Servicing the Arctic

Report 2: Evaluation of Damen Concepts in Arctic Conditions

Public Edition

Arctic Minor Team

Concepts survey

Delft University of Technology

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R.W. Bos (4114620)
T.J. Huisman (4080777)
M.P.W. Obers (4113187)
T. Schaap (4089561)
M. van der Zalm (4095316)

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Faculty of Mechanical, Maritime and Materials Engineering (3mE) · Delft University of Technology

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Abstract

Background At the start of a design it is often good to look at comparable designs. What choices were made, what are the operations, what equipment is used? This report looks at three Damen ships, which are already capable of offshore support. These vessels are designed for open water. Looking just at what has to improve for operating in the Arctic will give a feeling for the design of such vessels. The recommendations are taken into account in the next report, where a concept design of an Arctic Offshore Support Vessel will be developed.

Results There are two operational profiles per vessel. One is the original operational profile and the other one is about the same operations but then in ice. The operational profiles are used for calculating an indication of fuel consumption. The ships themselves are tested on winterization, resistance, propulsion, construction and stability. This is done according to rules and guidelines available. For the resistance prediction the Lindqvist and Riska formulae are used.

Winterization of the ships is very well possible, because the superstructure that is in place is already providing cover. The working and safety areas that are still outside have to be enclosed and the equipment that is on deck will have to be winterized. The resistance of the ships can only be determined with Riska, due to the fact that the bow angles are not intended for icebreaking. This results in a negative crushing component with Lindqvist. A high resistance is the result for the three vessels, leading to a high required propulsion power, around 30 MW. This is rather high compared to similar vessel, Vitus Bering, which requires 13 MW for the same speed and ice thickness. Sailing backwards through the ice could be an option to decrease this power requirement. There are relatively minor adaptions required to do so. Looking at the construction, a ice strengthening has to be applied to the hull. Dependent on the class notation and location around the hull, the steel thickness ranges from 20 - 80 mm. This is considerably thicker than the more common 15 mm. The general layout of the ship gives good stability, and meets any requirement on this subject.

Conclusions Optimizing a vessel for the Arctic requires a lot of adaptations. Due to the impact of these adaptations on the entire vessel design, a ship should be specially designed for operating in the Arctic, especially with the higher ice classes such as 1A Super, PC6 and PC 4.

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Preface

When gaining knowledge about a specific topic, it is often helpful to look at how things are done in reality. Doing a project with the industry helps a lot with this. This minor offers an unique opportunity to do this, by looking at three Damen vessels and their performance in the harsh Arctic environment.

The motives for a Dutch company to meddle itself in Arctic affairs might not be obvious at glance. However, after reading the first report of the Arctic minor trilogy, one knows that the Arctic is ’hot’, so to say. The ice melting away uncovers new possibilities for the gathering of resources, but also for green energy solutions, such as offshore windmill parks.

With the rise of these opportunities there is also the rise of the service industry, focusing on servicing operations in the Arctic region. That is were Damen comes in, a Dutch company with a great experience in the shipbuilding industry. But the experience in offshore alone is not enough, the Arctic requires experience with ice, cold and how to deal with both. The Norwegian classification society DNV is the chosen partner to provide knowledge about these subjects. Combining the knowledge and experience of these companies leads to a great deal of innovation. Therefore, the renown Dutch research institute Marin is a partner to this project as well.

The knowledge of these three companies together with the educational and scientific spirit of the Delft University of Technology makes this report a practical report with high standards. We hope this report brings you a clear overview of the calculations and considerations, surrounding the design of an Arctic Offshore Support Vessel.

Delft, University of Technology

R.W. Bos (4114620)
T.J. Huisman (4080777)
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Acknowledgements

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Finally, we want to thank the people around us, for supporting us in the goals we had and have.

Everything that is beautiful and noble
is the product of reason and calculation.
-Charles Baudelaire

Glossary

AHTS	Anchor Handling Tug and Supply vessel.
AOSV	Arctic Offshore Support Vessel.
Class Notation	Notation to determine applicable rule requirements for assignment and retention of a certain category of ships.
DNV	Det Norske Veritas, Class Society.
DP	Dynamic Positioning, computer-controlled system to maintain a vessel's position and heading.
drizzle	Droplets of water smaller than rain.
GA	General Arrangement of a ship.
Lindqvist	Empirical formula to predict ice resistance, explained in section 2-3-2.
MARPOL	International Convention for the Prevention of Pollution from Ships.
MCR	Maximum Continuous Rating.
MOB	Man Over Board boat.
Operational Profile	Quantitative characterization of how a vessel will be used.
per	Pollutant emission ratio.
PSV	Platform Supply Vessel.

Riska	Empirical formula to predict ice resistance, explained in section 2-3-3.
sfc	Specific fuel consumption.
SFICR	Swedish-Finnish Ice Class Rules.
spe	Specific pollutant emission.
SSV	Standby Safety Vessel.
Transit Model	Model used to describe the route of a ship through ice.
UPCR	Unified Polar Class Rules.

Nomenclature

Latin Letters

AF	Hull area factor	[-]
AR	Load patch aspect ratio	[-]
B	Breadth	[m]
b	Breadth of the area under consideration of UPCR	[m]
b_{bow}	Breadth of the bow area under consideration of UPCR	[m]
b_{nonbow}	Breadth of the non bow area under consideration of UPCR	[m]
BM	Distance between the center of buoyancy and metacenter	[m]
C_1	Constant in the level ice prediction of Riska et al. 1997	[-]
c_1	Constant for the plate thickness calculation of FSICR	[-]
C_2	Constant in the level ice prediction of Riska et al. 1997	[-]
c_a	Constant for the plate thickness calculation of FSICR	[-]
c_d	Constant for the plate thickness calculation of FSICR	[-]
c_p	Constant for the minimum engine output of DNV	[-]
c_s	Constant for the minimum engine output of DNV	[-]
CG	Distance between the keel and the center of gravity of a certain weight	[m]
D	Displacement	[ton]

D_p	Propeller diameter	[m]
CF_c	Constant for the pressure calculation of UPCR	[N]
F	Force	[N]
f_1	Constant for the plate thickness calculation of FSICR	[-]
f_2	Constant for the plate thickness calculation of FSICR	[-]
f_3	Constant for the plate thickness calculation of FSICR	[-]
f_4	Constant for the plate thickness calculation of FSICR	[-]
F_i	Force at position i of UPCR	[N]
f_1	Constant in the level ice prediction of Riska et al. 1997	$[N/m^3]$
f_2	Constant in the level ice prediction of Riska et al. 1997	$[N/m^3]$
f_3	Constant in the level ice prediction of Riska et al. 1997	$[N/m^3]$
f_4	Constant in the level ice prediction of Riska et al. 1997	$[N/m^3]$
F_{bow}	Force at the bow	[N]
F_{nonbow}	Force at the non bow area	[N]
fa_i	Factor fa at position i	[N]
Fn	Froude number	[-]
Fn_h	Ice thickness based Froude number	[-]
g	Gravitational constant	$[m/s^2]$
g_1	Constant in the level ice prediction of Riska et al. 1997	$[\frac{N}{m/s \cdot m^{1.5}}]$
g_2	Constant in the level ice prediction of Riska et al. 1997	$[\frac{N}{m/s \cdot m^{2}}]$
g_3	Constant in the level ice prediction of Riska et al. 1997	$[\frac{N}{m/s \cdot m^{2.5}}]$
GM	Distance between the center of gravity and metacenter	[m]
h	Height of load area in the FSICR	[m]
h_i	Ice thickness	[m]
i	Integer	[-]
IN	Ice class number according to DNV	[-]
IR	Icing rate	[m/h]
K_e	Constant for the effect of the propeller	[-]
K_Q	Torque coefficient	[-]
K_T	Trust coefficient	[-]
KB	Distance between the keel and center of buoyancy	[m]
KG	Distance between the keel and the center of gravity	[m]

l	Span of the frame	[-]
L_{pp}	Length between perpendicular	[m]
L_{wl}	Waterline length	[m]
m	Constant for the plate thickness calculation of FSICR	[-]
m_t	Constant for the plate thickness calculation of FSICR	[-]
n	Revolutions	[rpm]
P	Pressure	$[N/m^2]$
p	Ice pressure	$[N/m^2]$
P_i	Pressure at position i	$[N/m^2]$
p_{avg}	Average ice pressure	$[N/m^2]$
P_{bow}	Pressure at the bow	$[N/m^2]$
P_B	Brake power	[W]
P_{DNV}	Minimum engine output of DNV	[-]
P_D	Delivered power	[W]
P_{FSICR}	Minimum engine output of FSICR	[-]
P_{pl}	Pressure on the plating in the FSICR	$[N/m^2]$
PPF_p	Peak pressure factor	[-]
PR	Predictor of the icing conditions	[-]
Q	Line Load of UPCR	$[N/m]$
Q_i	Line Load at position i of UPCR	$[N/m]$
Q_{bow}	Line Load at the bow of UPCR	$[N/m]$
R_b	Resistance component due to buoyancy of the ice	[N]
R_c	Resistance component due to clearing the ice	[N]
R_i	Resistance in Ice	[N]
R_t	Total resistance in Ice	[N]
$R_{bending}$	Bending Component of the Lindqvist 1989 method	[N]
R_{br}	Resistance component due to breaking the ice	[N]
R_{CH}	Channel ice resistance	[N]
$R_{crushing}$	Crushing Component of the Lindqvist 1989 method	[N]
R_{ow}	Open water resistance	[N]
$R_{submersion}$	Submersion Component of the Lindqvist 1989 method	[N]
s	Frame spacing	[m]
T	Draught	[m]
T	Temperature	[K]
t	Plate thickness	[m]
$t1$	Material design temperature	[K]
$t2$	Extreme design temperature	[K]
T_a	Air temperature	[K]
t_b	Begin time window	[s]
t_c	Plate thickness increment	[m]
t_e	End time window	[s]

T_f	Temperature of saline ice at freezing point	[K]
T_w	Temperature of seawater	[K]
T_{NET}	Net thrust	[N]
t_{net}	Net plate thickness	[m]
T_{PULL}	Bollard Pull	[N]
t_s	Plate thickness addition for Corrosion/ Abrasion	[m]
V_a	Wind speed	[m/s]
v_s	velocity of the ship	$[m/s]$
v_{ow}	Maximum open water speed	$[m/s]$
w	Width of the area under consideration	[m]
W_i	Weight rate of the ice accretion	[kg/h]
w_{bow}	Width of the bow area under consideration of UPCR	[m]
w_{nonbow}	Width of the non bow area under consideration of UPCR	[m]

Greek Letters

α	Waterline entrance angle	[deg]
$\delta\rho$	Difference in density between ice and water	$[kg/m^3]$
η_{TRM}	Transmission efficiency	[-]
μ	Friction between hull and ice	[-]
ϕ	Stem angle	[deg]
ψ	Angle between normal of the surface and vertical vector	[deg]
ρ_{ice}	Density of sea ice	$[kg/m^3]$
ρ_w	Density of sea water	$[kg/m^3]$
σ_y	Yield strength	$[N/m^2]$
σ_b	Ice bending strength	$[N/m^2]$

Introduction

Three Damen offshore vessels are compared with the requirements of operations in the Arctic. These vessels are designed to be able to operate as offshore support vessel, each with its own specific operational profile and design. With a growing interest and decreasing amount of ice in the Arctic, it would be a feasible method to slightly adjust the Damen vessels to suit the needs of the Arctic.

Target

To be able to read the report, one should have the shipbuilding knowledge of a maritime engineering bachelor student. That is, basic knowledge about contructions, hydrodynamics and propulsion installations, but also about the Arctic and its perils. The background about this can be found in the literature survey - "Surfacing the Arctic".

The goal of this report is to show how the three Damen vessels hold themselves against the rules and requirements of the Arctic. This is done by using rules and guidelines that are already in effect and looking into the near future. The operational profile is based on the original operational profile of the ship, combined with the Arctic operations it will perform.

Scope of Work

From the operational profile, the scope of work can be defined. In general the report is limited to the requirements set in the operational profile. Since the ship has already been designed, adapting the additional requirements should suffice to ensure safe navigation in the Arctic. The recommendations for the ship will only include minor recommendations. A whole new design will be presented in the next report. The rules that are used are either already in effect or will be in effect in the near future and bind the ship to certain limits.

Structure

In the first chapter, the operational profile and ship data are given. After that, the methods used to calculate the requirements for the ship are explained. The following chapter shows the results of these methods, values used in the calculation are to be found in the appendix. The final chapter gives conclusions and recommendations.

Chapter 1

Operational profile

The specifications of the three concept ships of Damen are given for open water operations. This chapter focuses on the requirements that should be met when the ships are going to operate in the Arctic, following from the literature study and the courses followed at the Aalto University.

1-1 Original specifications

In the specifications the main dimensions and other main parameters of the ship are given. The general information of the ships is to be found in the ship brochures. This section gives for each of the three concept ships the original operational profile. This leaves out of account the optional fire fighting, oil recovery and higher class dynamic positioning installations.

1-1-1 PSV 3300

The definition for the vessel is according to Damen: "The Damen Platform Supply Vessel is a highly efficient, large-capacity ship, especially suited for transport of crew and supplies to and from offshore structures."

The vessel is designed for unrestricted service and is especially suited for:

1. Transport of supplies and crew to and from offshore drilling rigs and production platforms in support of hydro carbon exploration and production activities.
2. The vessel can be fitted with optional systems such as external fire-fighting, oil-recovery etc.

Endurance of 28 days is based on the operational profile:

- 80% of the time at transit, 12 kn and 5.0 m draught, wind force < 4 Bft

- 15% of the time at dynamic position at wind force 4 Bft
- 5% of the time in port

The class notation is according to Lloyds register: ✠100A1 Offshore Supply Ship, SG 2.8 (MUD tanks), EP (I, O, P), WDL, LMC, UMS, CAC 3, DP(AA)

1-1-2 AHTS 200

The definition for the vessel is according to Damen: "The Damen Anchor Handling Tug Supplier is, besides its anchor handling operations, also fit for transport of crew and supplies to and from oil rigs."

The vessel is designed for unrestricted service and is especially suited for:

- Torpedo-anchor handling operations
- Towing operations
- Transport of supplies and crew to and from offshore drilling rigs and production platforms
- Remote Operated Vehicle support
- The vessel can be fitted with optional systems such as external fire-fighting, oil-recovery etc

Endurance of 20 days is based on the operational profile:

- 50% of the time at transit, 12 kn and 5.3 m draught, wind force $<$ 3 Bft
- 50% of the time at transit, 10 kn and 6.3 m draught, wind force $<$ 3 Bft

The class notation is according to Lloyds register: ✠100A1 Anchor Handler, Offshore Supply Ship, Tug, *IWS, EP, LMC, UMS, CAC 3, DP(AA)

1-1-3 SSV 4711

According to Damen: "The Damen SSV 4711 is a fully dedicated design for standby and rescue operations with unrestricted service. Key design aspects are fuel economy and crew comfort for longer stand-by periods in the North Sea area."

Key features of this vessel are:

- Capacity for 125 survivors
- Rescue zone on port and starboard, equipped with reception area, hospital and winching zone
- Helicopter winching zone
- Endurance of 40 days or 5000 nm

The class notation is Lloyd's Register ✠100A1 ✠LMC UMS, Safety Standby Vessel. Next to that, the vessel is built in compliance with the NOGEPA and UKOOA industry guidelines.

1-2 Operating in the Arctic

Operating in the arctic brings extra requirements to the ship design, as stated in the literature study[3]. The operational profile with respect to ice classes and operation area is already stated as result of the literature study.

In general, the ships must be adjusted for Arctic operation with respect to the hull form and ice class, but also to be able to operate in the cold environment which has impact to the winterization and materials. The vessels should be equipped to perform emergency operations due to the remoteness of the area. Fire fighting, standby and rescue tasks, and oil recovery, all suited for arctic conditions, have to be part of the design requirements. Moreover, the ships are to be equipped to perform ice management tasks. This task is likely to combined with the emergency operations. These operations have impact on the endurance and therefore on the capacities of the ship.

In the literature study three areas were specified: Beaufort Sea, Baffin Bay and Barentz Sea[3]. The areas where the most activity will be on the short-term are the Baffin Bay and Barents Sea. It should be a requirement for the vessels to be able and allowed to operate in these two areas for an extended season.

The choice for these areas leads mainly to the use of two ports, namely Nuuk in Greenland for Baffin Bay and Murmansk in Russia for the Barents Sea. Both ports are well equipped with an hospital, an airport and possibilities for ship repair. Next to that, bunker facilities are available. The port of Murmansk is year round ice free, while the port of Nuuk has ice during the winter. Specific information on weather and ports can be found in the literature study [3], or in the ISO 19906 [1].

As stated in section 1-1, the operational profile of a vessel states the amount of days it has to operate under a certain condition and during certain operations.

Figure 1-1 gives the route from Murmansk to a potential rig [3, fig B-2]. The port is free of ice, but the sea does not have to be. Figure 1-1 gives also the maximum ice extent in a year. This fictional route is used to base the Arctic operational profile for the three vessels. More detailed calculations are to be found in section 3-3.

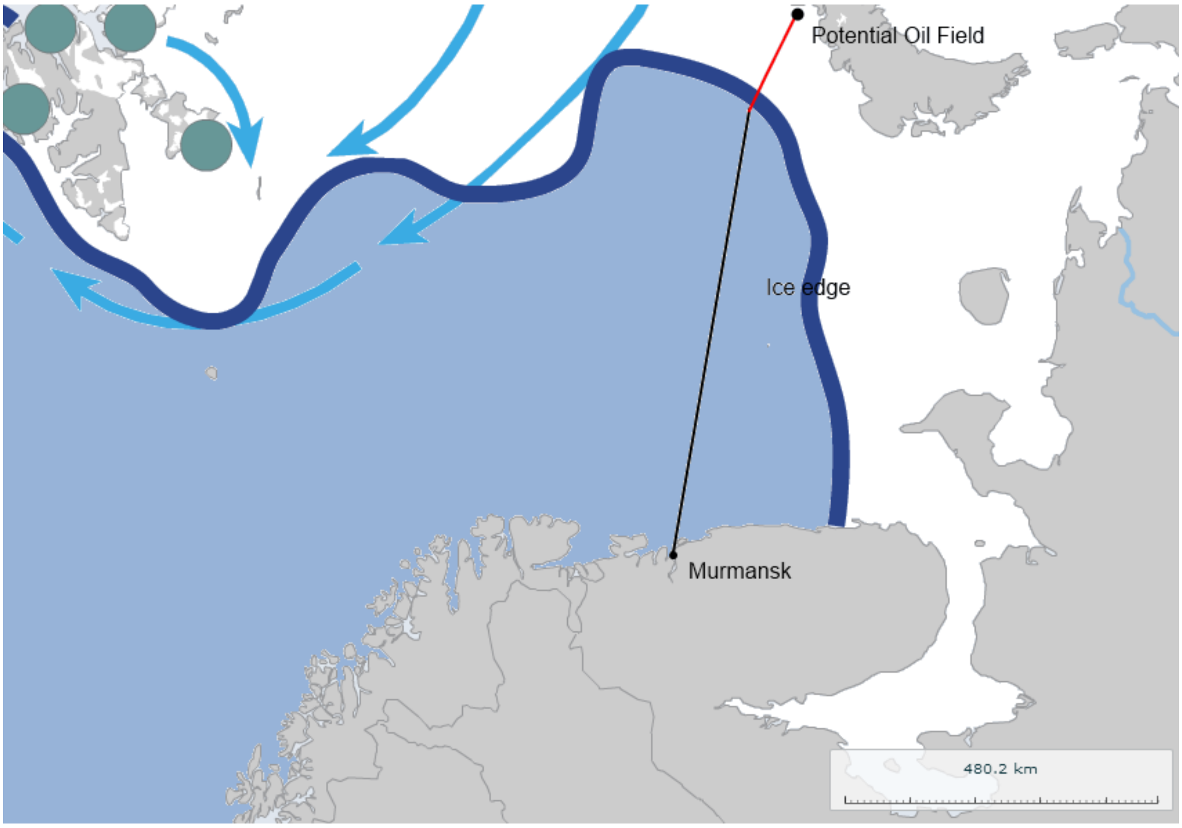
Bibliography

[1] ISO 19906 - Petroleum and natural gas industries - Arctic offshore structures. Technical report, ISO, November 2010.

[2] Arctic Portal. Interactive data map. http://www.arcticportal.org/, December 2012.

[3] R.W. Bos, T.J. Huisman, M.P.W. Obers, T. Schaap, and M. van der Zalm. Servicing the arctic, report 1: Design requirements and operational profile of an arctic offshore support vessel, literature survey. Technical report, TU Delft, November 2012.

Figure 1-1: Route from Murmansk to a potential offshore platform [2]



Chapter 2

Used Methods

For the three ships that are mentioned in chapter 1, the calculation method is the same. Therefore this chapter will explain the calculations, interpretations and methods that are used to review the usability of the Damen ships. The sections are arranged per subject, with their calculations accordingly. The order is adapted from the Design Spiral of Peter A. Gale[1].

First, the effects of winterization on the general arrangement and deck equipment are described. As third the calculations around ship resistance in ice are explained. With the resistance the power is calculated in the fourth section. Then the rules around the structure are explained and the final section explains the stability of the vessel.

2-1 Winterization

The goal of this section is to indicate the adjustments that should be made to create a user friendly working environment. Winterization is primarily intended to oppose the effects of ice accretion and low temperature, which adversely affects the seaworthiness and operations of the vessel as it leads to:

- Increase in the weight of the vessel, reduction of freeboard and buoyancy
- Lower GM due to high KG of the accumulated ice
- Increase of windage area, increase in the heeling moment
- Trim or list due to uneven distribution of ice
- Reduced maneuverability and speed

The sea spray is considered as main reason of ice accretion rather than rain, drizzle and snow. Frozen spray can shut the openings and creates trapped water on the deck. There will be a free surface effect, leading to loss of stability. [2]

The class notation for winterization is, according to DNV, WINTERIZED COLD (*t1*, *t2*), where *t1* = material design temperature in °C and *t2* = extreme design temperature in °C. Value *t1* should reflect the lowest mean daily average air temperature in the areas of operation which are defined in the literature study [3].

From the ISO 19906 and table 12.1 of the literature study follows that the mean minimum temperature is -39°C for the Baffin Bay, with a lowest annual value of -41°C. This means that the daily average air temperature is higher. However, the design temperature should be chosen according to the operational profile as defined in chapter 1. For this seasonally restricted service the lowest value of the mean daily average temperature curve within the time of operation applies. Figure 2-1 shows the daily temperature of a few weather stations in the Arctic and table 2-1 gives the estimated temperatures based on figure 2-1. These temperatures are plausible in comparison with reference ships.

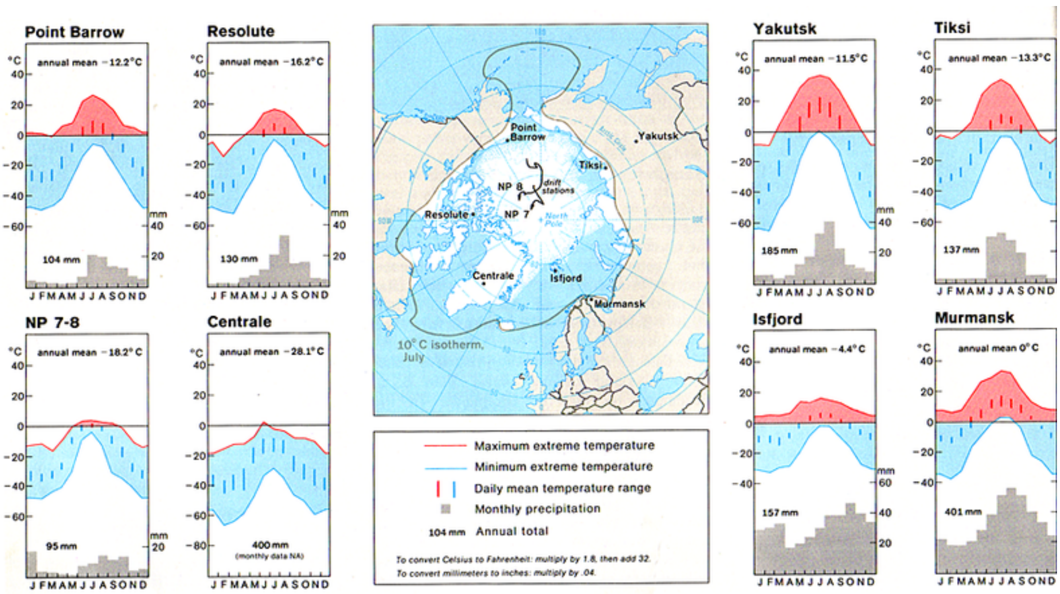


Figure 2-1: Annual daily temperature of a few weather stations in the arctic [4]

Table 2-1: Design temperatures for the three operational areas

	t_b	T	t_e	T	$t1$
Barents Sea	March	-30°C	January	-30°C	-10°C
Beaufort Sea	April	-45°C	November	-45°C	-25°C
Baffin Bay	May	-40°C	December	-45°C	-25°C

t_b = begin time window, t_e = end time window.
T represents the minimum extreme temperature.

To winterize the DAMEN concept vessels the guidelines and rules mentioned below will be followed:

- Winterization according to DNV WINTERIZED BASIC complemented with WINTERIZED COLD (-25,-45). [5]

- Literature survey by AMT chapter 9 'Crew Conditions' with its references [3]
- Guidelines IMO [6]

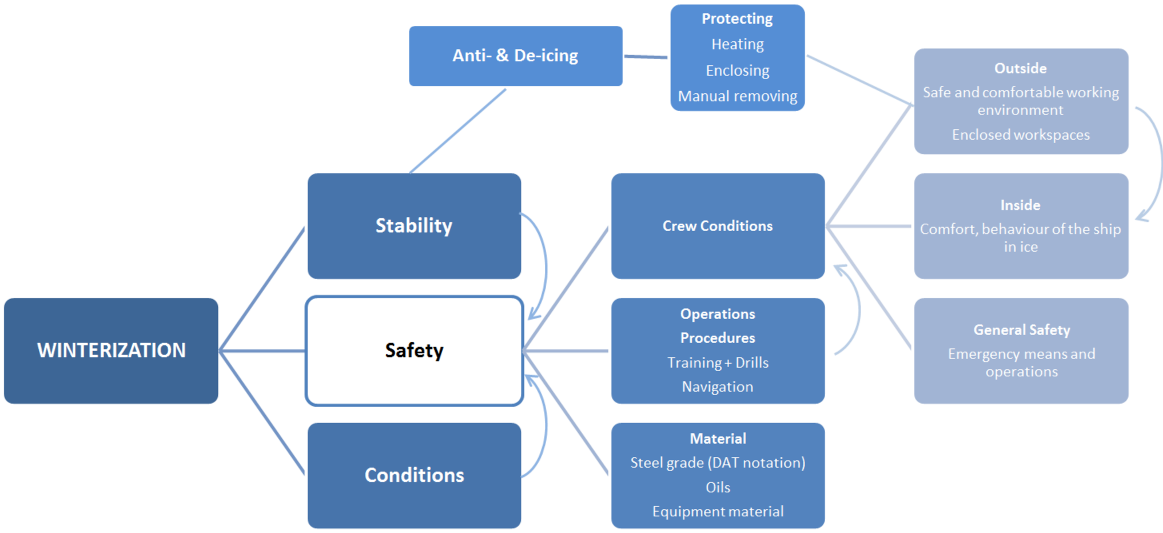


Figure 2-2: Components of winterization. [3, 5, 6, 7]

The factors of winterization are indicated by figure 2-2. They can be addressed by combining heating, covering, adaptation or automation of equipment and improvement of procedures. The main goals of winterization are to ensure safe and workable operations with respect to the ship stability, operations and crew conditions. The aspects indicated in figure 2-2 will be addressed for the DAMEN concept vessels in chapter 3

To operate in the Arctic regions, without the adjustments mentioned in figure 2-2, the operation time window will be shorter, nearly limited to non freezing conditions. Nevertheless, heating is not always necessary in freezing conditions, but only in certain conditions when there is a danger for ice accretion. Heating will even be more used during operations in open water due to the spray than in ice operations.

2-2 Deck equipment

In this section an overview is given off the adaptations that can or have to be done with regards to the deck equipment. Each subsection covers one specific type of equipment. An overview of the solutions is given. However, there is not much information available and for specific questions the sub-contractors will have to be contacted.

2-2-1 Control cabins

If a crew member is operating a crane or equivalent machinery it is sometimes required to be in a cabin for a long time, in arctic conditions this can be challenging. Several solutions include:

- Two layer glass
- Electric heated windows
- Thermal insulation of cabin enclosure
- Heating of the cabin
- Protection from ice drop
- Remote operation

At the moment there are several makers available that deliver all the aforementioned solutions except remote operation.

2-2-2 Anchor handling

Anchor handling in ice can cause greater stress on involved structures and crew than in open water. This is due to the fact that ice accretion can occur on the equipment and that the working environment is outside. Several solutions that can be considered are:

- Enclosed working decks
- Strengthened stern roller and deck
- Arctic approved lines

2-2-3 Winches

The use of winches in Arctic conditions is difficult due to low temperatures and ice accretion. Possible solutions include:

- Hot flushed hydraulic motors
- Seals and springs for low temperature
- Preheated housing and gears
- Ice protection cover

2-2-4 Cranes

As with winches, cranes can have difficulty in Arctic conditions. They can be exposed to the weather more due to the inability to cover them completely. Certain companies provide cranes with a design temperature of up to -20° C.

- Hot flushed hydraulic motors

- Seals and springs for low temperature
- Ice scrapers on cylinder rods
- Preheated housing and gears
- Ice protection cover

2-2-5 Control systems

For nearly al the deck equipment there will be control systems, electric cabinets, cables and sensors that can be exposed to the weather. These environmental conditions must be taken into account for the design of the deck equipment. Solutions can include:

- Heating of the cabinet
- LCD Screens only indoor
- Arctic electrical cables

These solutions are all readily available.

2-2-6 Emergency means

Emergency means such as life and MOB boats normally do not operate well in the Arctic. Because of the isolated area and lengthened time for rescue operations, high standards are required. Solutions for these challenges can be:

- Covered storage
- Specialized davit system
- Engine heating

Solutions provided by manufacturers are for instance the sliding davit system. This ensures covered storage and maintenance. Engine heating is also available. Some david systems can lower conventional lifeboats onto the ice without problems [8].

- Sliding davit system
- Engine heating

2-3 Ship resistance in ice

This section focuses on the estimation of the resistance in level ice. First a short theoretical background of level ice resistance is given in section 2-3-1. In section 2-3-2 the Lindqvist 1989 method is introduced to estimate the level ice resistance of a vessel with an ice breaking bow. The in 1997 published method by Riska et al. is explained in section 2-3-3. Section after that is a comparison between Lindqvist and Riska. The final section is the FSICR calculation method of resistance.

2-3-1 General definition of level ice resistance

According to the ITTC[9] the total resistance in ice is the sum of four individual, independent resistance components:

$$R_t = R_i + R_{ow} = R_{br} + R_c + R_b + R_{ow}$$

where R_i is the ice resistance, R_{ow} is the resistance component in open water, R_{br} is the resistance component to breaking the ice, R_c is the component due to clearing the ice and R_b is the component due to buoyancy of the ice[10]. In some studies R_b and R_c are taken together as a general ice clearing resistance and yet other literature uses a component for frictions as well. It is questionable to assume that all these components are strictly independent, but in this report it is assumed that they are, which is the usual approach. In predictions methods the ice resistance R_i is calculated.

2-3-2 Lindqvist 1989 method

The Lindqvist formula introduced in 1989 is a semi-empirical formula, it uses physical parameters as input but cannot be proven using existing laws of physics. The formula is based on a wedge shaped bow [11]. It must be noted that this formula can only be used for calculating resistance in level ice and no other ice features.

Input parameters

This method models the bow as a wedge to describe the behaviour in ice, figure 2-3. The ship is described by the main dimensions as seen in figure 2-3: the waterline length L_{wl}, breadth B, draught T, waterline entrance angle α, the stem angle ϕ and the angle between normal of the surface and vertical vector ψ [11]. Besides the main dimensions of the ship, ice parameters

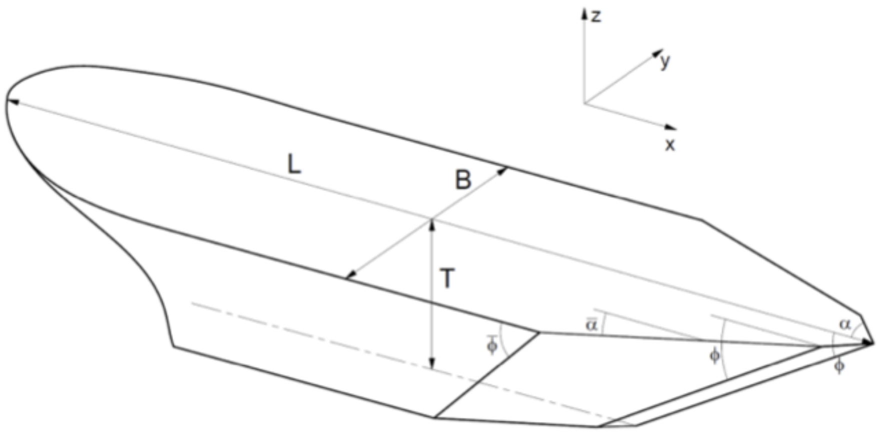


Figure 2-3: Lindqvist definition of the hull form[11]

such as ice thickness h_i and ice bending strength σ_b are taken into account, as well as the friction between hull and ice μ, gravitational constant g and the difference in density between ice and water as $\Delta\rho$ [11].

Lindqvist divides the resistance in three components, the crushing, bending and submersion component. The crushing and the bending component together are the breaking resistance and this is assumed to be proportional to the ice thickness based ice Froude number, equation 2-1. The submersion component is assumed to be proportional to the Froude number, equation 2-2. As result of the non-dimensional Froude number and additional empirical constants, the resistance components are speed dependent [11]. It shall be noted that for the submersion component it is assumed "that the bow of the ship is completely covered with ice and the bottom is covered with 70% of the length of the ship" [11, p. 22]. Therefore this component is a combination of R_b and R_c as described in equation .

$$Fn_h = \frac{v_s}{\sqrt{g \cdot h_i}} \tag{2-1}$$

$$Fn = \frac{v_s}{\sqrt{g \cdot L_{wl}}} \tag{2-2}$$

The Lindqvist formula is widely used because of its simplicity. The formula does not deal with the following effects according to Kaups: motions of the vessel, effect of the propellers, thrust deduction due to milling and variation in ice properties [11, p. 23]. In the subsection 2-3-2 the Lindqvist equations are shown in equation 2-3 to 2-7.

Equations

$$\psi = \arctan(\frac{\tan(\phi)}{\sin(\alpha)}) \tag{2-3}$$

Crushing component:

$$R_{crushing} = 0.5 \cdot \sigma_b \cdot h_i^2 \cdot (\tan(\phi) + \mu \cdot \frac{\cos(\phi)}{\cos(\psi)}) \cdot (1 - \mu \cdot \frac{\sin(\phi)}{\cos(\psi)})^{-1} \tag{2-4}$$

Bending component:

$$R_{bending} = 0.003 \cdot \sigma_b \cdot B \cdot h_i^{1.5} \cdot (\tan(\psi) + \mu \cdot \frac{\cos(\phi)}{\sin(\alpha) \cdot \cos(\psi)}) \cdot (1 + \frac{1}{\cos(\psi)}) \tag{2-5}$$

Submersion component:

$$R_{submersion} = \Delta\rho \cdot g \cdot h_i \cdot B \cdot [T \cdot \frac{B+T}{B+2 \cdot T} + \mu \cdot (0.7 \cdot L_{wl} - \frac{T}{\tan(\phi)} - \frac{B}{4 \cdot \tan(\alpha)}) + \mu \cdot T \cdot \cos(\phi) \cdot \cos(\psi) \cdot (\frac{1}{\sin^2(\phi)} + \frac{1}{\tan^2(\alpha)})^{0.5}] \tag{2-6}$$

Total level ice resistance:

$$R_{ice} = (R_c + R_b) \cdot (1 + 1.4 \cdot \frac{v_s}{\sqrt{g \cdot h_i}}) + R_s \cdot (1 + 9.4 \cdot \frac{v_s}{\sqrt{g \cdot L_{wl}}}) \tag{2-7}$$

Limitations

As mentioned earlier, the Lindqvist method is based on a wedge shaped bow, figure 2-3. The angles α, ϕ and ψ have a big influence on the resistance. They determine how big the ratio of the bending and crushing component. In general if a ship has a bow angle of 90°, the ship ice fails due to crushing. When the angle is decreased the ice begins to fail due to bending. The ratio between failing due to crushing and bending changes with the bow angle. At a theoretical bow angle of 0° the ice fails only due to bending. However, when Lindqvist is used this result is not given. This shows another limitation, the usable range is limited.

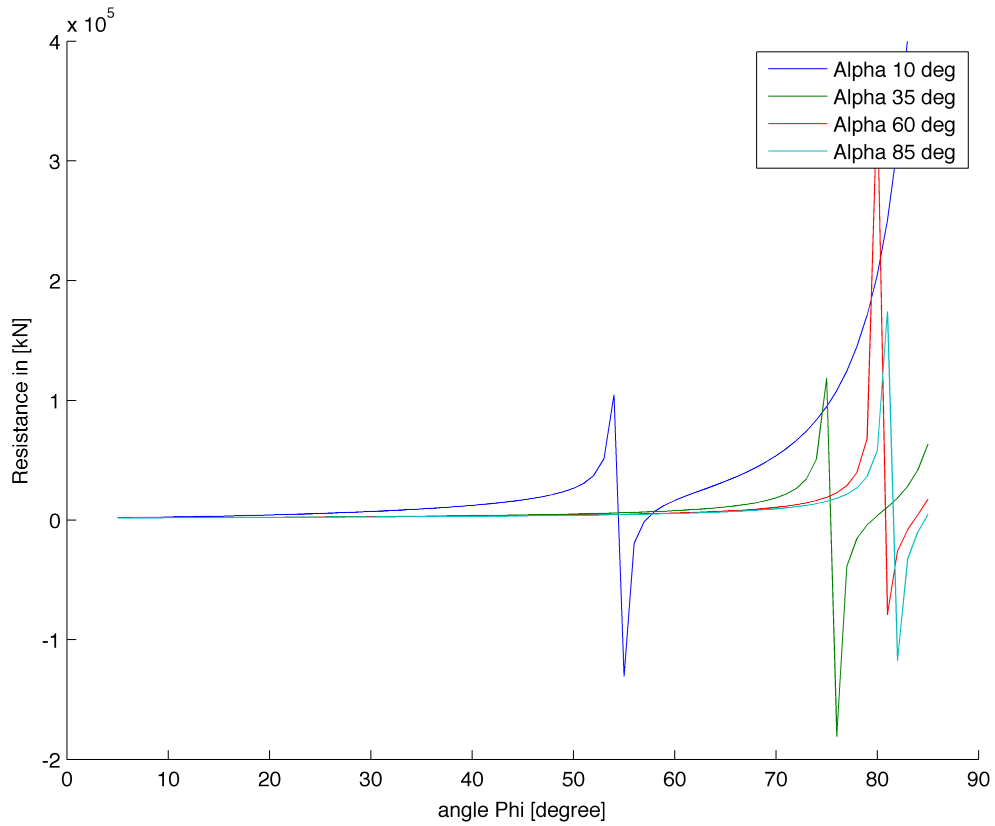


Figure 2-4: Lindqvist with different angles of alpha

The angle ψ is dependent on the angle α and ϕ. In figure 2-4 the resistance of four waterline entrance angles α was calculated based on different stem angles ϕ. It can be seen that the resistance gets unrealistic at certain α and ϕ angles by getting an asymptote. All values behind that point present wrong estimations and are caused by the behaviour of trigonometric functions used in the method. With an increasing angle α the failing point is also increasing.

Lindqvist will always fail when equation 2-8 is true. Equation 2-8 will cause the crushing component to become negative. If Lindqvist fails is therefore only depended on the waterline entrance angle α the stem angle ϕ and the friction coefficient μ.

$$1 < \mu \cdot \frac{\sin(\phi)}{\cos(\psi)} = \mu \cdot \frac{\sin(\phi)}{\cos(\arctan(\frac{\tan(\phi)}{\sin(\alpha)}))} \tag{2-8}$$

2-3-3 Riska et al. 1997 method

The Riska method can be used for level ice resistance. It's mainly based on three formulations. The three used formulations are: Ionov (1988), Lindqvist (1989) and Kämäräinen (1993). The aim from this method is to develop a tool to estimate the required power in ice for transit models [12].

Input parameters

The ice thickness h_i is the most important variable for the constants in equation 2-10 and 2-11 on which the speed dependent equation 2-9 is based. Other constants are: difference in density, bending strength and the friction between the ice and the hull also influence the level ice resistance, as listed in table 2-2. These are assumed to be constant throughout the estimate of ice resistance and are given in table 2-2. These values can be different depending on the ship, area of operation and time of the year, however, Riska chooses to use them as constants [12].

Table 2-2: Used constants in Riska et al 1997. Has to be changed to the specific conditions the vessels operates in, but can be used as an first estimation. Adapted from [12]

Constant	Value	Unit
ρ_Δ	125	kg/m^3
σ_b	500	kPa
μ	0.15	

There are also some other constants needed to calculate the resistance, these are given in table 2-3. These constants will be used in subsection 2-3-3.

Table 2-3: Constants in the equation for level ice resistance 2-10 and 2-11 adopted from Riska et al. (1997)

Variable	Value
f_1	0.23
f_2	4.58
f_3	1.47
f_4	0.29
g_1	18.9
g_2	0.67
g_3	1.55

Equations

The parameters for the ice resistance can be divided in three groups. The three groups are given below.

- External variables
  Ice thickness h_i and ship speed v_s
- Shape of the ship
  The following variables are in this group: $\phi, \frac{B}{T}, \frac{L_{pp}}{B}, \frac{L_{bow}}{L_{pp}}, \frac{L_{par}}{L_{pp}}$.
- Main dimensions of the ship
  Length (between perpendiculars), breadth and draft: L_{pp}, B, T

This gives equation 2-9 for the ice resistance, which is linearly dependent on the velocity.

$$R_i = f(h_i, v_s; \phi, \frac{B}{T}, \frac{L_{pp}}{B}, \frac{L_{bow}}{L_{pp}}, \frac{L_{par}}{L_{pp}}; B, T, L_{pp}) = C_1 + C_2 \cdot v_s \tag{2-9}$$

With C_1 and C_2 represented in formulas 2-10 and 2-11.

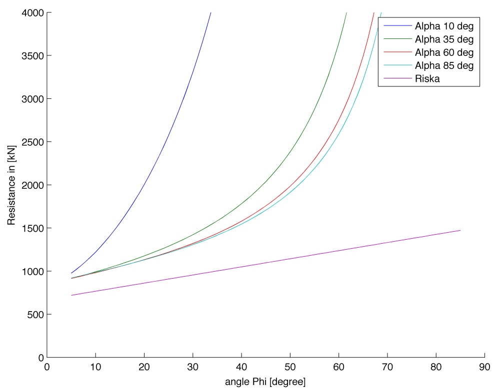
$$C_1 = f_1 \cdot \frac{1}{2 \cdot \frac{T}{B} + 1} \cdot B \cdot L_{par} \cdot h_i + (1 + 0.021 \cdot \phi) \cdot (f_2 \cdot B \cdot h_i^2 + f_4 \cdot B \cdot L_{bow} \cdot h_i) \tag{2-10}$$

$$C_2 = (1 + 0.063 \cdot \phi) \cdot (g_1 \cdot h_1^{1.5} + g_2 \cdot B \cdot h_i) + g_3 \cdot h_i \cdot (1 + 1.2\frac{T}{B}) \cdot \frac{B^2}{\sqrt{L_{pp}}} \tag{2-11}$$

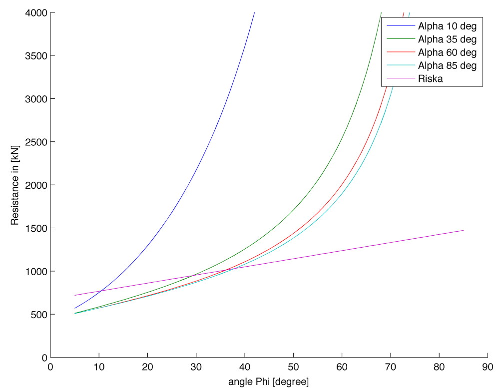
2-3-4 Comparison of Lindqvist and Riska

In this section the influence of the input parameters on the results of the Lindqvist and Riska predictions are shown and discussed. The figures shown in this section were based on the tanker MT Varzuga (until 2003 Uikku), all main parameters are shown in appendix B. In table B-2 the parameters for each situation is listed. For the reference figure 2-5a the friction factor μ is taken as 0.15, bending strength of the ice σ_b as 780 kPa, the speed as 1 m/s and ice thickness as 1 m. The changes compared to this reference situation are mentioned in the caption of the figures.

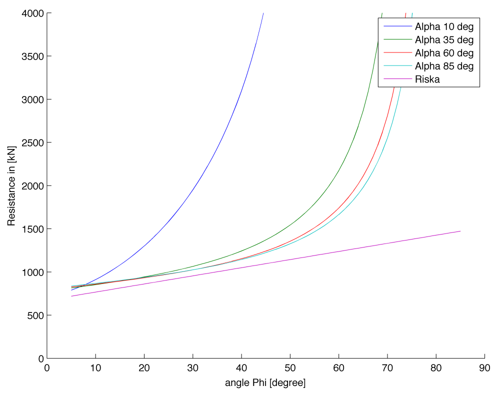
In figure 2-5b the effect of the friction factor μ is shown. Lindqvist uses the friction factor as a variable in this estimation, where as in Riska's prediction the friction factor is assumed to be constant. It should be noticed, that Riska was developed for the Baltic Sea and therefore ice conditions such as friction and bending strength were assumed to be constant as can be seen in table 2-2. One can see in figure 2-5b that with a decrease in friction Lindqvist resistance decreases as well. The stem angle ϕ can be higher with a smaller friction, the failing point moves to a higher stem angle.



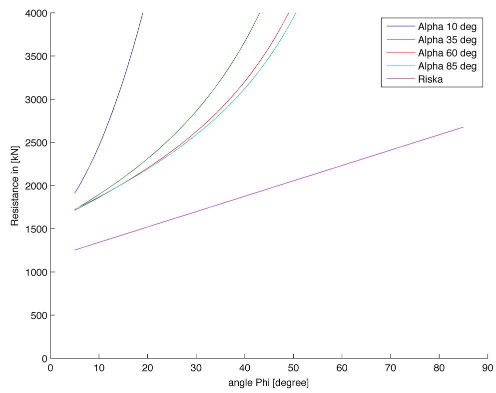
(a) Lindqvist and Riska prediction depending on the angles ϕ and α. Situation 1



(b) Lindqvist and Riska prediction depending on the angles ϕ and α. Situation 2, μ is 0.05



(c) Lindqvist and Riska prediction depending on the angles ϕ and α. Situation 3, σ_b is 390 kPa



(d) Lindqvist and Riska prediction depending on the angles ϕ and α. Situation 4, v_s is 5 m/s

Figure 2-5: Effect of ice friction on the resistance prediction of Lindqvist and Riska, where resistance depends on angle ϕ, as stated in figure 2-3

The effect of the bending strength is shown in figure 2-5c. With a decrease in bending strength the resistance prediction decreases as well. In this case the failing point is even higher compared to situation 2. It should be noticed that for this ship and bow angles α of 35 deg and higher are parallel to the Riska prediction for stem angles ϕ between 5 and 40 deg.

In the fourth situation the speed effect is shown in figure 2-5d. In this case the velocity is 5 times higher than in situation 1. The effect of velocity seems to have a bigger effect on the Lindqvist prediction. Both predictions are quite scattered from each other. Lindqvist is predicting high resistances even for small stem angles.

2-3-5 FSICR channel ice resistance

While going through a channel the ship has a different resistance than while going through level ice. This resistance is called the channel ice resistance. R_{CH} (equation 2-12) is the resistance of a ship in a channel with brash ice and a consolidated layer in Newton.

$$R_{CH} = C_1 + C_2 + C_3 C_\mu (H_F + H_M)^2 \cdot (B + C_\psi H_F) + C_4 L_{PAR} H_F^2 + C_5 \left(\frac{LT}{B^2}\right)^3 \frac{A_{WF}}{L} \quad (2\text{-}12)$$

C_μ and C_ψ are dependent on the angle of the waterline at B/4(α), rake of the bow at B/4(φ_2) and the rake of the stern at the centerline(φ_1). These angles are presented in figure 2-6. If these angles increase, the values for C_μ and C_ψ will also increase which will result in a higher resistance.

The variable H_F is dependent on H_M (which is dependent on the ice class) and the breadth B.

The constants C_1 and C_2 take the consolidated upper layer of the brash ice into account. For the ice classes IA, IB and IC they have to be taken zero. For ice class IA Super equation 2-13 and 2-24 are used.

$$C1 = f1 \cdot \frac{B \cdot L_{PAR}}{2 \cdot \frac{T}{B} + 1} + (1 + 0.021 \cdot \phi_1) \cdot (f_2 \cdot B + f_3 \cdot L_{BOW} + f_4 \cdot B \cdot L_{BOW}) \quad (2\text{-}13)$$

$$C2 = (1 + 0.063 \cdot \phi_1) \cdot (g_1 + g_2 \cdot B) + g_3 \cdot (1 + 1.2 \cdot \frac{T}{B}) \cdot \frac{B^2}{\sqrt{L}} \quad (2\text{-}14)$$

If the vessel has a bulbous bow, φ_1 shall be taken as 90°, because the bulb gives a great resistance in ice. The constants: $f_1, f_2, f_3, f_4, g_1, g_2, g_3$ are fixed values and are displayed in the FSICR [13, p. 7].

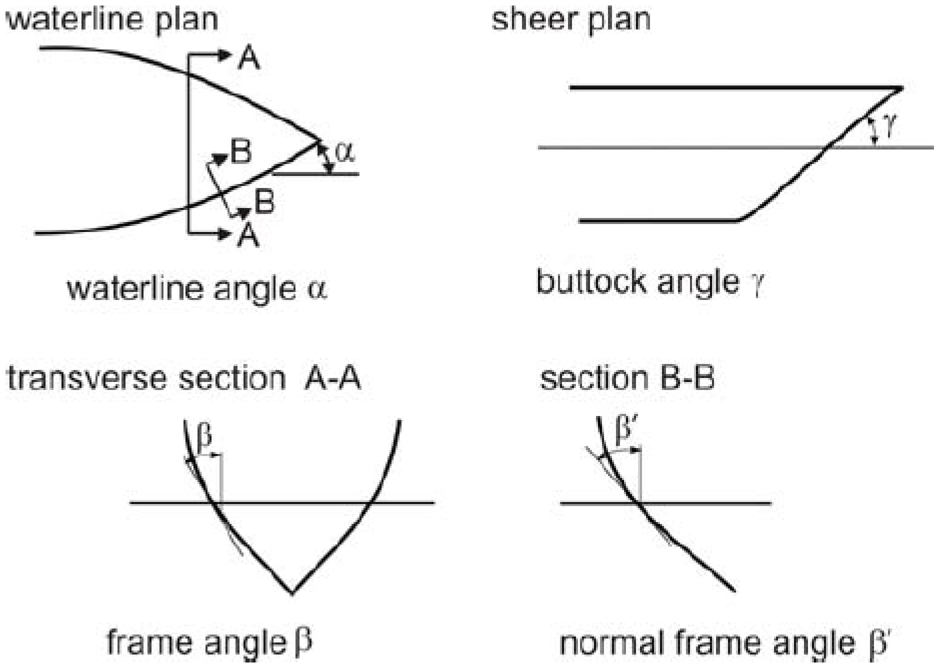


Figure 2-6: Hull angles [13]

2-4 Propulsion

To determine the necessary propulsion power, an engineer normally uses a desired speed to calculate the required power. This can be done using various efficiencies [14, p. 64]. However, these efficiencies are hard to predict in ice, therefore the rules have semi-empirical formulas for this.

2-4-1 Minimum Engine Output according to FSICR

According to the FSICR [13], the engine output shall be calculated for two draughts. The draughts that are to be used are the LWL (maximum draught at the midship) and BWL (minimum draught). The length and breadth of the vessel are only determined on the LWL. The engine output shall then not be less then the biggest one of these two values, equation 2-15 is used for the calculation. In equation , K_e depends on the amount of propellers and the use of a fixed or controllable pitch, which can be found in table 2-4.

$$P = K_e \frac{(R_{CH}/1000)^{3/2}}{D_p} [kW] \tag{2-15}$$

Riska and Juva provide a clear overview of how equation 2-15 is built up and the factors influencing it [15]. Normally the channel resistance found in the rules is used in this formula,

however, Riska and Juva state:
"The power requirement equation itself is the same for all ice classes. The difference between the classes is included in the channel resistance [...]." [15, p.33]

Therefore it is assumed that equation 2-15 can always be used, even if other types of resistance are used. A requirement to do this, is the assumption that the vessel will be operating in the circumstances that produce the used resistance.

Table 2-4: Values of the constant K_e in the Ice Class Rules [15]

Propeller type or machinery	CP or electric or hydraulic propulsion machinery	FP propeller
1 propeller	2.03	2.26
2 propeller	1.44	1.6
3 propeller	1.18	1.31

2-4-2 Minimum Engine Output according to DNV

In the DNV rules for "Vessel for Arctic and Ice breaking service" of January 2012 an engine output formula is presented [5, p. 71]. The formula is a semi empirical and depends on the ice class number IN, moulded breadth at the waterline in m B, rule draught T, the stem angle ϕ and constants c_s and c_p. The constant c_s is defined in equation 2-17. For a controllable pitch propeller the c_p shall be taken as 1.0 and for a fixed pitch propeller as 1.1. The ice class number IN stands for the nominal ice thickness h_{ice} in dm. For example the ice class ICE-15 is designed to go through 1.5 m nominal ice thickness and the ice class number IN is 15.

$$c_s = 1.0; \text{ for vessels with conventional icebreaker stem} \quad (2\text{-}16)$$

$$= 0.9 + \phi/200; \text{ minimum 1.0, but need not exceed 1.2} \quad (2\text{-}17)$$

With these constants and values the maximum continuous output of propulsion machinery shall not be less in kW than stated in equation 2-18.

$$P_{DNV} = 1.5 \cdot c_s \cdot c_p \cdot IN \cdot B \cdot [1 + 1.6 \cdot T + 27 \cdot (0.1 \cdot \frac{IN}{T^{0.25}})^{0.5}](kW) \quad (2\text{-}18)$$

2-4-3 Ice thickness - speed curve according to Riska et al.

To generate a ice thickness-speed curve a K_T-K_Q curve is needed, which shows the performance of a vessel at different speeds. K_T and K_Q are open water characteristics and it is assumed that the the open water resistance is not known. Therefore Riska et al. derived equation 2-19 where the net thrust T_{NET} is linear dependent on the bollard pull T_{PULL} and is a function of the speed v_s over open water speed v_{ow} [12]. It should be noticed, that this equation is zero when the $v_s/v_{ow} = 1$ and $T_{NET} = T_{PULL}$ when $v_s = 0$.

$$T_{NET} = T_{PULL} \cdot (1 - 1/3 \cdot v_s/v_{ow} - 2/3 \cdot (v_s/v_{ow})^2) \quad (2\text{-}19)$$

To determine T_{PULL} equation 2-20 from Riska is used. Values for K_E can be found in table 2-5 and are depending on the number of propellers [12]. The equation depends on the drive power P_D and the propeller diameter D_p. The factor η_{TRM} in equation 2-21 is the ratio between this drive power and the total brake power as shown in equation 2-21. The η_{TRM} for a direct drive is around 99 % for the losses in axis and 95-98 % in gearboxes [14]. A diesel-electric drive gives an η_{TRM} of 88-94 % according to the TU Delft [16]. Thus, all these parameters together give a T_{PULL}. When the net thrust T_{NET} is in equilibrium with the ice resistance R_{CH}, the speed is constant.

$$T_{PULL} = K_E \cdot (P_D \cdot D_p)^{2/3} \tag{2-20}$$

$$P_D = \eta_{TRM} \cdot P_B \tag{2-21}$$

Table 2-5: K_E value based on number of propellers [12]

Number of Propellers [-]	1	2	3
K_E [-]	0.78	0.98	1.12

With the known bollard pull and an open water velocity v_{ow} the net thrust curve can be plotted. To get a ice thickness versus speed curve (H-v curve) one has to plot the intersections of the ice resistance with the net thrust in a curve. In such a curve one can read how fast one can go through a specific thickness of level ice.

2-5 Structure

The structure of the ship can be calculated according to various rules. Two types of rules are used. The Finnish Swedish Ice Class Rules (FSICR) are used for calculations of lower ice classes 1C and 1A Super. Besides that, the Unified Polar Class Rules (UPCR) is used for a heavier ice classifications PC4 and PC6.

2-5-1 Plate thickness according to FSICR

In this section only the steps are explained that are needed to calculate the plate thickness and the section modulus the complete rules can be found in [13].

For the calculation of the plate thickness the ice pressure has to be determined. This can be done according to the following steps.

1. Determine c_d
   This factor dependants on: the region where the pressure needs to be calculated, the actual continuous engine output of the ship and the displacement at maximum ice class draught.

2. Determine c_1
   This factor takes the probability in account that the design ice pressure occurs in a certain region of the hull for the ice class in question.

3. Determine c_a This factor takes into account the probability that the full length of the area under consideration will be under pressure at the same time. It depends on the structure, type and length of framing.

4. Ice pressure p
   The pressure can be calculated by multiplying the factors above with the nominal ice pressure (5.6 MPa).

When the pressure is calculated the plate thickness can be determined. Besides the pressure the plate thickness is dependent on the yield stress, frame spacing and the design height under pressure at a certain time. When a stronger material is used, the yield stress will increase, this results in a decrease of the plate thickness. The plate thickness is linearly dependent on the frame spacing, this gives the frame spacing an important position in the equation. Also a factor is taken into account to compensate of abrasion and corrosion. The plate thickness is dependent on the same factors for longitudinal and transverse framing. The equation is however different, equation 2-22 is for transverse framing, and equation 2-23 for longitudinal framing.

$$t = 667s\sqrt{\frac{f_1 * p_{pl}}{\sigma_y}} + t_c[mm] \tag{2-22}$$

$$t = 667s\sqrt{\frac{p}{f_2 \cdot \sigma_y}} + t_c[mm] \tag{2-23}$$

$$Z = \frac{p \cdot s \cdot h \cdot l}{m_t \cdot \sigma_y} \cdot 10^6[cm^3] \tag{2-24}$$

The section modulus in equation 2-24 is dependent on the pressure, structural details such as frame spacing, yield strength and a design choice of connection m_t, depending on the use of brackets. Formula 2-25 is the formula for the section modulus of longitudinal frames. The factors f_3 and f_4 are only dependent of the height of the load area and the frame spacing.

$$Z = \frac{f_3 \cdot f_4 \cdot p \cdot h \cdot l^2}{m \cdot \sigma_y} \cdot 10^6[cm^3] \tag{2-25}$$

2-5-2 Plate thickness according to UPCR

To calculate the plate thickness with UPCR [17] , the ice pressure will be calculated first. Then the pressure is used to calculate the plate thickness. An explanation is given in the following sections about these two steps.

Ice pressure

According to I2.3.2.2. from the UPCR [17], the pressure can be calculated using equation 2-26.

$$P_{avg} = \frac{F}{b \cdot w}[MPa] \tag{2-26}$$

The variables in this equation have to be calculated different for the bow than for the rest of the ship. This will be explained in the next paragraph.

Ice pressure bow As stated in I2.3.2.1 from the UPCR [17] the bow region has to be divided into 4 subregions. The force (F), the load patch aspect ratio (AR), line load (Q) and pressure (p), combined in equation 2-27. All are to be calculated with respect to the mid-length position of each sub-region. The waterline length of the bow region is the length where the angle α is bigger than 10 degrees, as can be seen in figure 2-6. To determine the ice pressure, F_{bow} is needed. The first step is to calculate F_1, F_2, F_3 and F_4, according to equation 2-27.

$$F_i = fa_i \cdot CF_c \cdot D^{0.64}\ [MN] \tag{2-27}$$

Where fa_i is a function of the waterline angle, frame angle, ship displacement, length, distance from forward perpendicular and several class-specific factors considering the flexural and crushing strength of the ice. Because there are 4 subregions, $i = 4$. F_{bow} has to be taken as the maximum of these 4 values for F_i. The variables w_{Bow} and b_{Bow} are ratio between force and line load or the line load and the pressure respectively. For these values Q_{Bow} and P_{Bow} are needed. These are a function of the frame angle, load-patch -aspect ratio and -dimensions factor and the calculated force. P_{Bow} and Q_{Bow} are to be taken as the maximum of the 4 values of P_i and Q_i. When F_{Bow}, b_{Bow} and w_{Bow} are determined, the average bow pressure $P_{avg,bow}$ can be calculated according to equation 2-26.

Ice pressure midship and stern F_{NonBow} is calculated by multiplying a displacement factor with the crushing force factor and a numerical factor. Variables b_{NonBow} and w_{NonBow} can be calculated as a ratio between force and line load or the line load and a numerical factor respectively. When these values are calculated, with equation 2-26 the average ice pressure on the midship and stern ($P_{avg,nonbow}$) can be calculated.

Plate thickness

The required minimum shell plate thickness is given by equation 2-28. The value for t_s is an addition for corrision and abrasion.

$$t = t_{net} + t_s\ [mm] \tag{2-28}$$

Because the ships are transversely-framed, the net thickness is given by equation 2-29. Where AF is a Hull Area factor, and PPF_p is a peak pressure factor.

$$t_{net} = 500 \cdot s \cdot \frac{(\frac{AF \cdot PPF_p \cdot P_{avg}}{\sigma_y})^{0.5}}{\frac{1+s}{2 \cdot b}} \ [mm] \tag{2-29}$$

2-6 Stability

In section 2-1 the components of winterization of a vessel are explained. Figure 2-2 shows that stability is one of the purposes of winterization. However, in adverse weather conditions, the vessel will have to deal with ice accretion.

This section deals with the stability issues of ice going vessels specified to the Damen ships. The results of the calculations are given in section 3-6.

2-6-1 Rules

Initial Stability In the Intact Stability code is stated that "the initial transverse metacentric height (GMo) should not be less than 0.15 m" and "The calculations of loading conditions should, where appropriate, include allowance for ice accretion" [18]. Also the IMO guidelines give this recommendation. However, in the Polar Class Rules is referred to the DNV Ice Rules, section 4, where is stated: "L301 The initial metacentric height GMo shall not be less than 0.5 m" [5].

Riding up The stability case of the ship when riding up in ice during the penetration of ridges should also be part of the stability calculations. [6]

Damage Polar Class ships should be able to withstand flooding resulting from hull penetration due to ice impact, but no further additional rules exist.

2-6-2 Ice accretion calculation method

To give an indication of the initial metacentric height and the stability of the vessel, the amount of the accreted ice has to be known. Overland developed an algorithm to predict the icing rate. The algorithm generates an icing predictor based on air temperature, wind speed, and sea surface temperature which was empirically related to observed icing rates of fishing vessels in the Gulf of Alaska that were 20 to 75 meters in length. [19]

A predictor of the icing conditions PR is based on an approximated thermodynamic heat balance.:

$$PR = \frac{V_a(T_f - T_a)}{1 + \Phi(T_w - T_f)}$$

where V_a wind speed, T_f, T_w, T_a temperature of saline ice at freezing point, seawater and air, respectively and $\Phi = \frac{C_w}{L_i F} \approx 0.4°\mathrm{C}^{-1}$ with C_w, L_i, F the specific heat of seawater, latent heat of freezing of saline water and fraction of impinging seawater on the vessel, respectively.

The icing rate in cm/h is based on an empirical formula:

$$IR = A \cdot PR + B \cdot PR^2 + C \cdot PR^3$$

with A, B and C constant as defined by Overland.

The total ice accretion that will form on the ship is also dependent on the areas (A), with their centers of gravity (CG), where the ice is likely to form. This area is strongly dependent on the sailing direction with respect to the wave direction. With these areas the total weight of the ice accretion can be calculated which can be used in stability calculations.

The weight rate of the icing is then determined using $W_i = IR \cdot A \cdot \rho_i$ where ρ_i is the density of the ice.

It is recommended to perform the stability calculations as additional load to the loading conditions. The weight rate according to the icing rate is estimated for each ship. The stability calculations should give the maximum time in which the vessel can operate in such extreme conditions without ice removal. The exact data for the ships is not known. The whole hull form is needed to calculate BM and the weight distribution has to be known to calculate the center of gravity. Without knowing the hull form exactly only an indication of the stability can be given. With increasing load, not only the center of gravity changes, but also the draught of the ship changes which influences the KB and BM.

Although the calculations give an indication of the stability of the ship there is more to consider. In general stability is not a problem for ice strengthened vessels because of the additional steel weight at low centers of gravity. The stability calculations should be done for the ice capable vessel which has different properties.

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Chapter 3

Results and Improvements

All the results of the calculations and observations give results and improvements. The order of the sections is the same as of chapter 2. The criteria and methods of calculations can be found in that chapter.

3-1 Winterization

In this section the winterization issues will be addressed for the Damen concept vessels according to section 2-1.

PSV 3300

Figure 3-1 gives an indication of the factors that should be addressed when winterizing the vessel and should be considered with respect to heating, enclosing and other special measures. Also the layout of the engine room will change. Not only because more power is needed to operate in the Arctic, as stated in section 2-4, but also because of the extra systems for heating and control.

Since the superstructure is located in the front of the vessel and is mostly covered, limited adaptations are required. The superstructure gives protection against water spray that might accumulate as ice on the superstructure and work deck. Also the enclosure of the bow gives protection for the mooring and anchoring equipment so that icing is not a problem in the bow area.

The adaptions and changes with respect to winterization that should be made are relatively achievable. Especially the equipment should be designed to perform in the cold conditions which does not have a big impact on the basic design of the vessel.

AHTS 200

For the winterization of the AHTS 200 there is more to consider, as the AHTS 200 has more equipment outside. Figure 3-2 gives the additional factors that should be taken into account for the AHTS 200.

The cranes and winches have to operate under the most harsh conditions while not exposing the crew. This requires adjustments to the design. Although some winches are covered, they are not heated. The upper winch should also be covered to avoid icing and to create a more friendly work environment for the crew.

SSV 4711

For the SSV the same winterization issues apply as for the PSV 3300 and AHTS 200. The winterization of the SSV has to be more focused on the safety of the rescue operations. The rescue zones and operations have to be operable in all conditions.

The rescue boats should be covered when operating in icing conditions for fast and easy launching. It should be considered to place them after the bridge for a more clear view, since the covering might be too high. Also the winch area and the rescue zones should be easy and safe to access without any ice accretion. The gangways of the rescue zone can easily be covered to prevent the ice accretion.

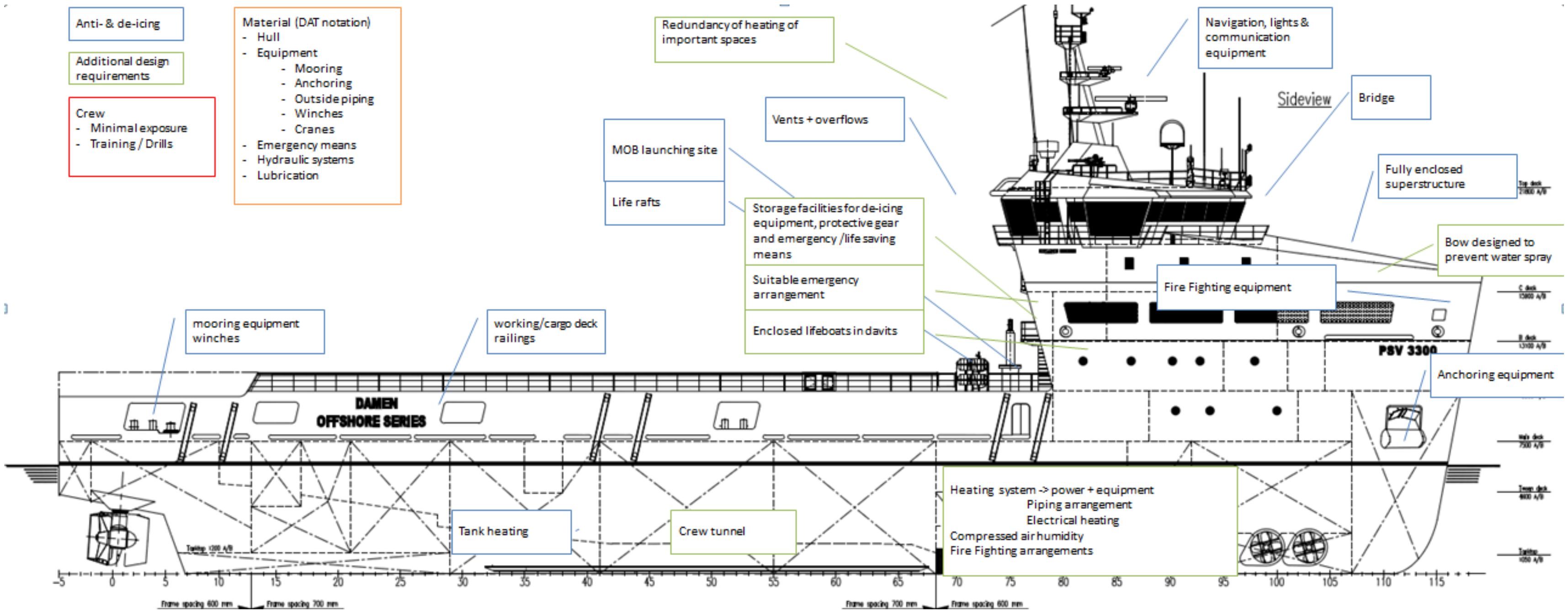

Figure 3-1: Winterizing specified for the PSV 3300

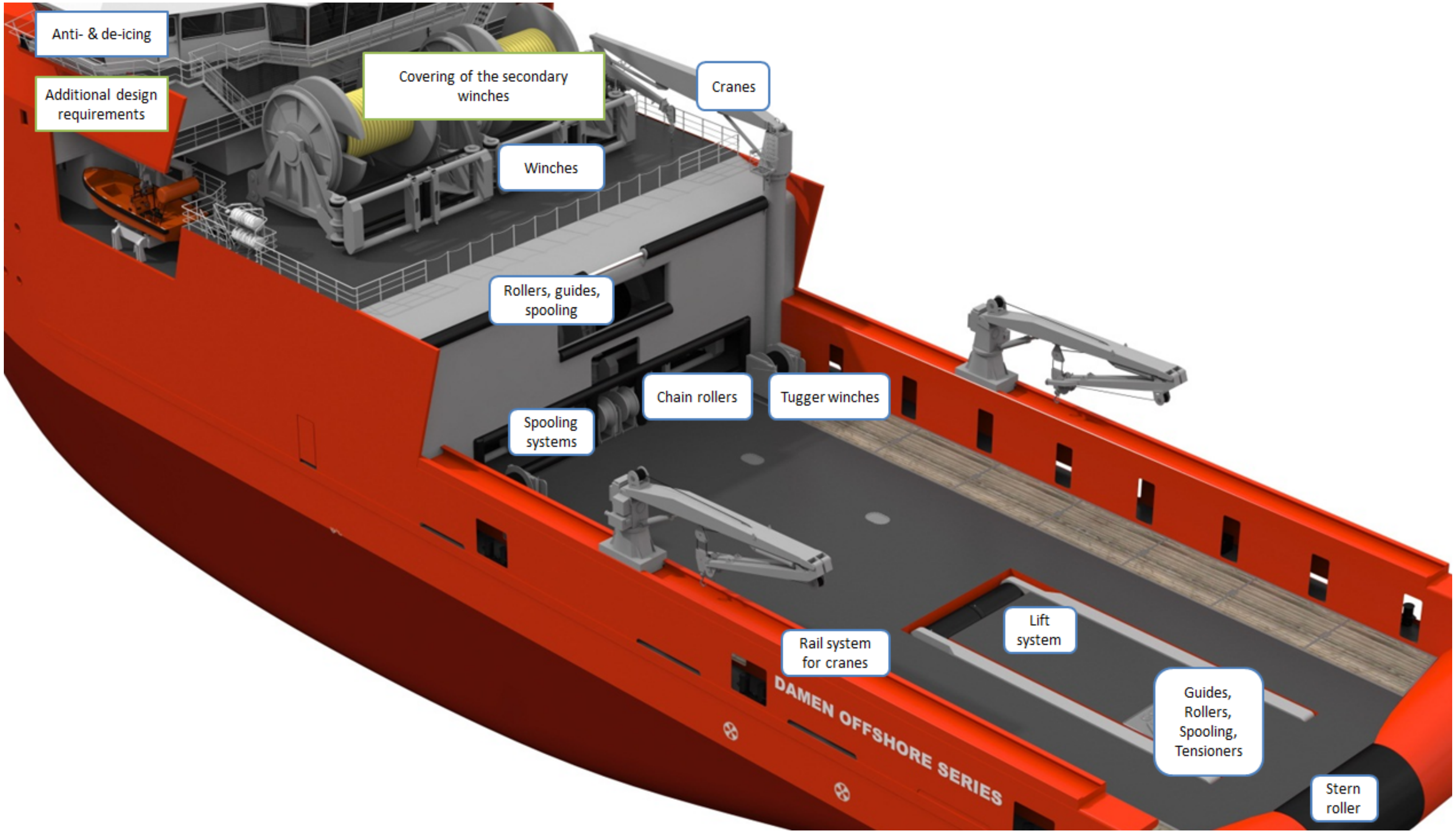

Figure 3-2: Winterizing aspects specified for the AHTS 200 in addition to the factors mentioned in figure 3-1

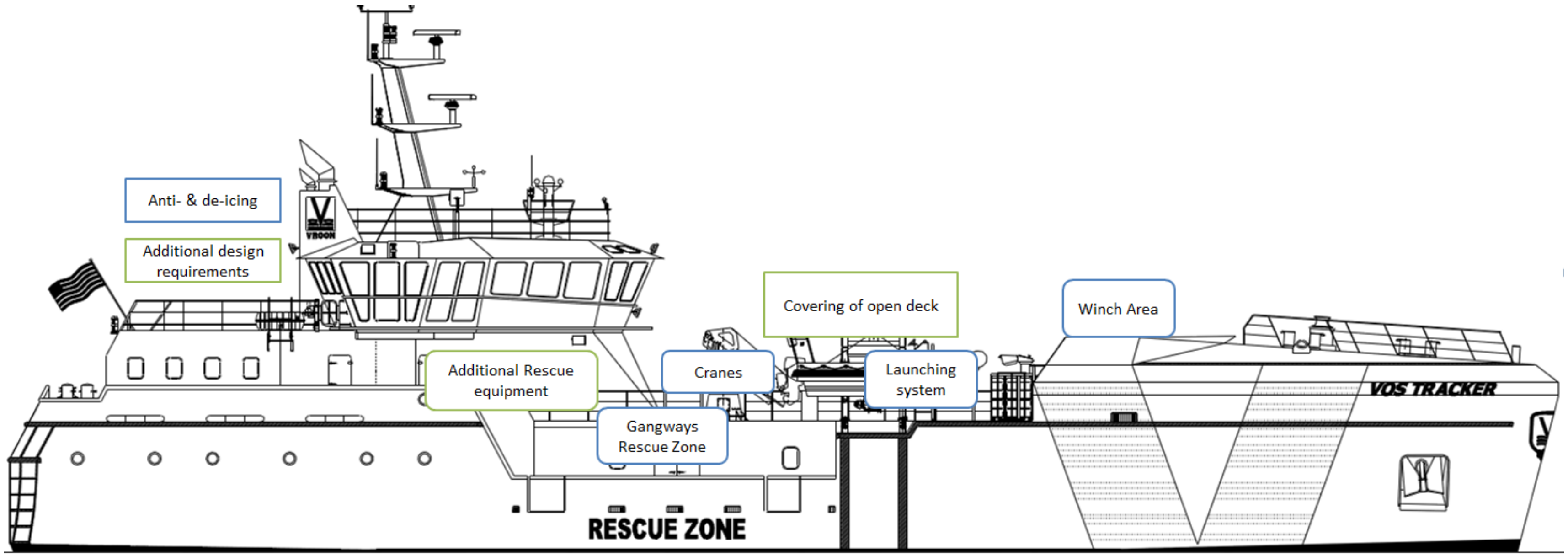

Figure 3-3: Winterizing aspects specified for the SSV 4711 in addition to the factors mentioned in figure 3-1

3-2 Resistance

For all three vessels the resistance is calculated with Lindqvist and Riska. However, it is not always possible to calculate the resistance with Lindqvist, as explained in section 2-3-2.

3-2-1 PSV 3300

Lindqvist is not suitable for the PSV 3300 because the bow angle is to high. As a result of this high angle the crushing component of formula 2-4 becomes $-3.96 \cdot 10^6\ kN$, which is unrealistic. The resistances from the Riska method with a velocity of 1, 2, 3, 4 and 5 kn and an ice thickness of 1.2 m, are given in table 3-1. The resistance at the target speed of 3 kn is therefore 1420 kN.

Table 3-1: Level ice Resistance of the PSV 3300 at different speeds according to Riska et al 1997 at 1.2 m level ice.

Parameter	v_1=1 kn v_1=0.51 m/s	v_2=2 kn v_2=1.03 m/s	v_3=3 kn v_3=1.54 m/s	v_4=4 kn v_4=2.06 m/s	v_5=5 kn v_5=2.57 m/s
R_i [kN]	1100	1260	1420	1580	1740

3-2-2 AHTS 200

The Lindqvist formula is not usable for the AHTS, as the combination of angles results in a negative crushing component. With the Riska formula, the resistance at 3 kn is 1980 kN, as shown in table 3-2.

Table 3-2: Level ice Resistance of the AHTS 200 at different speeds according to Riska et al 1997 at 1.2 m level ice.

Parameter	v_1=1 kn v_1=0.51 m/s	v_2=2 kn v_2=1.03 m/s	v_3=3 kn v_3=1.54 m/s	v_4=4 kn v_4=2.06 m/s	v_5=5 kn v_5=2.57 m/s
R_i [kN]	1560	1770	1980	2200	2410

3-2-3 SSV 4711

In table 3-3 the resistance of the SSV 4711 are listed at speeds of 1 - 5 kn. At the target speed of 3 kn the resistance is 950 kN. The Lindqvist formula gives no results, as the crushing component is negative. This vessel has the lowest resistance according to Riska, however, this is the smallest vessel and makes therefore the smallest channel.

3-3 Propulsion

Because a single power estimate is not very helpful, another ship is given which is also an AOSV. A ship which is operating in the Sub-Arctic is the Russian 'Vitus Bering'. This vessel

Table 3-3: Level ice Resistance of the SSV 4711 at different speeds according to Riska et al 1997 at 1.2 m level ice.

Parameter	v_1=1 kn v_1=0.51 m/s	v_2=2 kn v_2=1.03 m/s	v_3=3 kn v_3=1.54 m/s	v_4=4 kn v_4=2.06 m/s	v_5=5 kn v_5=2.57 m/s
R_i [kN]	700	830	950	1080	1200

has 13 MW installed propulsion power and a length of 99.9 m[1]. This ship is somewhat larger, but can be used as a reference for a rough estimate. This ship is designed for icebreaking and optimized for 1.2 m ice and 3 kn. The calculations are done in two different ways. The DNV and FSICR differ by a factor of three. As stated in section 2-4, the DNV formula is an emperical formula. The FSICR are based on the resistance estimation and is therefore taken to be more realistic.

Besides that, the engine output required for a 1C or 1A Super notation is far lower than the DNV and FSICR requirement. A reason for this is that both of these notations limit the ships to milder conditions. With the resistance based engine requirement a thust - velocity curve was plotted, as well as ice thickness - resistance lines. The intersection gives the speed at a certain ice thickness. An specific ice thickness - velocity plot is also given.

3-3-1 PSV 3300

The four propulsion power estimates are listed in table 3-4. Power based on FSICR and the required power for the operational profile is the highest and is far higher than the installed power on an even bigger ship, as stated in the introduction of this section. Figures 3-4 and 3-5 are the thrust - speed and ice thickness - speed curves.

Table 3-4: Minimum engine output of the PSV 3300 based on DNV, FSICR for target speed and ice thickness, FSICR 1C and 1A Super

Variable	Value
$P_{original}$	3,000 kW
P_{DNV}	9,430 kW
P_{FSICR}	32,142 kW
P_b 1C	1489 kW
P_b 1A*	5088 kW

Fuel rates

According to section 1-1-1 the operational profile with an estimation of the fuel consumption is given in table 3-6 together with the assumptions made.

As shown in table 3-6 the fuel consumption without adaptations of the ship will be 344% higher per nautical mile. The ice conditions are in this case only level ice with an average thickness of 0.4 m. This means that year around operations in this area of the Barents Sea

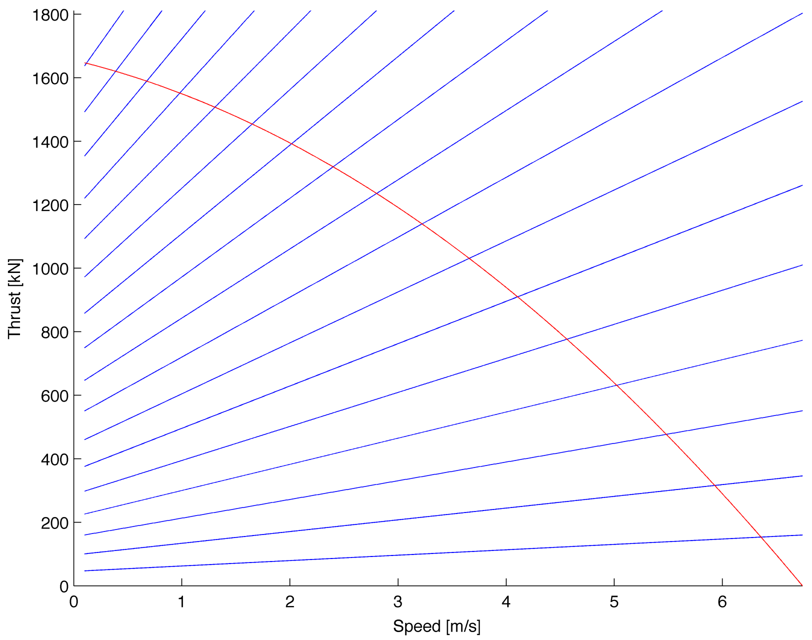

Figure 3-4: Thrust speed curve, with different ice thickness in steps of 0.1 m with an minimum engine output of 32.1 MW

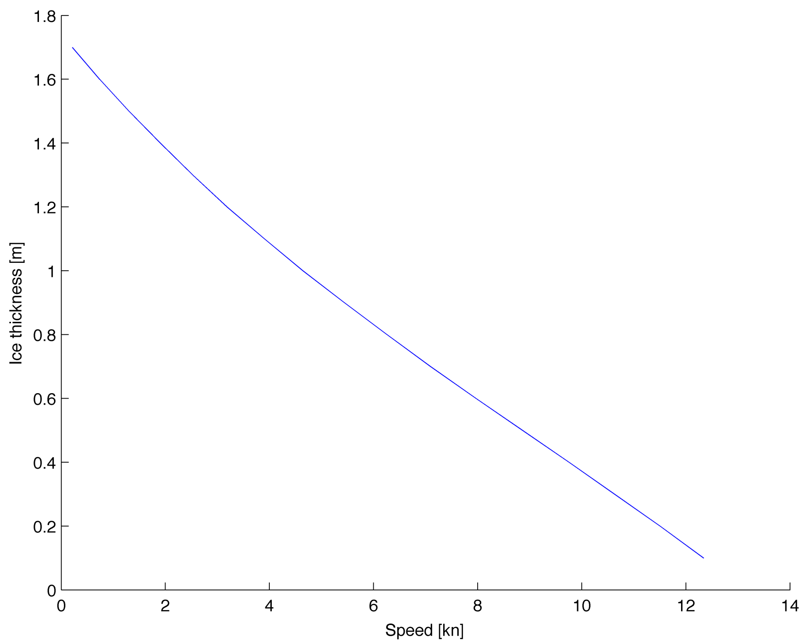

Figure 3-5: H-v curve with an minimum engine output of 32.1 MW

Barents Sea fictional operational profile

PSV 3300

Condition	Distance [nm]	Speed [kn]	Endurance [hr]	MCR [%]	Propulsion power [kW]	Auxilary power [%]	Total power [kW]	Average fuel rate [g/kW hr]	Fuel rate [tons/day]	Trip consumption [tons]	Trip average [tons/day]	Comparison Trips [tons/nm]	[%]
Harbour	-	-	34	20	600	200	1200	210	6.0	8.6			
Trip open water	746	12	62	90	2700	140	3780	210	19.1	49.3		0.066	**100%**
Trip to oil field in ice	194	3	65	100	3000	140	4200	210	21.2	57.1		0.294	**344%**
DP in ice	-	-	100	40	1200	250	3000	210	15.1	63.0			
Transit in ice			410	100	3000	140	4200	210	21.2	361.6			
		Subtotal	671						*Subtotal*	540	**19.3**		
			28.0 days										

Assumptions

Maximum ice thickness @ 100% MCR @ 3 kn: 0.35 m

The original maximum propulsion power of 3000 kW is used for this operational profile and determination of the maximum ice thickness

More auxiliary power in harbour and DP operations. In ice conditions and open water the percentage of auxiliary power is assumed the same although the usage is different

DP operations require more power for the bow thrusters, therefore the total power is assumed to be 250%

Average fuel rate is assumed to be constant in all conditions, the engines are mid-speed 4 stroke and have an assumed average consumption of 210 g/kW hr

The MCR rates are estimated based on the conditions, the MCR rate in level ice is maximal to indicate the maximum possible ice thickness @ 3 kn

The total endurance of the vessel is based on the original operational profile which is 28 days. The time in port, DP and transit is tuned to that

The auxilary power is estimated using a percentage of the propulsion power, which are based on the total installed power of the ship or on the estimated need of auxilary power.

Figure 3-6: Estimated operational profile with its fuel rates for the PSV 3300

are not possible, especially when facing ridges and multi year ice features. Also, the fuel cost and capacity is much higher.

3-3-2 AHTS 200

The AHTS 200 is the ship with high power requirements, to reach the high bollard pull, as stated in table 3-5. This is evident when the power is compared to the Vitus Bering, for instance. Figures 3-7 and 3-8 are the thrust - speed and ice thickness - speed curves.

Table 3-5: Minimum engine output of the AHTS 200 based on DNV, FSICR for target speed and ice thickness, FSICR 1C and 1A Super

Variable	Value
$P_{original}$	7,680 kW
P_{DNV}	13,210 kW
P_{FSICR}	30,284 kW
P_b 1C	1457 kW
P_b 1A*	4943 kW

Fuel rates

For the AHTS 200 the operational profile is different from the PSV 3300, see table 3-9. Therefore ship has more power installed to be able to perform the anchor handling operations. Because of this relatively high power the ship is capable of sailing through 0.8 meters ice according to Riska et al. The fuel capacity is not sufficient to sail through ice for an extended period.

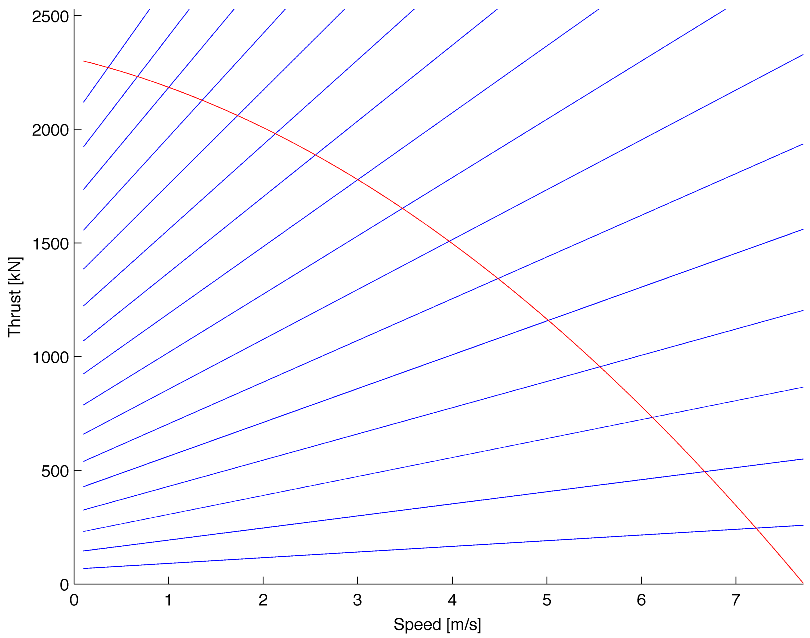

Figure 3-7: Thrust speed curve, with different ice thickness in steps of 0.1 m with an minimum engine output of 30.3 MW

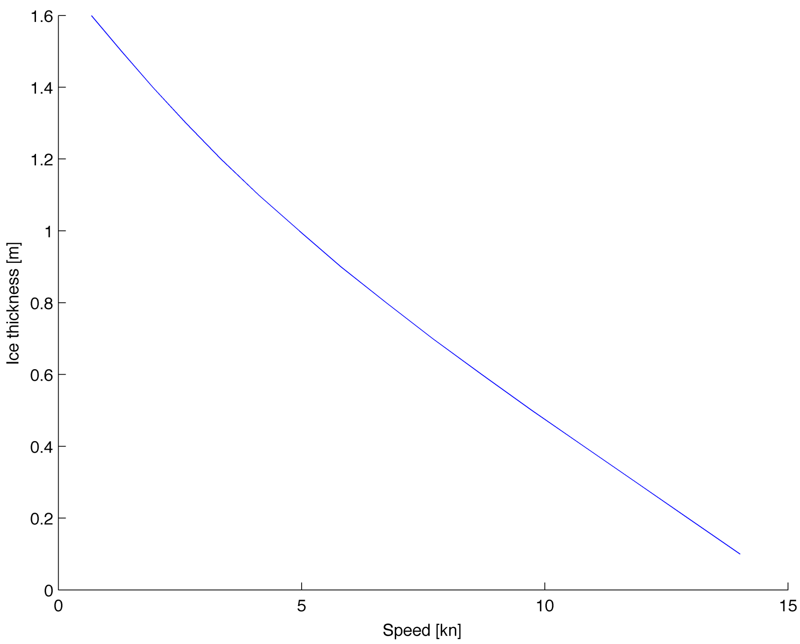

Figure 3-8: H-v curve with an minimum engine output of 30.3 MW

AHTS 200

Condition	Distance [nm]	Speed [kn]	Endurance [hr]	MCR [%]	Propulsion power [kW]	Auxilary Power[%]	Total power [kW]	Average fuel rate [g/kW hr]	Fuel rate [tons/day]	Trip consumption [tons]	Trip average [tons/day]	Comparison Trips [tons/nm]	[%]
Harbour	-	-	30	10	1210	200	2419	210	12.2	15.2			
Trip open water	746	11	68	40	4838	150	7258	210	36.6	103.4		0.139	**100%**
Trip to oil field in ice	194	3	65	100	12096	120	14515	210	73.2	197.5		1.016	**633%**
DP in ice	-	-	90	40	4838	150	7258	210	36.6	137.2			
Anchor Handling			80	70	8467	175	14818	211	75.0	250.1			
Transit in ice			140	100	12096	120	14515	210	73.2	426.7			
		Subtotal	473						*Subtotal*	1130	**57.4**		
			19.7 days										

Assumptions

Maximum ice thickness @ 100% MCR @ 3 kn: 0.8 m

The original maximum propulsion power of 12096 kW is used for this operational profile and determination of the maximum ice thickness

The MCR in open water is based on the resistance curve of the AHTS, given by DAMEN.

Installed power of the ship is in total: 14870 kW, of which 12096 kW propulsion power and 1430 auxilary power. Also 2400 kW by means of shaft generators.

The total endurance of the vessel is based on the original operational profile which is 20 days.

The percentage of total power vs propulsion power is different, but set so that the auxilary power for the 2 conditions is the same

For anchor handling the mean MCR is estimated. A some point full power will be needed. Also because of the ice conditions the average required power during achor handling will be higher.

Figure 3-9: Estimated operational profile with its fuel rates for the AHTS 200

3-3-3 SSV 4711

Compared to the other two vessels the SSV 4711 has the lowest power requirements, see table 3-6. The thrust - speed and ice thickness - speed curves are shown in figures 3-10 and 3-11.

Table 3-6: Minimum engine output of the SSV 4711 based on DNV, FSICR for target speed and ice thickness, FSICR 1C and 1A Super

Variable	Value
$P_{original}$	1,325 kW
P_{DNV}	6,610 kW
P_{FSICR}	25,128 kW
P_b 1C	1000 kW
P_b 1A*	2800 kW

With the engine requirement a net thrust curve was calculated. Riska was used to calculate ice resistance at different speeds and ice thickness. The results are plotted in a thrust - velocity curve in figure 3-10. The intersection between thrust and velocity gives the thickness - velocity curve in figure 3-11.

3-4 Double Acting Hull

In the last ten years there has been a lot of development in the double acting hull concept. The most important advantage is that the bow can be optimized for open water, and the stern for ice breaking. The change from a open water stern, to an ice breaking stern requires some adaptations. The type and the use of the propulsor is of even more importance[2]. In this subsection the three ships are discussed with respect to their stern ice breaking capabilities and recommendations are made.

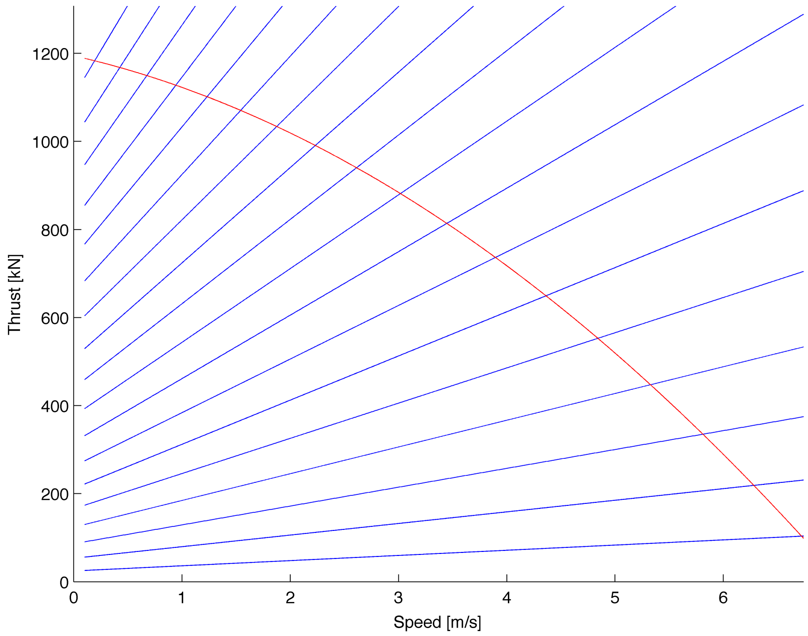

Figure 3-10: Thrust speed curve, with different ice thickness in steps of 0.1 m with an minimum engine output of 25.1 MW

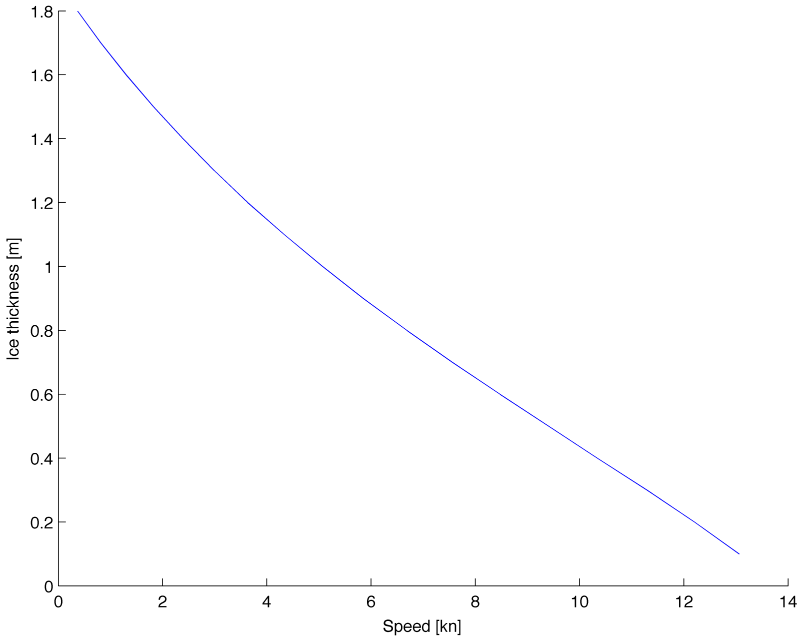

Figure 3-11: H-v curve with an minimum engine output of 25.1 MW

3-4-1 PSV 3300

For an ice breaking stern it is essential that the transom has a low angle of attack. When the angle is high, like in this vessel at both bow and stern, the ice will be crushed, instead of the more efficient bending, when sailing backwards [3]. By lengthening the stern of the vessel, as is shown in figure 3-12, the ice will be bended. Figure 3-12 is only a very rough indication of the adaption, the precise shape will not be discussed in this report.

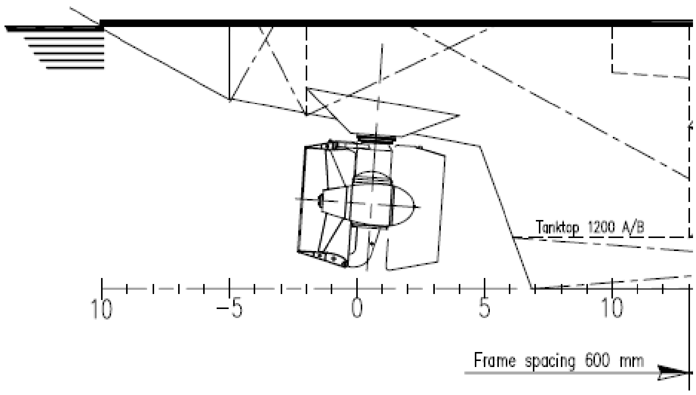

Figure 3-12: Adaption stern structure PSV 3300

An advantage of this ship is that it already has azimuthing thrusters [3]. This improves the maneuverability in ice, see report 1 [2]. Because there is a possibility that ice pieces will come close to and may even clog the propeller, high forces will act on the duct. When the duct is removed, the ship will perform better when sailing astern. Because all the adaptations are relatively small, it could be a good solution to adapt this vessel and let it sail through ice backwards. As shown in figure 3-13, the resistance in ice decreases by almost half, when using this adapted hull shape. With this calculation the effect of flushing was not taken into account, as well as the ice propulsor interaction. The outcome shows the effect of an decreased angle of attack, due to flushing and reduced ice friction the resistance sailing astern is even less than in this prediction. However at the moment no method is available for the prediction of ice resistance sailing astern through level ice.

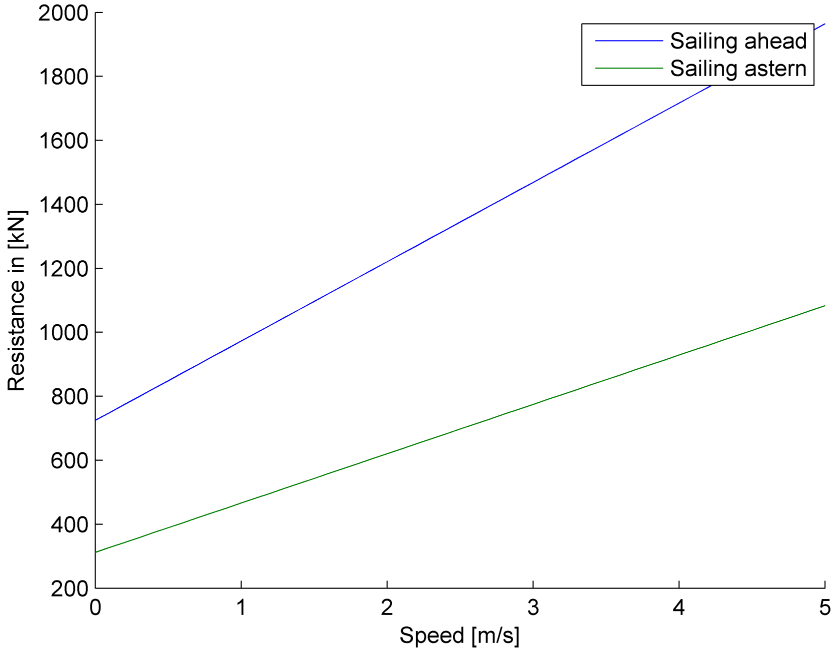

Figure 3-13: Results of stern adaption, stern angle at 30° and L at 81.80 m, as shown in figure 3-12. Calculations are done with Riska et al.

3-4-2 AHTS 200

As mentioned earlier, azimuthing propulsion is recommended when sailing astern through ice. This means that a major adaption, namely the change of the propulsion system, has to be made. Instead of the fixed axis and propeller with duct [4], an azimuth propeller is needed without a duct. This requires a whole new design of the stern. One of the problems is the stern roller [4], if this vessel is going to sail through ice backwards, the stern roller has to break the ice because it is located on the waterline. If it is placed higher, as shown in figure 3-14, the stern structure can be adapted to break ice. The stern roller has to be placed a little bit outside the vessel because otherwise the lines cannot reach the same angle as before. When the vessel sails into a ridge, the stern roller will receive high forces. A winterized stern roller should be capable of handling these forces. Because the propulsor, stern structure and stern roller have to be adapted, it could very expensive to give this vessel an Arctic refit.

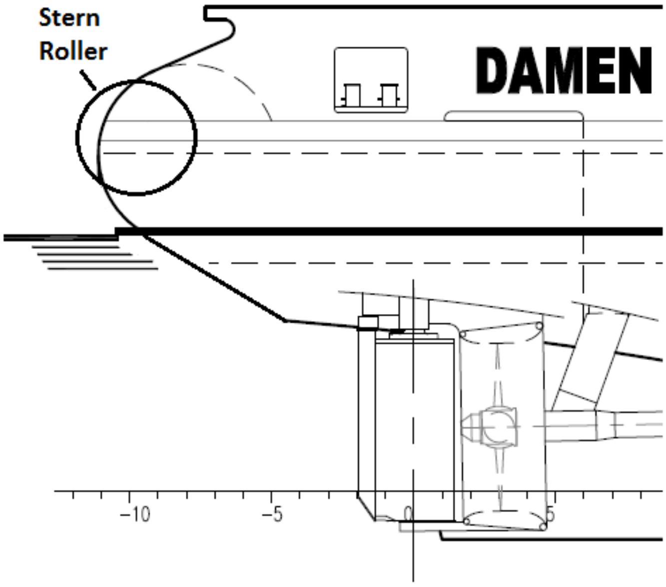

Figure 3-14: Adaption stern shape AHTS 200

3-4-3 SSV 4711

The shape of the aft is not optimal for sailing backwards through ice. One of the problems is the same as with the AHTS 200, the propulsor system has to be changed into an azimuthing thruster. Also the stern structure is not optimal, for example, the stern angle is to high and has to be adapted for bending the ice. In figure 3-15 a possible adaption is given. When using this shape, the vessel will be able to break the ice by bending. Because all these things have to be changed, it will be an expensive solution for this vessel to sail astern trough ice.

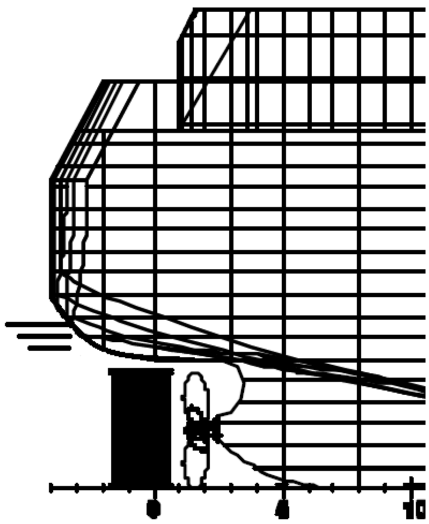

Figure 3-15: Adaption stern shape SSV 4711, additional azimuthing propulsor has to be fitted

3-5 Plate thickness

The plate thickness is calculated for four different ice classes. The FSICR 1C and 1A Super and the PC6 and PC4 of the UPCR are used. Ice class 1A Super should be comparable to the PC6. The results of the calculations are listed in the following subsections. It should be noted that these are the minimum required plate thickness and the real plate thickness needs to be rounded upwards to the next full or half integer. For all the vessels the plate thickness in the ice belt is shown.

3-5-1 PSV 3300

In table 3-7 the plate thickness in the ice belt in three regions bow, midship and stern are shown of the PSV 3300. The strange thing is that PC6 requires a thicker plate at midship than at the bow. This is due to a 117% larger frame span at the midship compared to the bow and the stern in this case.

Table 3-7: Required plate thickness at different ice classes for the PSV 3300

Ice class	Issuer	Bow [mm]	Midship [mm]	Stern [mm]
1C	FSICR	44.3	22.2	15.5
1A Super	FSICR	51.7	35.8	29.5
PC6	UPCR	41.1	46.5	38.6
PC4	UPCR	78.4	66.8	60.9

3-5-2 AHTS 200

Table 3-8 displays the plate thickness that are calculated for the AHTS 200. With the exception of PC4, the strengthening is less in the aft. The reason that this is different with PC4, might be that the ship requires extra strength when turning the vessel. This puts an extra strain on the aft.

Table 3-8: Required plate thickness at different ice classes for the AHTS 200

Ice class	Issuer	Bow [mm]	Midship [mm]	Stern [mm]
1C	FSICR	49.9	23.3	17.1
1A Super	FSICR	58.7	37.8	33.0
PC6	UPCR	46.8	43.1	40.8
PC4	UPCR	83.2	62.0	64.6

3-5-3 SSV 4711

The plate thicknesses of the SSV 4711 are shown in table 3-9. This ship is the smallest of the three and requires far less strengthening, because the ice loads are lower. This is because the mass and velocity are lower.

Table 3-9: Required plate thickness at different ice classes for the SSV 4711

Ice class	Issuer	Bow [mm]	Midship [mm]	Stern [mm]
1C	FSICR	29.7	16.7	11.8
1A Super	FSICR	34.6	26.7	22.0
PC6	UPCR	40.5	32.5	27.5
PC4	UPCR	56.2	47.2	43.7

3-6 Stability

This section gives the calculations and considerations of section 2-6 applied to the Damen concept ships. Only for the AHTS 200 more detailed calculations were made, which are assumed representative for the two other vessels.

The icing rate is dependent on the conditions in the operation area. Icing mainly occurs during sailing in open water with freezing temperatures, because of spray in high sea states. Shown in table 3-10 the constants are assumed to represent the conditions in the open water season for the areas of operation. This gives $PR = 115$ °Cm/s and IR = 9.9 cm/h accordingly.

Table 3-10: Constants for ice accretion prediction

Constant	Value	Unit	Definition
V_a	25	m/s	wind speed
T_f	-1.7	°C	temperature of saline ice at freezing point
T_w	3	°C	temperature of seawater
T_a	-15	°C	air temperature
ρ_i	920	kg/m^3	density of the ice accretion

3-6-1 PSV 3300

The area where ice accretion is likely to occur is estimated as shown in table 3-11 by means of the General Arrangement.

Table 3-11: Ice accretion variables for PSV 3300

	Area [m^2]	CG [m]	factor
Superstructure	300	20	1
Deck	850	8	0.5

However, the superstructure protects the deck area from ice accretion and will therefore not be considered completely, but only half. Therefore the total area of ice accretion is assumed to be 725 m^2, according to table 3-11. This gives the weight rate $W_i = 66$ ton/h with $CG = 13$ m.

3-6-2 AHTS 200

On this ship the superstructure is also located in the front of the vessel and therefore the same estimation method will be used as for the PSV 3300. The equipment on the C-deck is assumed to be protected by the superstructure. A factor of 0.3 is assumed for the exposed area.

Table 3-12: Ice accretion variables for AHTS 200

	Area [m^2]	CG [m]	factor
Superstructure	520	24	1
Deck	450	9	0.5
Exposed C-deck	100	19	0.3

The total area of ice accretion is assumed to be 775 m^2, according to table 3-12. This gives the weight rate $W_i = 70$ ton/h with $CG = 19.5$ m.

For this vessel some information was available to give an indication of the stability. The displacement, KB, BM and KG were known for a certain loading condition. The new KG is calculated using

$$KG_i = \frac{KG \cdot D + W_i \cdot i \cdot CG}{D + W_i \cdot i}$$

From this the new GM follows with

$$GM_i = KB + BM - KG_i$$

The result is given in figure 3-16.

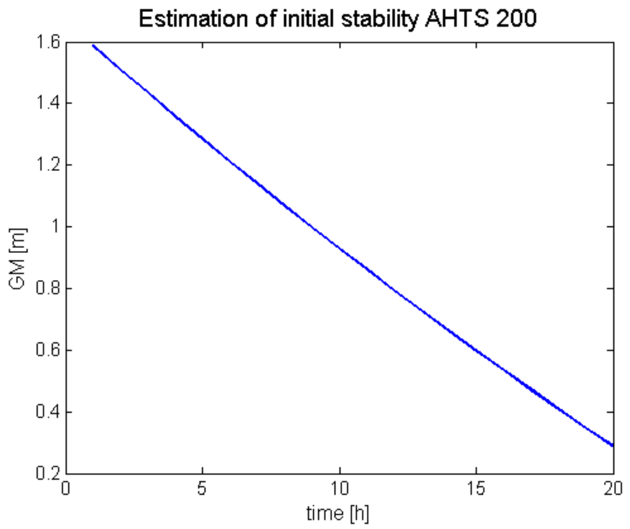

Figure 3-16: Estimation of initial stability of the AHTS 200

This stability calculation is further simplified, in addition to the assumptions made in section 2-6, by assuming that KB and BM do not change during the ice loading. In fact the ship will have more stability than indicated by figure 3-16. The draught will be higher due to the mass of the icing. This results in a higher KB and because of the increased waterplane, which gives a higher moment of inertia, BM will also be higher.

Figure 3-16 is obtained by calculating the KG values which give: GM_i = KB + BM - KG_i where i = hours of icing according to the icing rate IR. As shown the ship can safely sail about 15 hours in extreme icing conditions. At that time the icing has accumulated to about 15 hours · 9.9 cm/h ≈ 1.5 meter which is very unlikely to occur on all surfaces even in a longer period. The vessel is capable of taking the additional load with respect to stability.

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As result of the size of the ship and the low superstructure the whole ship can be subject to ice accretion. The area of ice accretion is assumed to be 340 m^2 based upon the dimensions of the vessel and a factor of 0.8 of the area of the decks which is sensitive to ice accretion. The mean is estimated as CG = 12 m.

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Chapter 4

Conclusions and Recommendations

This chapter is intended to satisfy the goal of this report, to show how the three Damen vessels hold themselves against the rules and requirements for the Arctic. This is done by using rules and guidelines that are already in effect and looking into the near future. All results of the resistance and propulsion calculations, together with detailed recommendations of winterization and double acting hull considerations, are to be found in chapter 3.

4-1 Conclusions

In this section the main conclusions are listed per subject. The conclusions are based on the design of the Damen vessels, the literature research and the calculations in this report.

Winterization The winterization issues outlined in this report are meant to ensure safe operations for the ship and crew in Arctic conditions by means of de- and anti-icing methods, additional design requirements, materials and procedures. The ship specific recommendations are given in section 3-1. Without these adaptations the ships are not able to perform safe and efficient in cold environments.

Resistance All three ships have approximately the same bow form, which is highly efficient in open water. This bow form gives relatively high ice resistance, the ice breaks more by means of crushing instead of bending. This leads to high pressures at the bow and is reflected in a high power requirement and a greatly dimensioned structure. The double acting hull concept gives a lower resistance, however, adaptations have to be made for that.

There is however another problem. The emperical formulas used are not suitable for ships with such a high bow angle. The Lindqvist formula gives no realistic results. Besides that the ice is not uniform and very much dependent on weather conditions.

Propulsion As stated above the high resistance in ice leads to an great propulsion power, as the power requirement is based on it. It can be argued that this power requirement is realistic. However, it gives a rough estimate of the magnitude. The reasoning is applicable for the double acting hull. Besides the formulas by Lindqvist and Riska there are no methods of determining the resistance and required power. However, an estimation with Riska shows that the power requirement is less than halve.

Structure Plate thickness dependents, among others, on the engine output and the shape and size of the hull. When using the stern as bow with the double acting hull concept, extra strengthening should be applied in the stern, to ensure safe operation.

Stability The possibility of ice accretion gives also considerations about the stability of the vessels. In extreme icing conditions the vessels are still complying with the stability rules. Moreover, vessels designed for the Arctic will have a higher GM because of the weight of the ice strengthening.

4-2 Recommendation

The recommendations are listed below and follow from the calculations and the literature research.

- The superstructures that are currently in place should be maintained as they provide shelter and withstands icing well.
- Heating should be applied to all ships to prevent icing and improve workability.
- Any other winterization and crew related recommendations and requirements should be met at all times to ensure safe operation.
- The hull is not able to perform well in ice. An adaption of the stern would be to enable the vessels to sail astern through ice.
- A completely different hull shape optimized for performance in ice will lower the structural requirements and is therefore recommended.
- Azimuthing propulsion should be installed to enhance flushing and milling capabilities and allow the vessel to penetrate ridges.
- The stability of all ships is good and should be maintained by keeping the general layout.
- In general, further research on the following topics is required: winterization measures, crew conditions in the Arctic, ice resistance determination, propulsion - ice interaction, required strength of the ship, stability while breaking ice.
- Operating in the Arctic has large implications on the entire design of the ship. Therefore the ship should be designed for the Arctic from the start, especially with the higher ice classes.

Appendix A

Assumptions

In this appendix the assumptions made are listed that have been made for all vessels.

1. Frame spacing, frame span and framing
   The frame spacing, frame span and framing remain the same for the ice class ship, for comparison purposes. The values from the specifications of the vessel are used. When designing an ice strenghtened vessel also the frame spacings should be adjusted to have a more optimal structure.

2. Different ice classes
   The only thing that changes for different ice classifications are the corresponding parameters which are depending on the ice class, the complete vessel remains the same, for comparison purposes.

3. R_{CH} is ice resistance
   We define R_{CH} as the ice resistance in level ice without the open water resistance. The open water resistance R_{ow} is assumed to be about 1 to 5 % of the total ice resistance R_T [1, p. 35].

4. R_i is linear
   It is assumed that the ice resistance is linear depending on the ship velocity. This is a common approach, among others used by Riska et al. Therefore it is also assumed that R_{CH} is linear.

5. Volume, dead weight and size of the vessel
   The volume, dead weight and size of the vessel remains the same throughout the comparison, even though an increase in structural strength increases the weight of the structure. In general, weight effects are not taken into account in the calculation part of this report.

6. Angles are manually measured
   All required angles were manually measured from the lines drawing at can therefore contain uncertainties.

7. A_{wf} is estimated
   The bow area is estimated on the lines drawing without using intergration method and is therefore uncertain but assumed to be correct.

8. Effective protection, framing support ans structure
   The plate thickness is calculated only for the shell of the vessel, the vessel has no effective protection against ice [2, p. 116 | Table H1] and that there is "one simple support outside the ice-strengthened areas" [2, p. 104] in place.

9. Boundary condition m_o
   The boundary condition m_o of the FSICR is taken as 5 for all vessels according to figure A-1. This is a conservative assumption, but makes results comparable.

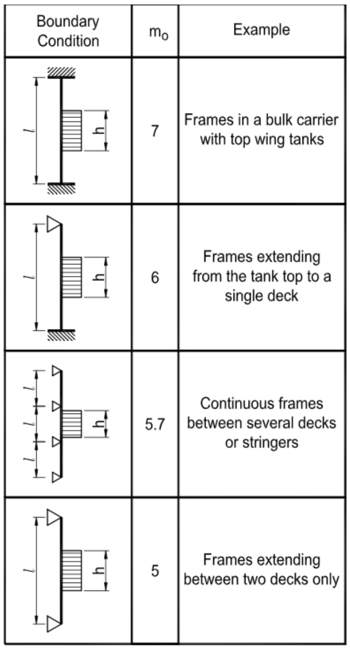

Figure A-1: Determination of the boundary condition m_o in the FSICR, adapted from [3, Sec. 4.4.2.1]

10. Effective frame span
    The effective frames span is taken as the frame span. This is an conservative assumption, but makes results comparable.

11. Propeller type and number of propeller
    The propeller type and the number of propeller are assumed to be the same for the original concept and the concept in ice.

12. Engine Output used for net thrust and ice thickness curve
    The maximum of the engine output according to FSICR and the engine output according to DNV is used for the calculation of the thrust-velocity and ice thickness-velocity curves.

13. Significance of ice thickness curve
For the calculation of the ice thickness-velocities curve ice thickness the significance of the ice thickness is taken as 0.1 m and for the speed 0.01 m/s. For all speed and ice thickness combinations the thrust and resistance are calculated.

14. Ice parameters are constant
It is assumed that the the following ice parameters are constant: ice thickness, bending strength, nominal ice pressure, density of ice and friction coefficient.

15. Global parameters are constant
It is assumed that the density of sea water, the standard gravity and the yield strength of steel are constant.

16. Transmission efficiency
The transmission efficiency η_{trm} for the vessels under consideration is assumed to be 0.9.

17. Speed of the vessel
The speed of 3 knots at 1.2 m level ice is a realistic speed for an Arctic Offshore Support Vessel. It is referred to in this report as target speed and target ice thickness.

18. Fuel consumption
The average fuel rate is assumed to be 210 g/kW hr which is representative for mid-speed 4 stroke diesel engines [4]The comparison between open water and ice conditions related to the fuel rates is based on the propulsion calculations with the original hull forms. The fuel rates are assumed to give a good indication of the magnitude of extra fuel consumption. More assumptions about this are to be found in tables 3-6 and 3-9.

19. Stability calculations
KB and BM are assumed to be constant with increasing ice accretion to give an indication of the stability by means of the GM. Only KG varies due to the changing load of the ice accretion.

20. Ice accretion
The used extreme ice accretion for the stability indications is assumed to be constant over time.

21. Ship area sensitive for ice accretion
The estimated areas with their centers of gravity and weight factors are assumed to represent the average area that is sensitive for ice accretion.

22. Winterization
The mentioned winterization issues are assumed to give a good indication of the factors that should be adjusted when designing for the Arctic.

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Appendix B

General Parameters of MT Varzuga (Uikku)

In this appendix the general parameters of the ice class 1 A Super tanker are shown in table B-1.

Table B-1: General Parameters of MT Varzuga (Uikku), adapted from [1, p. 61]

Parameter	Unit	Value
DWT	[ton]	15954
α	[deg]	24
ϕ_1	[deg]	29
ϕ_2	[deg]	29
L	[m]	150
B	[m]	21.5
T	[m]	9.5
L_{bow}	[m]	32.4
L_{par}	[m]	77
A_{wf}	$[m^2]$	490
D_p	[m]	5,45
Propeller	no	1
Propeller	type	CP
P	[kW]	11470

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Table B-2: Values for different situations, that were used in the comparison between Lindqvist and Riska

Situation	Ice Friction [-]	Bending strength [kPa]	Velocity [m/s]	Ice thickness [m]
1	0.15	780	1	1
2	0.05	780	1	1
3	0.15	390	1	1
4	0.15	780	5	1
5	0.15	780	1.54	1
6	0.15	780	1.54	1.2
7	0.1	780	1.54	1.2
8	0.1	550	1.54	1.2