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# Validation of the New Risk Based Design Approaches (POLARIS) for Arctic and Antarctic Operations

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## ABSTRACT

Selection of suitable ice class for ships operation is an important but not simple task. The process of selecting an appropriate ice class is of high importance both from a safety as well as an economical perspective, but the selection process is still based on accumulated experience and traditions within the areas of existing operations. The increased exploitation of the Polar waters, both seasonal periods and geographical areas, as well as the introduction of new international design standards such as Polar Code, reduces the relevancy of using existing experience as basis for the selection, and new methods and knowledge have to be developed. This paper will critically review the current knowledge of applying risk based design methodologies for ice covered waters. To illustrate the current best practice, the new polar code and especially the new Polar Operational Limit Assessment Risk Indexing System (POLARIS) is applied for two vessels: one navigating independently in the Antarctica (SA Agulhas II) and one navigating with icebreaker assistance on the Kara Sea on the Russian Arctic (MT Uikku) to evaluate the suitable ice class for these waters. It is found the PC 3 is the most suitable ice class for ships navigating in harsh Antarctic ice conditions and PC 6 is enough behind an icebreaker on the Kara Sea during hard winter conditions.

KEY WORDS Polar Code, Ice load, Full-scale measurements

## INTRODUCTION

The increased activity in the Arctic involves hazards such as harsh environment, especially the ice cover and cold temperature, remoteness and lack of infrastructure, lack of information about bathymetry, among others. Ice cover is also highly variable and dynamic with increasing variation in future as due to the changing effects of the world climate, also ice conditions on all ice-covered areas are under dynamic change. This effect on Arctic operations is a complicated task to solve. The remoteness of the Arctic areas means that in case of an accident, the search and rescue (SAR) capability is low. Also the fairways are not marked very extensively and especially the soundings taken for charting are relatively scarce. These Arctic hazards are compounded by the fact that the rate of recovery of the Arctic nature is slow, meaning that environmental hazards are made more serious.

The scope of this paper is first to shortly review the present knowledge for risk based ship design (RBSD) for ice conditions as RBSD is the current trend also in the other maritime activities. In addition, the current best practice is described by analyzing the functionality of the proposed POLARIS through comparison of the risk index output with some full-scale observations onboard SA Agulhas II in Antarctica and onboard MT Uikku on Russian Arctic. The International Maritime Organization (IMO) has been developing a mandatory International Code of Safety for Ships Operating in Polar Waters (Polar Code), which will come into force on 1st January 2017. The guidance is planned to include an example of an acceptable methodology for assessing operational capabilities and limitations for ships operating in ice, the so called Polar Operational Limit Assessment Risk Indexing System (POLARIS). POLARIS provides a standard approach for the evaluation of risks to the ship and the ice conditions encountered/expected (ice regime).

## RISK BASED DESIGN FOR ICE CONDITIONS

### Arctic shipping and accident statistics

There is a long history of Arctic marine transport and year round navigation has been maintained since 1978-1979 in the ice-covered western regions of the Northern Sea Route (between the port of Dudinka on the Yenisei River and Murmansk), see e.g. AMSA (2009). Arctic transport today is destinational, conducted for community re-supply, marine tourism and moving natural resources out of the Arctic. Still, due to the limited amount of traffic, the accident statistics form the Arctic activities are rare

Kubat and Timco (2003) compiled and analyzed a database of ship damage in the Canadian Arctic for the period between 1978 and 2002. Marchenko's (2012) book on the Russian Arctic waters goes into some detail regarding accidents in the Arctic seas bordering Russia. Her coverage is fairly comprehensive as she provides details on accidents since 1900 up until the early 1990's, when the volume of Arctic traffic in Russian waters dropped off dramatically due to the collapse of the Soviet Union.

As part of the Arctic Council's Arctic Marine Shipping Assessment (AMSA) 2009 Report, a database of a summary of the incidents and accidents occurring in the Arctic region between 1995-2004 was developed from several other existing data sets. While this data set is one of the more comprehensive available, it does not include any incidents that occurred in Russian waters, which is unfortunate.

The challenge with all this type of damage databases is that they are not detail enough to evaluate the sequence of events causing the accidents and therefore they cannot be easily applied in the development of proper risk based design methodologies. In the development of the Finnish-Swedish ice class for the Baltic Sea, damage statistics have played an important role and there exist extensive data bases starting from the early work of Johansson (1967) and continuing by Kujala (1991) and Hänninen (2004). There is a lot of useful information about possible damages for ships in ice.

### Present ice class approaches

Ice class rules are based on the long term experience of navigation in ice in various sea areas and typically the used design scenarios are not clearly specified. The most obvious definition of the design scenario is given for the IACS Unified Requirements for Polar Class Ships (IACS

UR I.1-3), in which a glancing impact between ship and ice is used. This is based on the original theory developed by Popov et al. (1967) and developed further by Daley (1999) assuming that the ship kinetic energy is spent for ice crushing when a ship hits ice edge on a glancing impact. The scantling formulae are set with the use of plastic limit state equations for plating and frames (Daley et al. 2001, Kendrik 2015).

For other relevant Arctic ice class rules such as Canadian ASPPR (Carter et al., 1992) and Russian rules (RMRS, 2010), the design scenarios are not so clearly illustrated. Both are using so called ice numerals to relate the required ice class with the prevailing ice conditions, which are based mainly on the long term experience of navigation in ice in these waters. For Finnish-Swedish ice class the design scenario can be described as hitting the ice edge with level ice thickness of about 1.0 m for ice class IA Super and this is decreasing down to 0.4 m for ice lass IC even though there is still a remarkable uncertainty which ship-ice interaction scenario causes the highest loads, (Riska et al., 2012).

## Challenges to apply risk based ship design for ships in ice

The risk based design for ice-going ships have not been extensively studied. The main challenges are related to the definition of the ice environment and the ship-ice interaction on this varying environment (Kujala et al., 2019). Unfortunately, the ice environment is a complicated obstacle to define properly. When comparing ice environment to open water, in which typically only two parameters are needed i.e. the wave height and period, it is far more complex as ice can have various forms and typically at least the following parameters are needed to describe it: level ice thickness, floe size, ice concentration, amount of rafted or ridge ice, frequency and height of ridges, amount of compression in the ice field. In addition, ice field are very dynamic and changes on the ice cover characteristics can happen rapidly e.g. due to the wind and currents. In addition, ice can be first, second or multiyear ice, which will have large impact on the strength properties of ice as well as on the possible thickness of ice.

Ship-ice interaction has been under extensive research at least during the last 50 years. Russian scientists made the pioneering work as was summarised by Popov et al. (1967). A number of fundamental theoretical approaches were developed both to analyse the ship-ice contact and the possible highest loads occurring using the energy approach i.e. assuming that the ship kinetic energy is spent in ice crushing and changes in the kinetic and potential energy of the vessel hitting the ice edge. After that there have been a lot research trying to observe and model the ship-ice contact as summarised e.g. by (Enkvist et al., 1979, Daley et al., 1990, Jordaan et al. 1993, Kendrick et al., 2011). Typically this research can consists of laboratory measurements of ice failure, full-scale field tests of ice failure or full-scale measurements of ice induced pressure contact or local loads on board various ships. Unfortunately still the knowledge of the variation of the contact on the ship hull and this relation to the ice induced loads in various ice conditions and operation situations is limited to form a good basis for the risk based design. Due to this complexity, no sound and reliable approach to evaluate the risks exists and the few existing approaches to evaluate risks are summarized next.

Daley and Ferregut (1989) presented a model of structural risk for ice going ships, called ASPEN (Arctic Shipping Probability Evaluation Network). The ASPEN model used a cell grid map of the arctic, with ice statistics in each cell for each month. A user would specify a route in terms of cells (and month). The model calculated the encounter-detection-avoidance-impact damage probabilities using a set of probability algorithms. The program could evaluate the sensitivities of aspects such as route selection, detection strategies, and structural capacity. Buzuev and Fedyakov (1997) examined the reliability and risk of shipping in ice along the northern sea route (NSR) in Russia. The focus was more about transportation reliability than structural risks, though both rely on similar models of ice conditions. Loughnane et.al (1995) examined the risks for an arctic oil tanker with a focus on oil spill risks and mitigation costs and strategies.

More recently there have been studies related to the probabilistic analysis of the ship ramming through an Arctic ice field (Ralph and Jordaan, 2013), analysis of the probability of a ship to get stuck in ice (Montewka et al., 2015) and risk analysis of the winter navigation system of Finland (Valdez et al., 2015, Goerlandt el., 2016). The best present practice for the risk based design is the new POLARIS system as part of the new Polar Code and therefore this is presented next with two practical examples how to apply it.

## DESCRIPTION OF THE POLARIS APPROACH

POLARIS uses a Risk Index Outcome (RIO) value to assess limitations for operation in ice (MSC. 1/Circ 1519, 2016). Risk Index Values (RIVs) are assigned to the ship based on ice class. For each ice regime encountered the Risk Index Values are used to determine a RIO that forms the basis of the decision to operate or limitation for operation. The RIO is determined by a summation of the RIVs for each ice type present in the ice regime multiplied by its concentration (expressed in tenths):

$$RIO = (C_1 RIV_1) + (C_2 RIV_2) + (C_n RIV_n) \quad (1)$$

where C1…Cn are the concentrations (in tenths) of ice types within the ice regime and RIV1…RIVn are the Risk Index values corresponding to the ships ice class, Table 1.

Table 1. Risk index values (RIV) for various ice classes, winter conditions

| Ice Class | Ice Free | New Ice | Grey Ice | Grey White Ice | Thin First Year Ice, 1st Stage | Thin First Year Ice, 2nd Stage | Medium First Year Ice, less than 1 m thick | Medium First Year Ice | Thcik First Year Ice | Second Year Ice | Light Multi Year Ice, less than 2.5 m thick | Heavy Multi year Ice |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PC1 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| PC2 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 0 |
| PC3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 0 | -1 |
| PC4 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 0 | -1 | -2 |
| PC5 | 3 | 3 | 3 | 3 | 2 | 2 | 1 | 1 | 0 | -1 | -2 | -2 |
| PC6 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 0 | -1 | -2 | -3 | -3 |
| PC7 | 3 | 2 | 2 | 2 | 1 | 1 | 0 | -1 | -2 | -3 | -3 | -3 |
| IA Super | 3 | 2 | 2 | 2 | 2 | 1 | 0 | -1 | -2 | -3 | -4 | -4 |
| IA | 3 | 2 | 2 | 2 | 1 | 0 | -1 | -2 | -3 | -4 | -5 | -5 |
| IB | 3 | 2 | 2 | 1 | 0 | -1 | -2 | -3 | -4 | -5 | -6 | -6 |
| IC | 3 | 2 | 1 | 0 | -1 | -2 | -3 | -4 | -5 | -6 | -7 | -8 |
| No ice class | 3 | 1 | 0 | -1 | -2 | -3 | -4 | -5 | -6 | -7 | -8 | -8 |

The operational limitations for ships operating independently are based on the evaluation criteria so that the RIO should be positive to indicate normal operations and when the value of RIO is below 0 but higher than -10, limited speed requirements is established for various ice classes of PC1 to PC,  for other ice classes operations in ice should be avoided for voyage planning purposes when RIO is negative. For ships under escort by an icebreaker where the track created by the icebreaker(s) is wider than the beam of the ship under escort operational limitations are basically based on the ice conditions on the channel behind an icebreaker. For voyage planning purposes when ice-breaker is intended to be used, the RIO derived from non-escorted historical ice data may be assumed to be modified by adding 10 to its calculated value, given that due caution of the Mariner will be exercised, taking into account such factors as changes in weather and visibility.

## SHORT DESCRIPTION OF THE FULL-SCALE MEASUREMENTS

### Ship particulars

The POLARSIS approach is validated next by comparing this approach with the full-scale observations onboard two vessels: Research vessel SA Agulhas II in Antarctica and tanker Uikku in the Russian Arctic. Table 2 summarises the main characteristics of the vessels and Fig.1 illustrates the ships.

Table 2. Main particulars of SA Agulhas II and MT Uikku

| | SA Agulhas II | MT Uikku |
|---|---|---|
| Length, $L_{pp}$ (m) | 121,8 | 150 |
| Breadth  (m) | 21,7 | 22,2 |
| Draught (m) | 7,65 | 9,5 |
| Deadweight (t) | 5000 | 15748 |
| Displacement (t) | 13632 | 22654 |
| Speed (kn) | 14 | 17 |
| Propulsion power (MW) | 9 | 11,4 |

### Instrumentation

PSRV S.A. Agulhas II was built in STX Finland in Rauma into the Polar ice class PC5 and the hull was constructed in accordance with DNV ICE-10. Three areas of the starboard side of the hull were instrumented with strain gauges when she was under construction in 2011/2012. The upper and lower parts of the frame were instrumented with V-shaped strain gauges, which measured the shear strains occurring in the frame. The instrumentation consists of two, three and four adjacent frames at the bow, bow shoulder and stern shoulder respectively. In addition, the hull plating was instrumented with strain gauges in these areas. See Suominen et al. (2013) for more detailed description of the instrumentation.

MT Uikku is classified by DNV for class +1 A 1 Tanker for Oil, and by Finnish Board of Navigation to ice class 1 A Super. Ship was built 1976 in Werft Nobiskrug Gmbh, and Helsinki New Shipyard rebuilt Azipod conversion 1993. Ship has a diesel electric propulsion system with four diesel generators. The ship hull and propulsion system was instrumented on 1997 for the EU funded ARCDEV project and the instrumentation was extensive including: load on the shell transverse frame at bow area, at bow shoulder area, at midship area and at aftship area (measured by shear strain gauges), load on the shell longitudinal frames at midship area (measured by shear strain gauges), stresses on the shell plating and frames at waterline at bow area, at bow shoulder area, at midship area and at aftship area, the longitudinal bending stresses on deck and vertical accelerations at the bow and stern of the ship and longitudinal acceleration at bow. More detail description of the instrumentation can be found in Kotisalo and Kujala (1999).

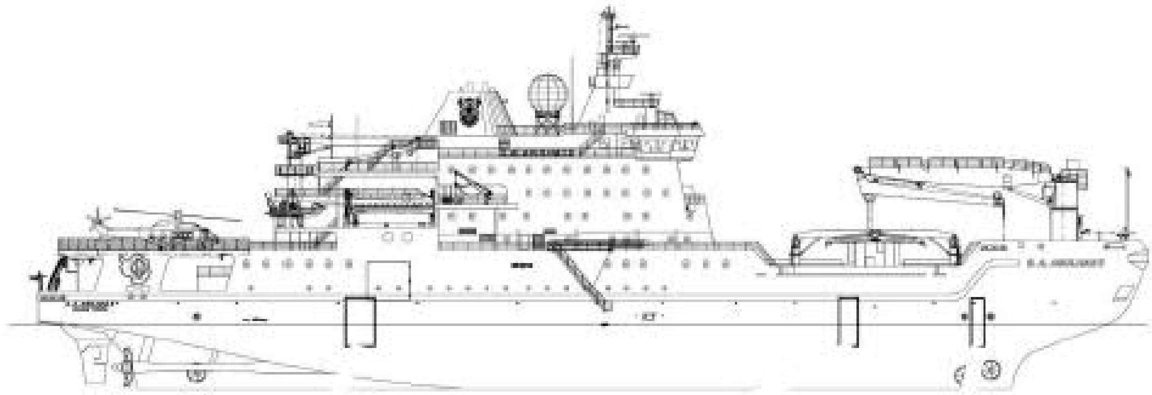

Fig.1a. Profile of SA Agulhas II showinG also the instrumented areas

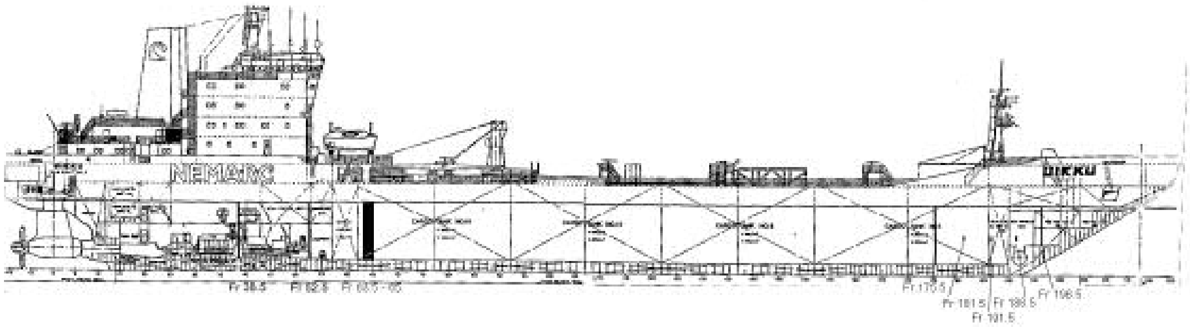

Fig.1b. Profile of MT Uikku.

## Description of the measuring voyage

SA Agulhas II

Full-scale measurement data on ice conditions in Antarctic waters was collected in the Antarctic waters onboard S.A. Agulhas II between Dec 6, 2013 and Feb 2, 2014. The ice conditions were observed visually and the machinery control and navigational data were recorded continuously. The ice-induced loads were also measured at the bow, bow shoulder and stern shoulder of the ship hull.

The ship departed Cape Town on November 28th, 2013 (Suominen et al., 2015a, 2015b). From Cape Town, the ship headed to the zero Meridian, which she followed to Antarctica, see Fig.2. The first time the ship encountered ice was on December 7th. On December 23rd, the ship arrived the Akta Bukta close to the Neumayer III (the German Antarctic research station).

Between December 24th and 30th, the ship operated between the Akta Bukta and the Penguin Bukta (the location at the ice shelf with the shortest distance to the South African Antarctic research station, SANAE IV, see Fig.2a) close the ice shelf. On December 30th, the ship headed towards South Georgia and the South Sandwich Islands. The ship arrived at the South Sandwich Islands January 4th when also the extent of sea ice ended.

The ship returned in ice-infested waters January 23rd to get through the pack ice to Penguin Bukta for the passengers and cargo unloading, where she arrived January 25th. The ship operated between the Penguin Bukta and Akta Bukta between January 26th and 31st. The ship headed back to Cape Town on January, 31st and the last ice was observed 1st February.

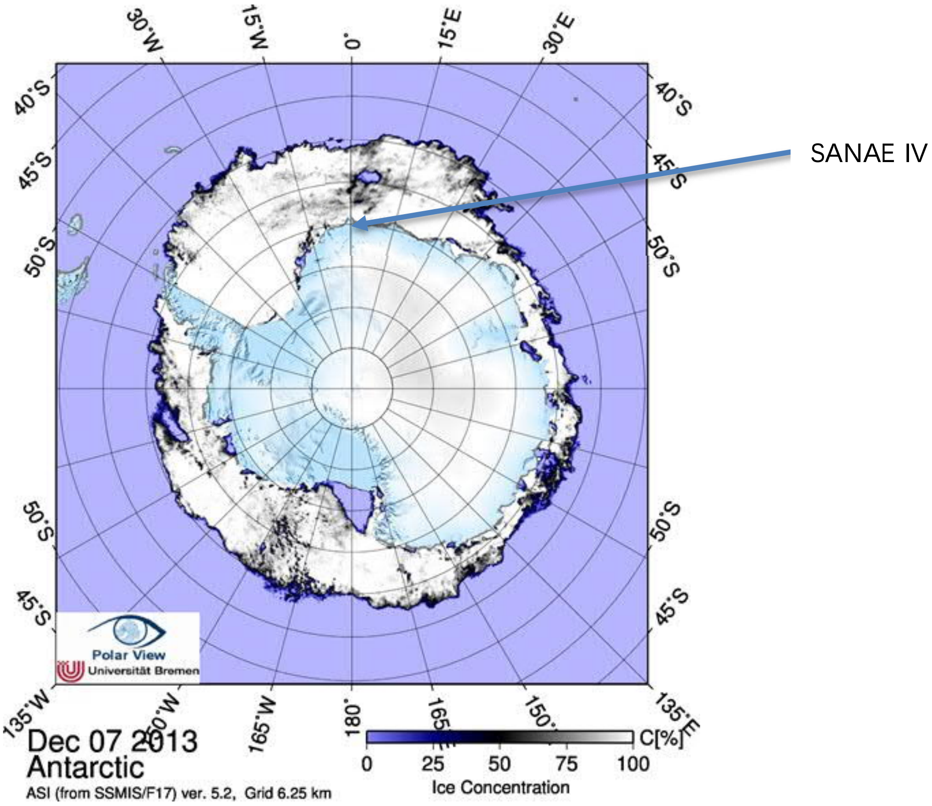


Fig.2a. Sea ice extent on Antarctica on 7th December 2013.

MT Uikku

The voyage started from the port of Murmansk on 26th of April 1998, so this presents hard winter time ice conditions for the studied area. The route of the convoy is presented in Fig.2b. Due the heavy ice conditions and the east wind the passage through the Kara Gate was blocked and the convoy –MT Uikku and IB Kapitan Dranitsyn entered the Kara Sea using the northern route. North edge of the Novaya Zemlja was passed on 29th of April and the nuclear icebreaker Rossiya joined to the convoy.

While the convoy was proceeding through the Kara Sea the IBN Vaygach broke a channel through the fast ice of the bay of Ob to the town of Sabeta. The convoy reached the entrance of this channel on 3rd of May, when the IBN Rossiya left the convoy. MT Uikku and IB Kapitan Dranitsyn proceeded on their own to Sabeta, and the convoy reached subice loading terminal on 4th of May.

Loading was completed on 8th of May and the convoy proceeded back to the Kara Sea. When the convoy reached to the Kara Sea IBN Rossiya joined to the convoy and assisted the convoy through the Kara Sea and through the Kara Gate to the Barents Sea, where the convoy arrived on 12th of May. After light ice conditions and open water were reached MT Uikku proceeded independently to Murmansk, where she arrived on 13th of May.

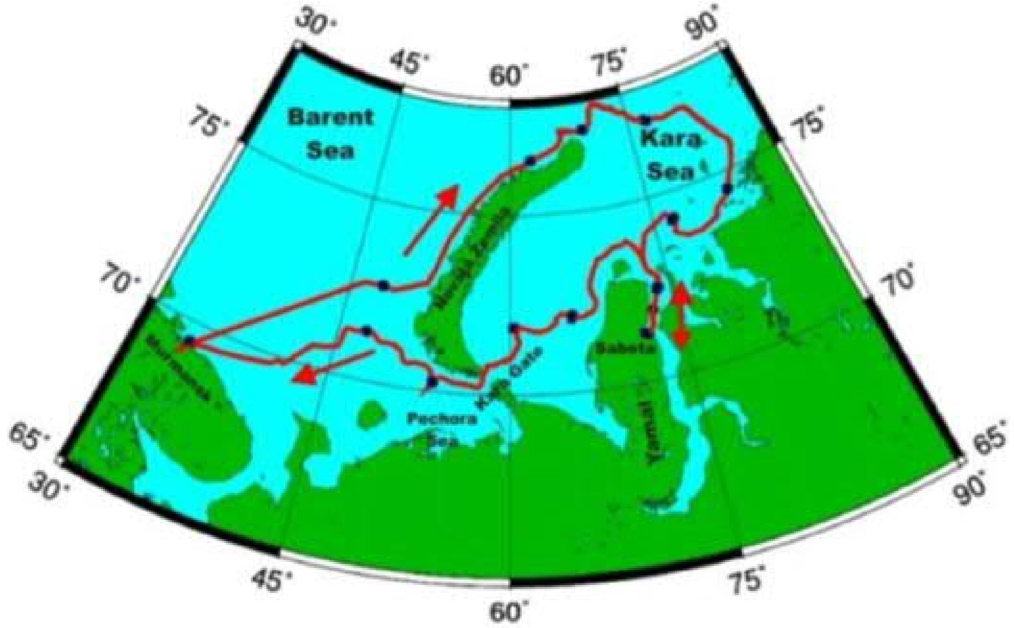


Fig.2b. Route of the convoy during ARCDEV voyage

## Observed ice conditions

SA Agulhas II

Ice conditions were observed continuously by visual observations on the ship and reported in 15 minutes intervals during the first day and in 10 minutes intervals thereafter. The ice concentration was observed in tenths during each observation period. The mean ice concentration during each observation period was calculated as a weighted average. The sea ice concentration was high, almost 10, most of the time.

Ice thickness was estimated by observing the thickness of the turning ice floes at the bow of the ship both visually and by using stereo-camera photos. Observations of ice thickness have been reported at a 20 cm ice thickness interval from 0 to 2 meters and at 50 cm intervals thereafter for each observation period. This was possible when the ice thickness was up to about 2 m as when the ice thickness exceeded 2 m, the ice pieces did not turn anymore and the thickness estimation was more complicated. Thick snow cover made also the thickness observations difficult.

Most of the time, the level ice thickness encountered at a certain 10 minutes observation period varied quite much. Typically 4 to 6 different ice thicknesses were observed during each 10 minutes periods. Obviously, the ice fields are often moving out to the open sea from Antarctica due to the wind, waves and currents and therefore the level ice field is broken into ice floes. New ice is then formed between the broken ice floes, which can explain the existence of different thicknesses of level ice at open sea. The ship had large difficulties to get through the thick ice regime when approaching Akta Bukta before Christmas 2013. The ship was stuck a number of times, but got however slowly forward independently by ramming through the thick ice.

MT Uikku

Ice conditions were observed continuously by visual observations on the ship and reported in 20 minutes intervals. The ice concentration was observed in tenths during each observation period. The mean ice concentration during each observation period was calculated as a weighted average.

Ice thickness was estimated by observing the thickness of the turning ice floes at the bow of the ship visually. Observations of ice thickness have been reported on five classes: below 10 cm, 10- 30 cm, 30-70 cm, 70-120 cm and above 120 cm. The ship could keep fairly high speed of 10-15 kn most of the time as there was always icebreakers to assist the ship.

## POLARIS CALCULATIONS

### Risk index values for SA Agulhas II

The Risk Index Values (RIV) for the various ice thickness values were determined in accordance with Table 1 (MSC. 1/Circ 1519, 2016). It was decided to use the RIV values for decayed ice conditions, because the measured sea ice strength was rather low, the temperature measurements made during the voyage showed positive or close to zero air temperatures and the sea ice extent around Antarctica was diminishing during the voyage. As it is mentioned above, it was not quite clear, if ice thicker than 2 m was second year ice or multi-year ice. However, it was decided to consider ice thicker than 2 m but less than 2.5 m as second year ice, ice at least 2.5 m thick but less than 3 m thick as light multi-year ice, and ice 3 m thick or thicker as heavy multi-year ice. The POLARIS calculations were done for IACS PC classes PC3, PC5 and for the Finnish-Swedish ice class IA Super.

### Risk index values for MT Uikku

The Risk Index Values (RIV) for the various ice thickness values were determined in accordance with Table 1 MSC. 1/Circ 1519, 2016). In this case the winter ice conditions are used as during this voyage it was still hard winter in the Russian Arctic.

It should be noted that the range of the reported ice thicknesses do not always coincide with the range of ice thicknesses in Table 1, as e.g. for the observation range of 30-70 cm and 70-120 cm, the lower value is used for the whole range.

### Results of POLARIS calculations for SA Agulhas II

The POLARIS calculations for ice class PC3, PC 5 and IAS were done in accordance with the formula (1) for assessing operational capabilities and limitations in ice: Polar Operational Limit Assessment Risk Indexing System (POLARIS) using the Risk Index Values (RIV) given in Table 1 above and the ice concentration data. The results of the calculations are given in Fig.3 below.

The results of Fig.3 indicate that for most of the time the RIO values are positive for PC3, but occasionally negative up to -20 for PC 5 and mostly negative to IAS ice class getting values even close to – 40. This indicates that for independent Antarctic operation, ice class PC 3 is obviously most suitable to be in the safe side, for more detail discussion of this topic, Kujala et al. (2015).

**Results of POLARIS calculations for MT Uikku**

The POLARIS calculations for ice class PC3, PC 5, PC 6, IAS and IA were done in accordance with the formula (1) for assessing operational capabilities and limitations in ice: Polar Operational Limit Assessment Risk Indexing System (POLARIS) using the Risk Index Values (RIV) given in Table 6 above and the ice concentration data. The results of the calculations are given in Fig.4.

Comparing Fig.4 with the allowable values and adding the value 10 due to the icebreaker assistance, it seems that ice classes PC 6 is the most suitable for navigating in the Kara Sea behind an icebreaker during hard winter time ice conditions.

## COMPARISON OF POLARIS CALCULATIONS WITH MEASURED ICE LOAD DATA

The ice load measuring system onboard both SA Agulhas II and MT Uikku enable also the evaluation of the proper ice class by calculating the required hull strength so that the damage probability will be on a right level. This has been done on a recent master thesis by Kurmiste (2016). Using the long term measurements onboard SA Agulhas during 2013-2015 and the three week data on MT Uikku, he fitted Gumbel 1 extreme value distribution on these data and forecasted the life time extreme loads for these ships. Then by comparing these load values with the ultimate strength of the frames using various ice classes to determine the scantlings, he could evaluate the probability of reaching the planned limit state. Similar analysis has been conducted before e.g. by Kujala (1991) and Kaldasaun and Kujala (2011). As a result, a reliability index $\beta$ is obtained by defining a probability of failure for the frames. For ice-strengthened ships, typically it is accepted that the $\beta$ values should be in the range 1-2, i.e. approximately 1 in 10 to 100 ships will experience some local damages on the shell structures during ship life time. Fig.5 shows the obtained safety index values using SA Agulhas II data and Fig.6 using the MT Uikku data.

It is really interesting that also based on this analysis PC 3 seems to be the proper ice class for independent navigation on the Antarctic ice conditions and similarly PC 6 is the proper ice class for ships following an ice-breaker on the Kara Sea during hard winter time ice conditions. This is strong evidence that the developed POLARIS gives reliable estimates for the safety of ships in various ice conditions.

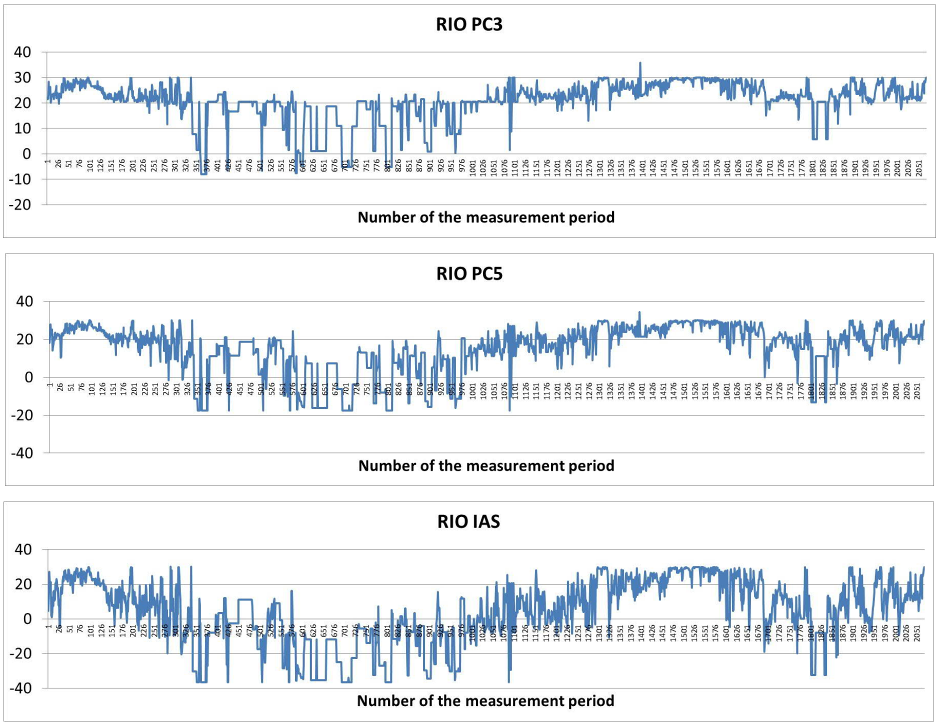


Fig.3. The results of POLARIS calculations for PC3, PC 5 and IAS using SA Agulhas II data.

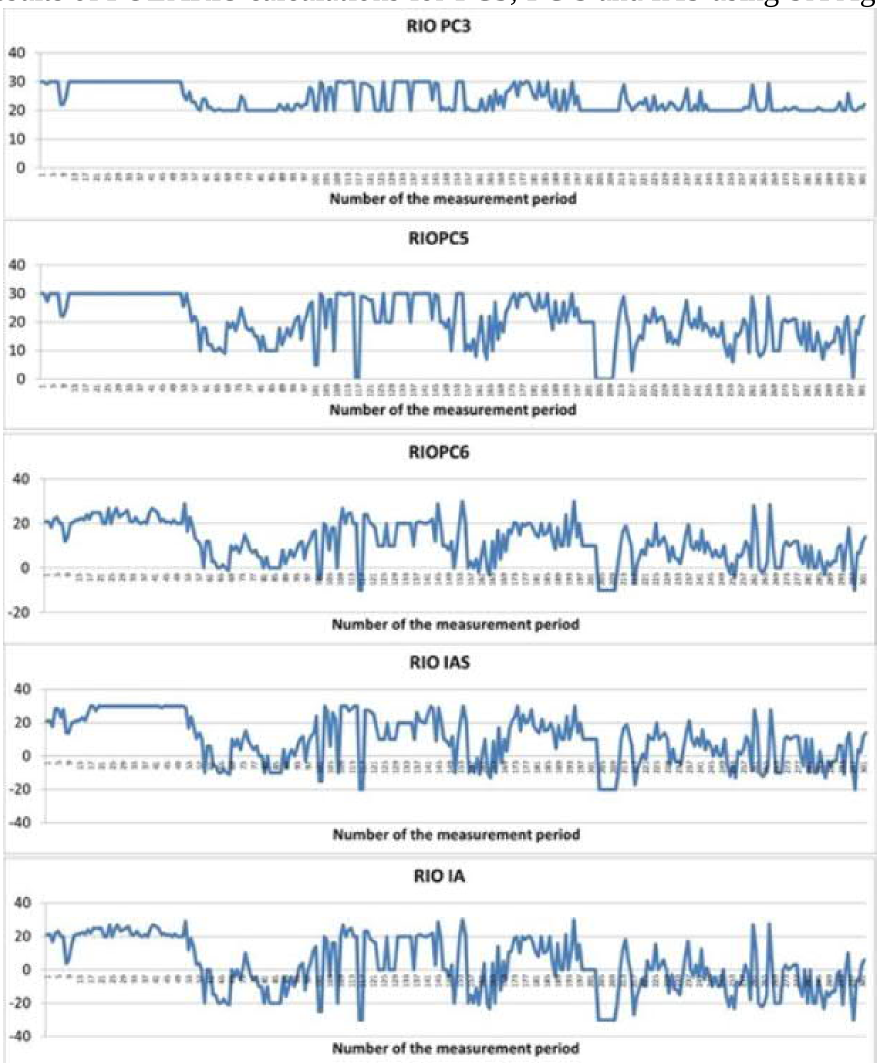


Fig.45 The results of POLARIS calculations for PC3, PC 5, PC6, IAS and IA using MT Uikku data.


Fig.5. Safety indices of the bow frames of SA Agulhas II (Kurmiste, 2016)


Fig.6. Safety indices of the bow frames of MT Uikku (Kurmiste, 2016)

## CONCLUSIONS

The POLARIS calculations for ice classes PC3, PC5, PC6 IA Super and IA were done in accordance with the formula given in the Polar Operational Limit Assessment Risk Indexing System (POLARIS) using the Risk Index Values (RIV) and the ice concentration data observed onboard SA Agulhas II and MT Uikku. The results indicate that PC 3 is the most suitable ice class for Antarctic operations and PC6 for a ship navigating behind an ice-breaker on the Kara Sea during hard winter time ice conditions. Similar results for also obtained by calculating the probability of hull damage based on the measured full-scale ice induced load data onboard SA Agulhas II and MT Uikku. The POLARIS approach is fairly easy to apply and it seems to give a reasonable estimate for the risk index to indicate whether navigation on the planned ice conditions is safe with the chosen ice class.

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