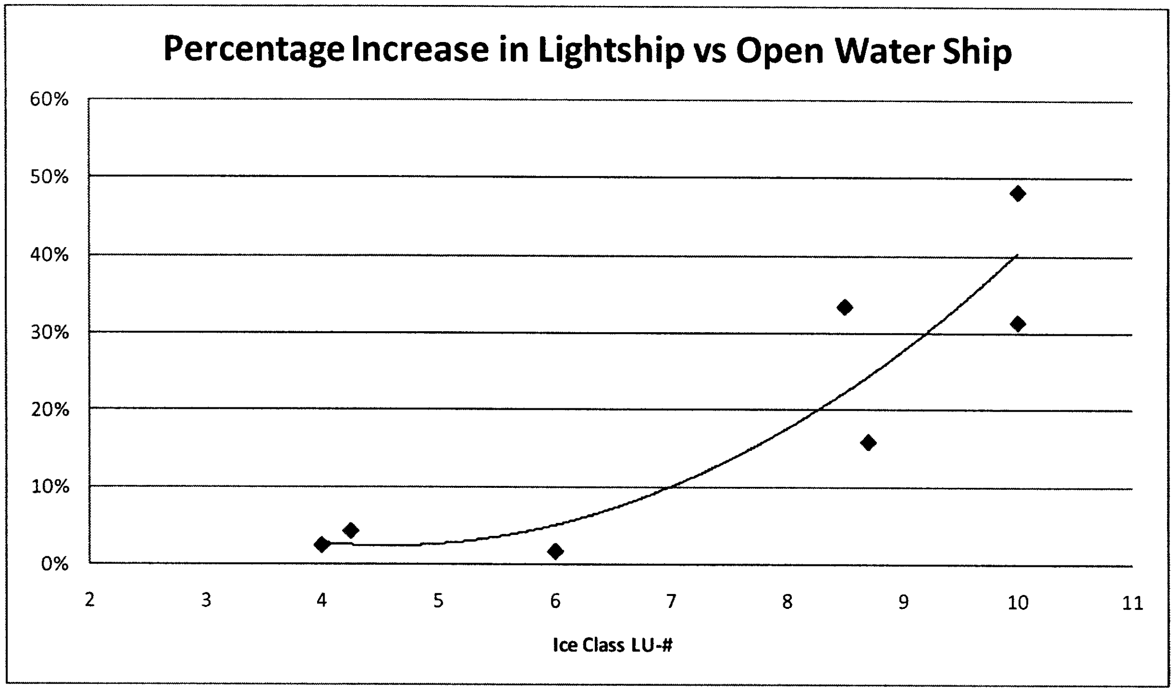

Figure 3.12: Increase in Lightship due to Ice-Class

From the data in Appendix A, it was determined that, in general, a 5% increase in hull steel weight results in roughly a 3% increase in lightship weight. However, actual data was available and used for the A1, A3, and A5 ice-classed containerships.

3.5.1.2 Construction Costs

In order to estimate the relationship between the construction cost and the hull steel weight for the ice-class vessels in question, the construction costs of other representative ice-classed containerships were determined using the proprietary HEC-ABS model and industry values. These representative containerships and their costs are shown in Table 3.3. The ABS D0 class cost was taken from industry data. For the 5000 TEU vessel, costs were calculated for both the open water and LU-8 or LU-9 ice-class using the HEC-ABS model since the parametric model was for larger containerships. This model breaks the ship's weight into several categories including: hull steel, coatings, accommodation outfit, hull outfit and piping, cargo equipment, machinery and electrical, and engineering and fees.

Table 3.3: Cost of Different Ice-Classed Containerships [50]

Ice-Class	Length	TEU	Cost	% Increase
	(m)		(Million)	
ABS D0 Class	283	4800	$90	
Open Water	269	5000	$91.3	
RMRS LU-8 or LU-9	269	5000	$110.9	21.5%

Figure 3.13 shows the building prices for several different size conventional containerships.

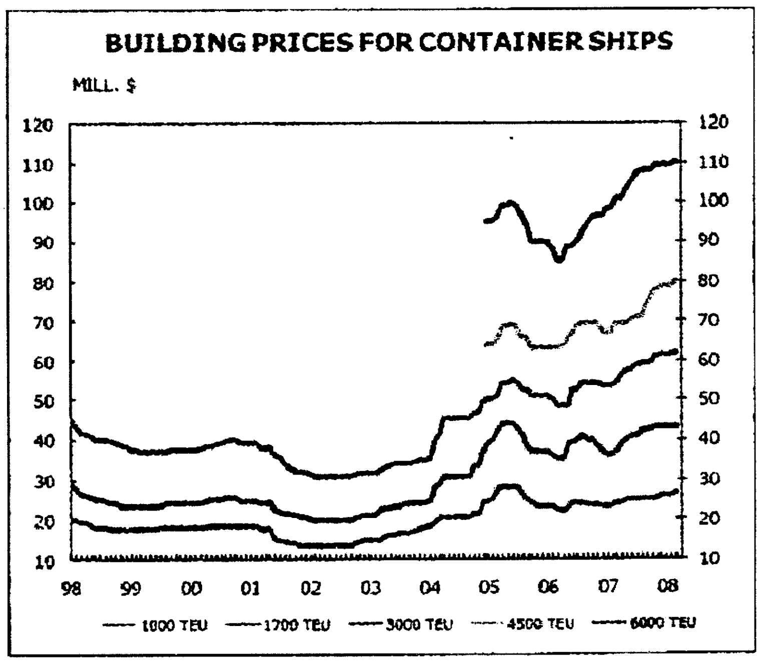

Figure 3.13: Building Prices for Containerships [59]

Using these values, the calculated ice-class values were plotted. Figure 3.14 shows that the open water value follows the trend and the ice-classed values are above their open water counterparts. The D0 Class is only slightly above the trend since it is a very low ice-class (See Section 2.8).

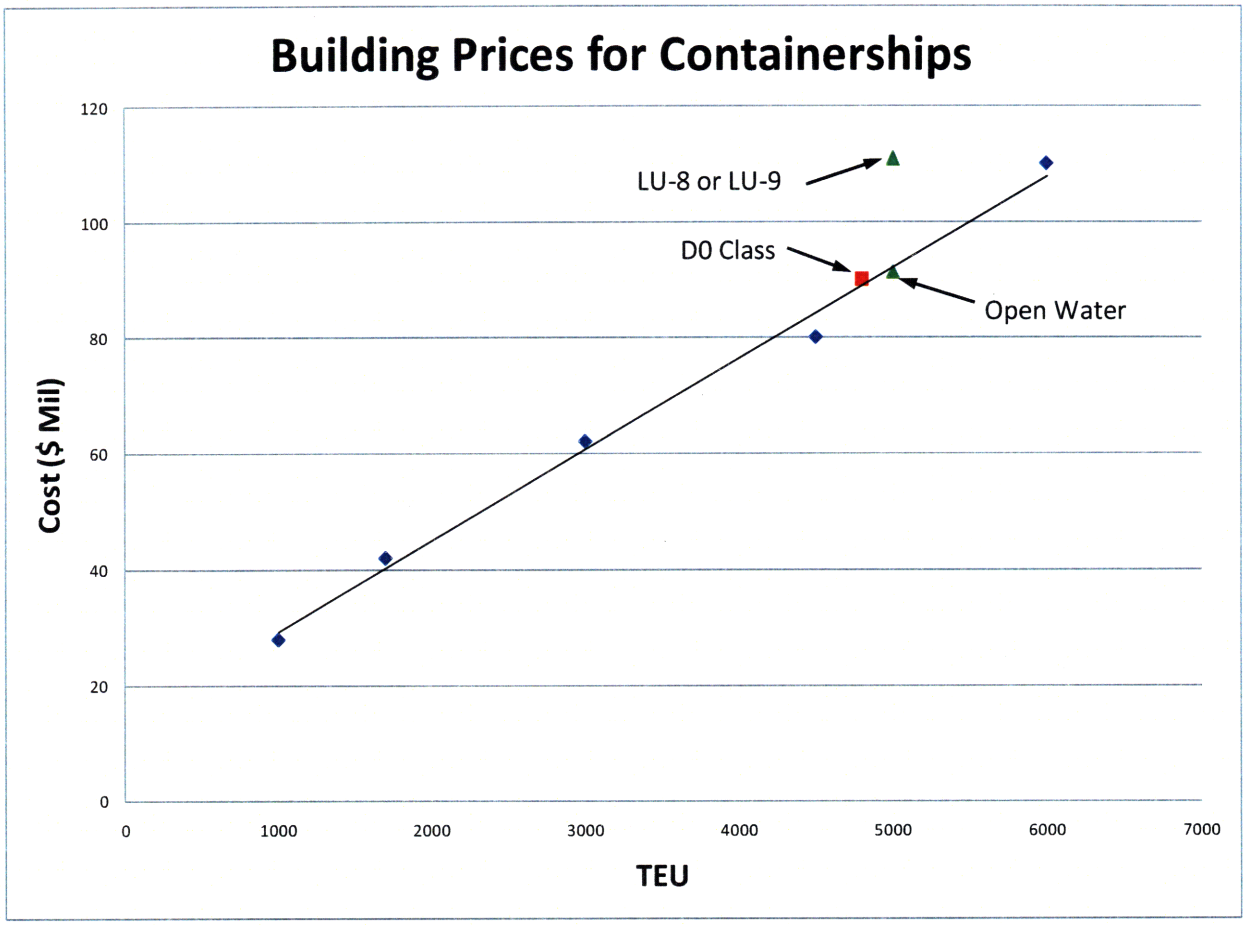

Figure 3.14: Comparison of Open Water and Ice-Classed Containership Prices [59]

In summary, the data show that for a 10% increase in hull steel weight, cost increases by roughly 4%. This relationship is used in Section 3.5.3 to determine the total cost for the A1, A3, and A5 ice-classed containerships.

3.5.2 Operating Costs

The operating costs of an ice-classed containership will be higher than a conventional containership. The power and, thus, fuel consumption will be significantly higher for an ice-classed vessel, increasing operating costs. Additionally, the crew must have experience operating in ice, resulting in higher wages (described in Section 3.5.4.2). Also, the insurance costs more for an ice-classed vessel for obvious reasons. The additional crew and insurance costs were not included in the analysis of the operating costs.

3.5.2.1 Resistance and Power Calculations

The effect of added hull steel weight on fuel consumption is analyzed in this section. The additional weight increases the resistance of the ice-classed containership, resulting in a lower maximum speed. Furthermore, the specific fuel consumption of an ice-classed containership will be compared to the open water specific fuel consumption of a conventional containership.

Calculations were performed on the vessel described below. Industry contacts provided information about the weight and power of this vessel at several different ice-classes. Table 3.4 shows the principal dimensions of the ship. This vessel is very similar in size to the 5000 TEU containership that is being analyzed.

Table 3.4: General Characteristics of Ship

L_{OA}	279	m
L_{BP}	266	m
B	42.6	m
T	11.3	m
D	26	m
C_B	0.75	
Δ_{SW}	107,000	MT
V_S	20.1	knots
Power, Installed	29,050	kW
Power, NCR	24,700	kW
Compared to the 5000 TEU Ship		
L_{BP}	269	m
Δ_{SW}	100,000	MT

To determine the increased resistance of the ice-classed containerships, the overall approach is to calculate the total resistance of the baseline (open water) ship and then determine the changes in the resistance coefficients for the ice-classed ships.

Several assumptions are relevant to this approach. The first is that the assumed operating speed for the analysis is 20.1 knots. Others are that the ship is operating at 70°F in salt water and is wall-sided. The wall-sided assumption may lead to some errors when higher ice-classes (greater increase in weight, thus more sinkage) are analyzed, but will be considered sufficient for the work presented below. Additionally, it is assumed the extra hull steel weight is distributed evenly; this allows the use of TPI without trim concerns. Table 3.5 shows the assumed values used in the following calculations.

Table 3.5: Given and Assumed Values for Fuel Calculations

Installed Power	29,050	kW
NCR Power	24,700	kW
Speed	20.1	knots
Displacement	107,000	MT
Sea Margin	15	%
Length	266	m
Beam	42.6	m
Kinematic Viscosity	1.1057×10^{-5}	ft^2/s
Density	1.9876	$lb_f\text{-}s^2/ft^4$
Waterplane Coefficient	0.61	
Residual Resistance Coefficient	5×10^{-4}	
TPI	180	MT/in

The total resistance for the open water ship was calculated using the following equation:

$$R_T = \frac{P}{V_S}$$

The installed power value is used since the analysis is relative and to facilitate comparison of the actual vs. required installed power for the ice-classed ships. The next step is to determine the baseline resistance coefficients for the open water ship.

The open water frictional resistance coefficient was calculated using the ITTC 1957 Formula with the Reynold's number, as shown below.

$$Re_N = \frac{V_S\,L}{\nu} = 2.68\ \times 10^9$$

$$C_F = \frac{0.075}{(\log_{10}(Re_N) - 2)^2}$$

Also, the Froude number and speed to length ratio were found using:

$$Fr = \frac{V_S}{\sqrt{g\,L}} = 0.202$$

$$\text{Speed-to-Length Ratio} = \frac{V}{\sqrt{L_{WL}}} = 0.68$$

The open water residual resistance coefficient was then determined. Table 3.6 describes the characteristics of a containership for which the residual resistance coefficients are known at various speeds. Figure 3.15 shows the corresponding residual resistance coefficient plotted against Froude number with a red line marking the Froude number of the ship analyzed for this section's calculations.

Table 3.6: Principal Characteristics of the Containership in the Graph Below [52]

L_{BP}	230	m
B	32.2	m
T	10.8	m
C_B	0.65	
WSA	9,424	m^2

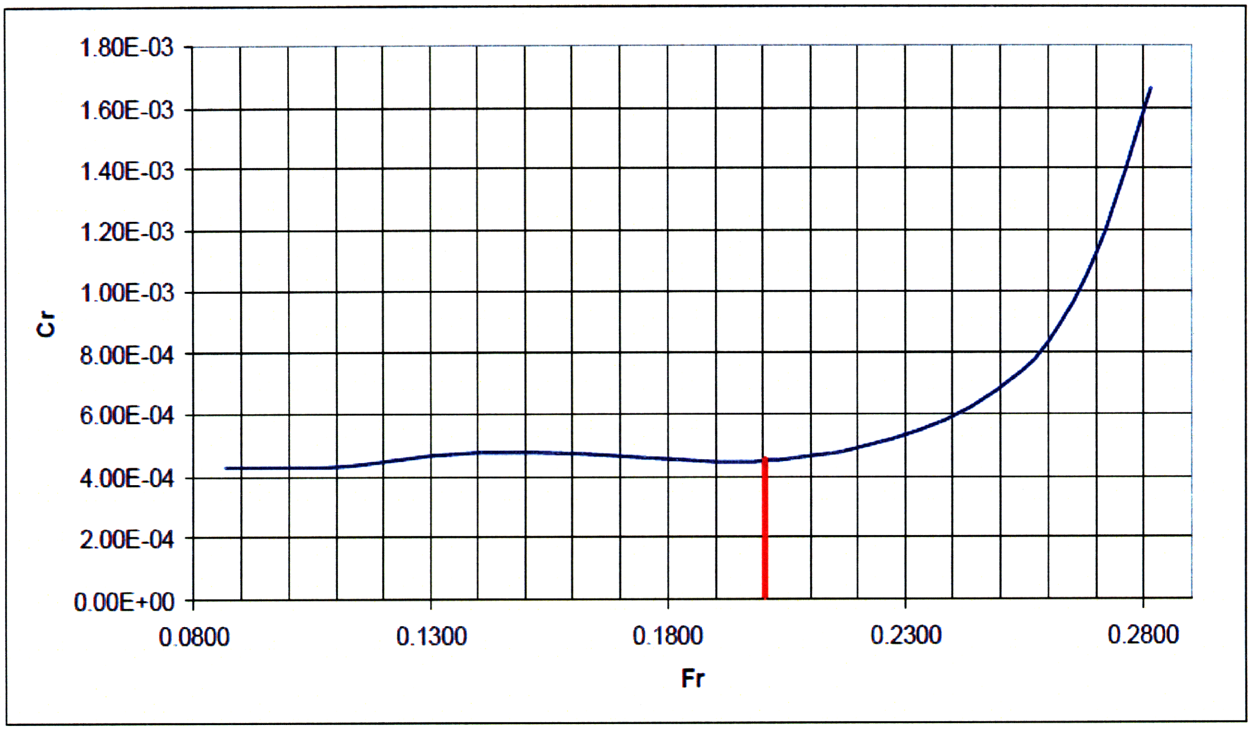

Figure 3.15: Experimental Dependence of Residual Resistance Coefficient on Froude Number [52]

After reviewing the various sources [52, 64, 31] and Figure 3.15, a residual resistance coefficient of 5×10^{-4} was used for the open water vessel in the calculations.

Next, the total resistance coefficient for the open water ship was determined, using the following equation:

$$C_T = C_F + C_R$$

Since the change in resistance was examined, a correlation allowance was not used since it would drop out.

The wetted surface area of the open water ship was caluclated, using the following equation:

$$WSA = \frac{R_T}{\frac{1}{2}\, C_T\, \rho_{SW}\, {V_S}^2}$$

Now, the frictional resistance and residual resistance for the ice-class cases are determined. The new frictional resistance was found using the following formula.

$$R_{F,New} = \frac{1}{2} C_F \rho_{SW} V_S^2 (WSA + WSA_{Add'l})$$

To determine the additional wetted surface area, the TPI is found. Figures 3.16 and 3.17 show trends for the TPI for containerships of different sizes. This data is used to parametrically determine a suitable TPI to use in the calculations to obtain additional wetted surface area due to the added weight of the additional steel. The parametric analysis led to a TPI of 180 being used for the ship.

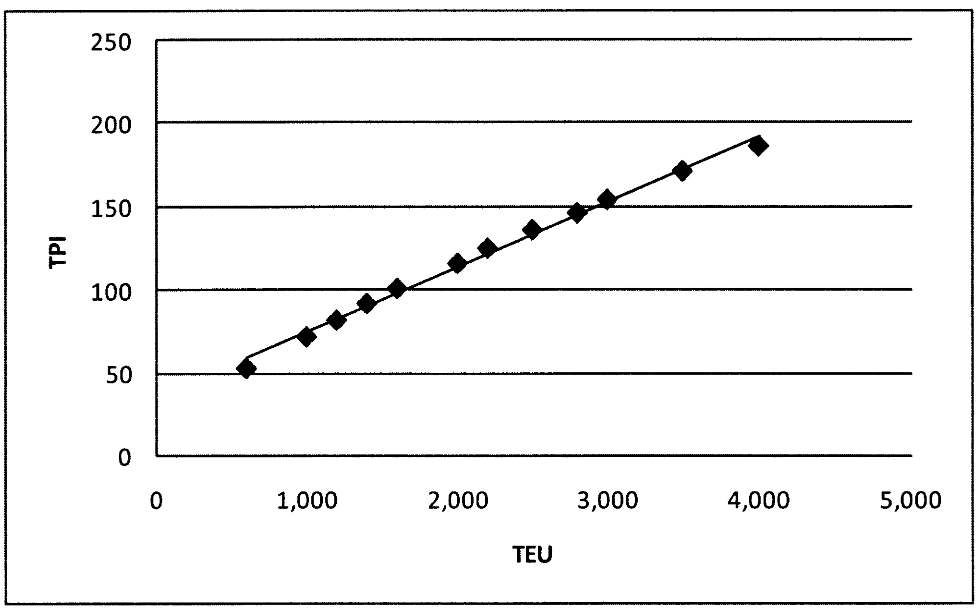

Figure 3.16: TPI for Different Size Containerships [22]

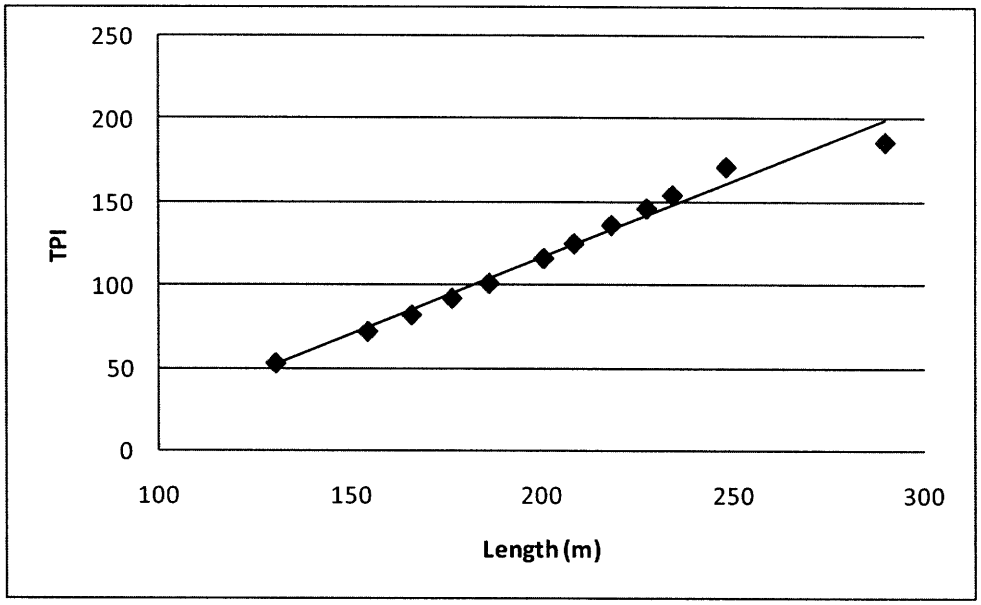

Figure 3.17: TPI for Different Size Containerships [22]

Using the TPI and the extra weight (additional hull steel), the sinkage (or immersion) of the ship was found:

$$h_{Immersed} = \frac{\Delta_{Add'l}}{TPI}$$

The waterplane coefficient was found using the formula below.

$$C_{WP} = \frac{\Delta_{Add'l}}{\rho_{SW}\ \mathrm{L\ B\ (h_{Immersed})}}$$

The extra submerged volume was calculated using the waterplane coefficient.

$$\nabla_{\mathrm{Add'l}} = \mathrm{C_{WP}\ L\ B\ (h_{Immersed})}$$

As a check, the extra weight was found to make sure it correlates to the previous value.

$$\Delta_{Add'l} = \rho_{SW}\ \nabla_{\mathrm{Add'l}}$$

The wetted length was determined using the equation below.

$$L_{Wetted} = B + 2\,L$$

The additional wetted surface area was found, assuming the ship is wall-sided, which is plugged into the above $R_{F,New}$ equation.

$$WSA_{Add'l} = L_{Wetted}\, h_{Immersed}$$

To determine estimates of the residual resistance coefficient when the displacement of the vessel was increased, the US Navy's Advanced Surface Ship Evaluation Tool (ASSET) was used. Table 3.7 shows the ships that were analyzed in ASSET. The Resistance Module was used to analyze the Full Load and Average Displacement conditions, thus providing the residual and frictional resistance at two different displacements. The operating speed of the containership being analyzed is 20.1 knots, so the resistance at 20 and 21 knots was examined.

Table 3.7: Comparison of ASSET Ships with the Containerships

Ship	L_{BP} (m)	B (m)	T (m)	Δ (MT)	% Change in Δ
SEALIFT FTV MKI	193.5	32.2	10.4	42,523	1.28%
TAO 187	198.1	29.8	10.5	41,319	1.00%
AOE 6	222.5	32.6	11.7	48,679	2.13%
LSD 41	176.8	25.6	5.9	14,736	2.22%
PD 337E	183.9	32.2	9.1	36,390	2.43%
LPD 17	200.0	29.5	7.0	22,635	2.72%
5000 TEU Containership	269.0	34.6	13.5	100,000	
Comparison Ship - Open Water	266.0	42.6	11.3	107,000	0.00%
Comparison Ship - A1					0.75%
Comparison Ship - A3					4.26%
Comparison Ship - A5					13.0%

Table 3.8 shows the percentage change in residual resistance due to a percentage change in displacement.

Table 3.8: Effect of Changing Displacement on Residual Resistance

	20 knots			21 knots		
Ship	% Change in R_R	% Change in R_F	$\%R_R / \%\Delta$	% Change in R_R	% Change in R_F	$\%R_R / \%\Delta$
SEALIFT FTV MKI	0.73%	0.56%	57.0%	0.68%	0.56%	53.3%
TAO 187	0.67%	0.62%	66.8%	0.74%	0.62%	74.3%
AOE 6	1.23%	1.16%	57.9%	1.29%	1.15%	60.7%
LSD 41	0.40%	1.03%	18.0%	1.13%	1.04%	51.1%
PD 337E	0.62%	1.33%	25.4%	0.23%	1.33%	9.6%
LPD 17	1.67%	1.61%	61.3%	0.93%	1.60%	34.1%

After analyzing the ASSET data, the relationship identified was that the residual resistance coefficient increased by 50% of the displacement increase. For example, if the displacement increased 10%, the residual resistance coefficient was increased 5%.

The total resistance was then determined for each ice-class case, using the following equation:

$$R_{T,New} = R_{F,New} + R_{R,New}$$

Then the new required power for each ice-class was found, using the equation below.

$$P = R_{T,New}\ (V_S)$$

Tables 3.9 and 3.10 show the results of the calculations outlined above. The installed power is the power installed on the icebreaking ships, while the required power is that power required to maintain the 20.1 knots (operating speed) in open water.

Table 3.9: Change in Draft with Differing Ice-Classes

Ice-Class (ABS)	Increase in LS Weight (MT)	% Increase in Lightship Weight	% Increase in Overall Weight	Immersion (in)	New Draft (m)
A1	800	2.78%	0.75%	4.44	11.41
A3	4,557	13.7%	4.3%	25.3	11.94
A5	13,892	48.2%	13.0%	77.2	13.26
Open	-	28,800 MT	107,000 MT	-	11.3 m

Table 3.10: Change in Power with Differing Ice-Classes

Ice-Class (ABS)	New Power Required to Maintain Speed (kW)	% Increase in Power to Maintain Speed	Installed Power (kW)	% Increase Installed over Required Power
A1	29,129	0.27%	29,050	-0.27%
A3	29,501	1.55%	41,845	41.8%
A5	30,424	4.73%	102,370	236%
Open	29,050 kW	-	29,050 kW	-

As an aside, the installed power for the A5 class is reasonable even though it is over 230% greater than the power required to maintain the open water speed. The most powerful icebreaker in the world has two nuclear reactors which develop approximately 500,000 horsepower (≈360,000 kW), and has a huge steel ice belt 5 meters wide that can easily break through ice up to 2.5 meters thick [33].

Figure 3.18 shows the effect the added steel weight has on the power requirements of the ship in open water. See Appendix B for the description of nominal ice-classes.

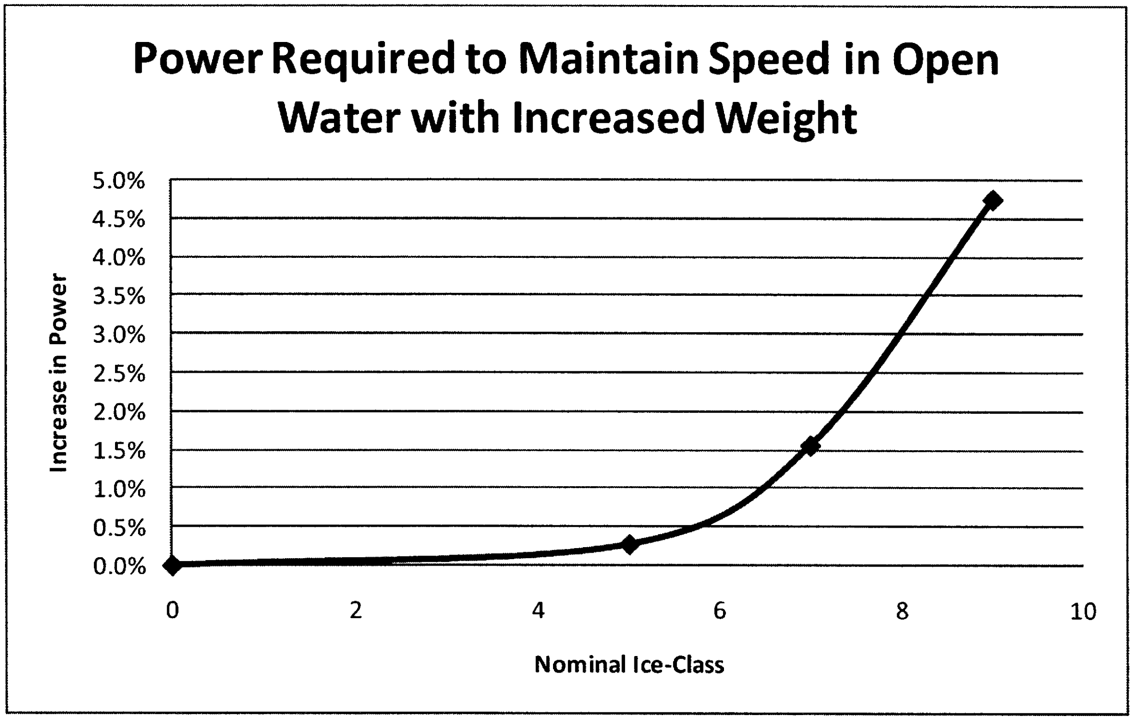

Figure 3.18: Power Required to Maintain Speed in Open Water

Figure 3.19 shows the decrease in speed as the weight increases if the power isn't changed. For the highest ice-class, the maximum open water speed decreases about one knot.

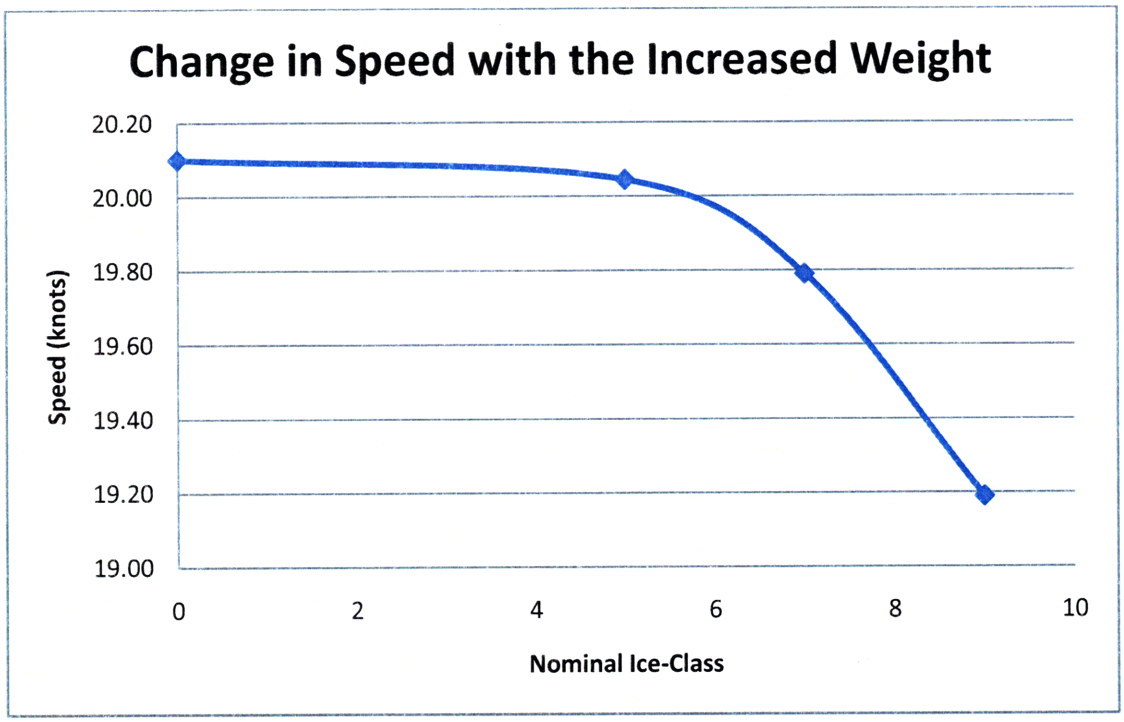

Figure 3.19: Difference in Speed with Increased Weight

Figure 3.20 shows both the installed and required power for the ship over the three different ice-classes and open water. For the A3 ice-class, about 1.4 times the power was installed on the ship and for the A5 ice-class, about 3.4 times the required power was installed. This extra power is installed as part of the ice-class rules (stating a minimum power) and includes several factors of safety. Also, towing is usually part of an icebreaker's mission, which substantially increases the installed power. This aspect was not taken into account in these calculations; only the power necessary to maintain the given operating speed was found.

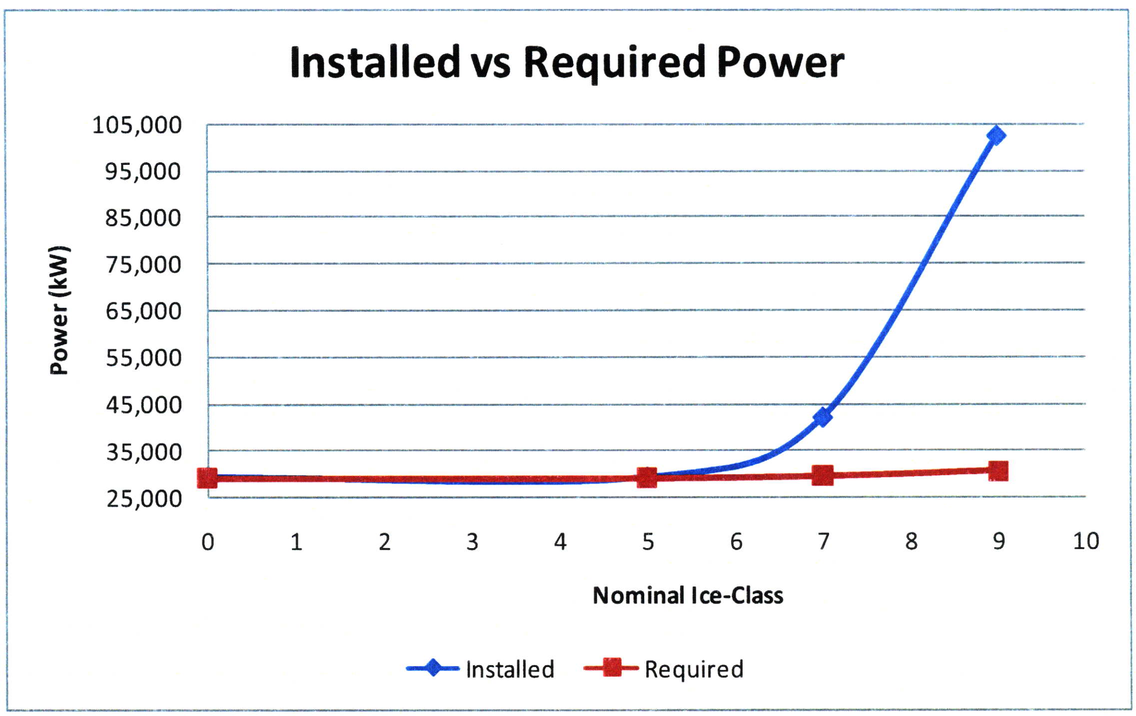

Figure 3.20: The Installed Power and Required Power for Differing Ice-Classes

3.5.2.2 Fuel Consumption Calculations

Next, the fuel consumptions were calculated for the open water and the three different ice-classed ships. First, an average fuel consumption for an open water containership was found using various sources.

Figure 3.21 shows an average specific fuel consumption of 135 g/bhp-hr, which is equivalent to 181 g/kW-hr.

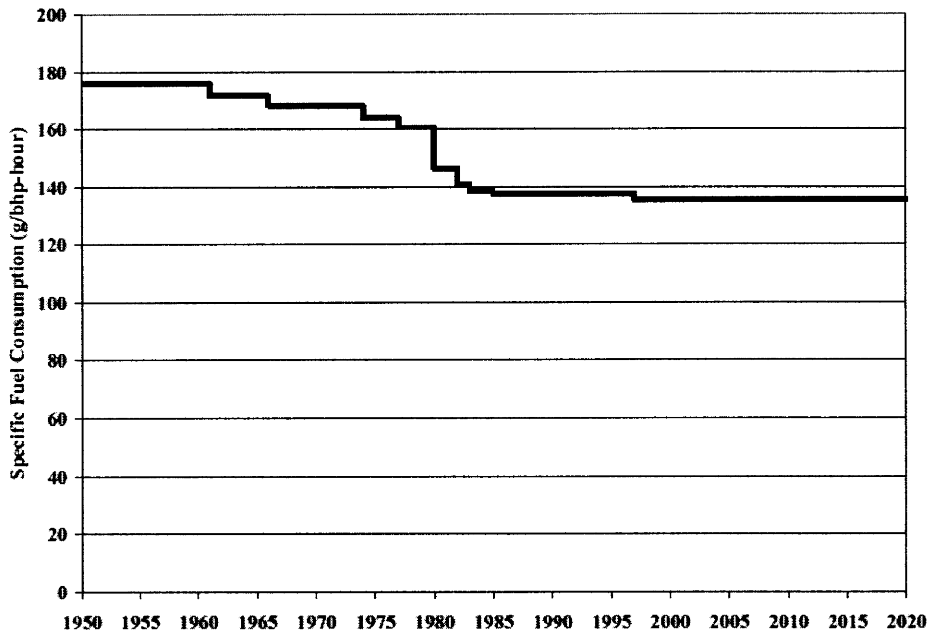

Figure 3.21: Specific Fuel Consumption Over Time [30]

Table 3.11 shows several medium speed diesels' power and fuel consumption data. The 85% load was assumed to be the normal operating load.

Table 3.11: Specific Fuel Oil Consumption for Various Man B&W Medium Speed Marine Diesel Engines [21]

Engine	Power (kW/Cylinder)	Speed (RPM)	Percent Load: 100	85	75	50	25
			Preliminary Fuel Consumption with MGO propeller operation and with all attached pumps* (g/kW-hr)				
28/33D STC	420	1000	190	188	192	194	198
28/33D	450	1000	190	188	189	197	217
L+V 32/40	500	750	181	179	180	185	198
L 32/44CR for Emission Standard DNV Clean Design	550	750	180	178	185	190	204
L 32/44 CR	560	750	177	175	179	184	197
L 40/54	720	550	183	181	182	188	200
L+V 51/60 DF	975/1000	500/514	184	183	184	190	
L 48/60B	1200	500/514	178	175	178	186	203
V 48/60B	1200	500/514	176	173	176	184	201
L 48/60CR	1200	500/514	178	175	178	183	190
V 48/60CR	1200	500/514	176	173	176	181	197
L 48/60CR IMO Tier II	1200	500/514	180	176	180	185	201
V 48/60CR IMO Tier II	1200	500/514	178	174	178	183	199
L 58/64	1310/1400	400/428	174	173	177	186	199
*Tolerance Warranty +5%							

For the purposes of this thesis, a specific fuel consumption of 180 g/kW-hr will be assumed for a conventional containership. There is a 5% margin on the numbers given by industry (in Table 3.11). However, the relative changes will be examined for the purposes of this work.

Tables 3.12 and 3.13 show the results of the above calculations. A price of $450/MT of MDO was used in the calculations [14]. Also, the ship was assumed to be operating 8,400 hours a year (350 days). Again, the required power is that needed to maintain the given operating speed in open water and the installed power is the power that is installed on the icebreaking variant of the vessel.

Table 3.12: Change in Specific Fuel Consumption with Differing Ice-Classes using Required Power

				Required Power		
Ice-Class (ABS)	SFC (85%) (g/kW-hr)	SFC (Increased) (g/kW-hr)	Hours of Operation (hr)	Fuel Usage (MT)	% Increase in Fuel Usage	Price using MDO
A1	-	180.5	8,400	44,163	0.54%	$19,873,269
A3	-	182.8	8,400	45,298	3.13%	$20,384,105
A5	-	188.5	8,400	48,177	9.68%	$21,679,576
Open	180.0	-	8,400	43,924	-	$19,765,620

Table 3.13: Change in Specific Fuel Consumption with Differing Ice-Classes using Installed Power

				Installed Power		
Ice-Class (ABS)	SFC (85%) (g/kW-hr)	SFC (Increased) (g/kW-hr)	Hours of Operation (hr)	Fuel Usage (MT)	% Increase in Fuel Usage	Price using MDO
A1	-	180.5	8,400	44,043	0.27%	$19,819,372
A3	-	182.8	8,400	64,252	46.3%	$28,913,414
A5	-	188.5	8,400	162,104	269%	$72,946,698
Open	180.0	-	8,400	43,924	-	$19,765,620

3.5.3 Cost Summary

To estimate the total increase in cost for an ice-classed containership, the costs were broken down into several categories as shown in Figure 3.22. These percentages are derived from Russell Pollock's thesis, the "Economic Feasibility of Shipping Containers through the Arctic". Thus, hull steel comprises 9% of the total cost and fuel makes up 56% of the total cost.

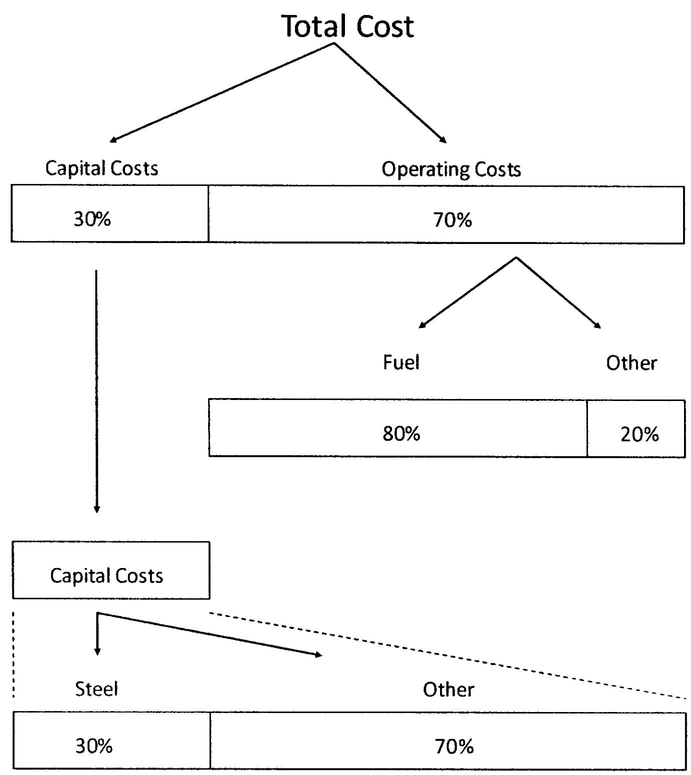

Figure 3.22: Ship Cost Breakdown

Table 3.14 shows the effect of different ice-classes on the weight, power, fuel consumption, and cost of containerships.

Table 3.14: Overall Summary of Ice-Class Differences

Percentage Increase over Open Water	Ice-Class		
	A1 (FS 1A-Super)	A3	A5 (PC1)
Weight (Lightship)	2.8%	15.8%	48.2%
Weight (Hull Steel)	2.7%	15.5%	35.4%
Power (Installed)	-0.3%	41.8%	236%
Power (Required)	0.27%	1.55%	4.73%
Fuel Consumption (Installed)	0.27%	46.3%	269%
Fuel Consumption (Required)	0.54%	3.13%	9.68%
Cost - Steel	1.1%	6.20%	14.1%
Cost - Fuel	0.27%	46.3%	269%
Cost - Total	0.25%	26.5%	152%

Note: Installed - Power installed on the icebreaking variant of the vessel to satisfy the higher power demand (ice-breaking or max speed).
Required - Power needed to maintain the given operating speed in open water.

As seen, the increases in installed power have the greatest impact on total cost, particularly for the A3 and A5 ice-classes.

3.5.4 Other Cost Considerations

3.5.4.1 Icing

An ice-classed ship needs to have many additional features. An ANTI-ICE class notation can be achieved if several criteria are met. These deal primarily with the prevention of icing of ship structures and equipment: including anchor and mooring equipment, lifeboat hook releasing devices, survival craft launching arrangements, liferafts, special Arctic foam for firefighting, pre-heated combustion air, insulation, defrosters for navigation-related areas on deck, use of special ice-resistant materials, and special cold-weather outfits for the crew [57, 58]. The steel above the waterline is exposed to harsh conditions including temperatures around -40°C. Sonar and helicopters (electromagnetic imaging for icebergs) can also be used to detect current ice conditions.

DNV has a similar notation to provide additional protection in the Arctic. The DEICE notation provides operational safety through proactive preparation. The ship has to be outfitted with de-icing equipment to remove ice within a period of 4-6 hours. It is important to keep certain areas where continuous operation is required, such as navigational equipment and fire lines, ice-free. If this equipment becomes ice-covered, the level of safety decreases substantially [43].

Icing usually leads to several problems including the impairment of stability due to the lifted center of gravity, the limitation on safe navigation caused by antenna and radar equipment being out of operation, and icing on wheelhouse windows. In addition, liferaft release mechanisms may become jammed, scuppers can clog, and gangways and railings are unsafe to use.

All of these extras, increasing a ship's capability to operate in the Arctic, lead to an increase in cost. Additionally, supplemental insurance is usually required for operations in the Arctic. There has been an increase in the number of ice-related claims. Usually the ice damage is a small incident that turns into a major claim because of the remoteness of the location [46].

Ice navigation poses additional stability issues. The ship is subject to movements from ramming and ice impacts as it moves through the ice. Also, damage stability criteria must be able to withstand flooding resulting from hull penetration due to ice damage, and to return the ship to equilibrium after such damage. When hot cargoes are carried, a thermal stress is created in the hull, so the permissible still water bending moments should be reduced. Additionally, rapid icing can occur since large quantities of sea spray hit the ship. This can result in topside ice accumulations of over 10cm. This may adversely affect the ship's stability [20].

When navigating in the Russian Arctic, an Ice Certificate is required. There are also different rules in effect, for example, the 'sanitary rules', which include requirements for noise, vibration and ventilation [43].

3.5.4.2 Crew

When a vessel is operating in ice, the major increase in noise and vibration will affect the crew's ability to get proper rest when off duty, and thus reduce their ability to work safely while on duty. There is research underway to improve human performance in cold and dark conditions. The skill and experience of the crew will prove to have a significant and direct impact on the safety level. Furthermore, most ship operations are different in ice and low temperatures and require experienced crews in order to maintain the same safety level as for worldwide operations. Unavailability of competent crews may limit safe operation [43].

4.0 Chapter 4: Conclusions and Recommendations

4.1 General Conclusions

Some experts believe global warming is opening up the Northwest Passage like a hot knife through butter and predict that it will be an established year-round route within 50 years. However, some think the Northwest Passage will bring a stop-start trade since ships would be continually hampered by weather and ice and couldn't meet the modern demands for efficient shipping. With the added insurance premiums and other increased expenses, the route might not bring in the optimistic returns some promise [9].

There is concern that the number of ships on order with high ice-class may exceed the need for the Baltic and Arctic areas. If so, many of these ships will operate only sporadically in ice and will not be able to build up and maintain the necessary experience to operate safely in cold climates [43].

The acceptance of the Polar Class rules will harmonize all of the ice-classes and make it easier to transit the Arctic. The basic philosophy of the rules is that the structural strength of the hull and the power of the propulsion machinery should be able to withstand ice loads with minimum safety margin. Excessive ice strengthening is avoided for economic reasons [20].

In summary, a voyage from Shanghai to New York via the Panama Canal takes 25 days to complete, covers 20,000 km and entails Canal fees. The same trip taking the Arctic route through an ice-free Northwest Passage would be around 16,000 km. Is it cheaper? Open water in the context of ice navigation merely means water less than 10% of which is covered by ice. Under these circumstances, there will be fog and plenty of growlers, car-size torpedoes of more or less invisible glacial multi-year ice, both of these natural impediments require slower speeds. An average of 14 knots is one estimate, which translates to about 25 days. But then the insurance premium probably wipes out any savings to be had from the Panama Canal fees. Furthermore, after denting the ship in the Northwest Passage, there may be a dry docking required [47].

Politics also plays a role in Arctic business. It depends on communicating with Arctic populations in the sparsely settled north to control the impact of icebreaking bulkers on their fragile communities. The vessels make a 24 meter hole 100 km long right through their world. The aboriginal people use the ice for transport, as an extension of their highway system, so the icebreakers could not separate their islands. After an icebreaker passes, the ice refreezes, and local workers smooth the surface so sleds and snowmobiles can pass easily at predetermined points.

Table 4.1 summarizes the calculations in this thesis. To slightly increase a vessel's ice-class a very small change in weight, power, fuel consumption, and cost is seen (particularly for a high powered LNG ship or containership). These changes are all within acceptable margins of error. However, to ice-class a vessel to the highest class examined in this work, an A5 class (an independent icebreaker), requires a huge investment. Thus, this vessel should be used exclusively for Arctic operations if possible.

Table 4.1: Summary of Ice-Classes Effect on Weight, Power, Fuel Consumption, and Cost

Percentage Increase over Open Water	Ice-Class		
	A1 (FS 1A-Super)	A3	A5 (PC1)
Weight (Lightship)	2.8%	15.8%	48.2%
Weight (Hull Steel)	2.7%	15.5%	35.4%
Power (Installed)	-0.3%	41.8%	236%
Power (Required)	0.27%	1.55%	4.73%
Fuel Consumption (Installed)	0.27%	46.3%	269%
Fuel Consumption (Required)	0.54%	3.13%	9.68%
Cost - Steel	1.1%	6.20%	14.1%
Cost - Fuel	0.27%	46.3%	269%
Cost - Total	0.25%	26.5%	152%

Note: Installed - Power installed on the icebreaking variant of the vessel to satisfy the higher power demand (ice-breaking or max speed).
Required - Power needed to maintain the given operating speed in open water.

Presently, routing containerships over the Arctic is generally not considered by the industry to be economically, politically, or environmentally feasible for continuous, reliable service. In the future, when more experience is gained operating in the Arctic along with decreasing ice cover and the harmonization of the ice-class rules, ice-classed containerships may emerge as a popular niche market.

One must remember the basic principles of ice navigation. The first principle of ice navigation is to *avoid ice*. The second is when that's not possible, avoid the thicker ice. From the bridge, it all looks white [47].

Appendix A: Summary of Weight Data

Table A.1: Summary of Weight, Power, and Cost Data

Type	Ice Class	L_{BP} (m)	B (m)	T (m)	D (m)	Δ (MT)	Hull Steel (MT)	Lightship (MT)	Power (kW)	Cost $Million	% Increase in Hull Steel	Hull Steel/Lightship	% Increase in Lightship
Germanischer Lloyd													
Suez-Max Tanker	Open Water	269	48	17		180,000	19,400						
	1A						20,361		22,500		5.0%		
	1A-Super						20,802		27,500		7.2%		
Aker Study													
Norilskiy Nickel (650 TEU)	LU-7	160	23.1	9	14.2				13,000				
750 TEU (Cap. 815 TEU)	LU-7	160	23.1	9	14.2				13,000				
5000 TEU	LU-8 or LU-9	269	34.6	13.5	21.3	100,000		32,000	36,000				
NYK													
4800 TEU	D-Class	283	32.2	13.5	21.8				51,390	$80-$90			
ABS													
150,000 LNG Carrier	Open Water	275	44.2	11.4	26		21,500	29,500	38,000			72.9%	
	1A						22,200	30,200	38,000		3.3%	73.5%	2.4%
	PC7						22,735	30,735	38,000		5.7%	74.0%	4.2%
INSROP													
Multi-Purpose (532 TEU)		160	24.5	9	15.2	25,900		11,200	15,400				
Herbert-ABS													
750 TEU	Open Water	160	23.1	9	14.2		3,916	6,750	13,000			58.0%	
5000 TEU	Open Water	269	34.6	13.5	21.3	100,000	15,304	23,979	36,000	$91.3		63.8%	
5000 TEU	LU-8 or LU-9	269	34.6	13.5	21.3	100,000	23,325	32,000	36,000	$110.9	52.4%	72.9%	33.4%
ABS													
138,000 m^3 LNG Carrier													
	Open Water	266	42.6	11.3	26	107,000	22,600	28,800	29,050			78.5%	
	A1					107,000	23,061	29,261	29,050		2.0%	78.8%	1.6%
	A3					107,000	26,105	33,357	41,845		15.5%	78.3%	15.8%
	A5					107,000	30,592	42,692	102,370		35.4%	71.7%	48.2%
	A5 - Power of A3					107,000	30,592	37,844			35.4%	80.8%	31.4%

Appendix B: Description of Nominal Ice-Class

In several graphs and tables, the heading of 'nominal ice-class' appears. The different ice-classes were given nominal ice-classes as described in Table B.1 below.

Table B.1: Nominal Ice-Classes

Ice-Class	ABS	Nominal
Open	-4	0
A1	1	5
A3	3	7
A5	5	9

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