**Setting the Standards for a New Generation of Tugs Operating in Ice and Cold Climate**

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**SYNOPSIS:** With the offshore oil & gas industry moving further into the ice infested waters of the arctic and other regions with ice and cold climate, a new generation of winterised tugs is required to meet the challenges of operating in such climates. The key to a successful ice-going tug design is in the proper understanding of the operational profile of the vessel. The operating location, time window and the requested duties determine the degree of ice reinforcement and winterisation and, consequently, the applicable class notations. Particular attention is to be paid to the design of tugs which are also engaged in icebreaking and ice management duties.

This paper provides overview of the conditions to be expected in key navigation areas and provide guidance towards the selection of the applicable rules and regulations. The key principles of the Ice Class, Polar Class and icebreaker rules will be introduced, as well as the correspondence between the different sets of class rules and national regulations. Relevant links to the harmonised safety standards for tugs, which are jointly developed by Bureau Veritas, Lloyd’s Register of Shipping and the American Bureau of Shipping (the first draft was presented at ITS 2010) are provided.

Analysis of the applicability of the existing ice class rules to tugs shows that there are some specific technical issues, which are addressed by introducing an advanced strength assessment methodology, based on direct analysis of ice-hull interaction. This approach, which has been incorporated into Bureau Veritas’ recently upgraded simulation software IceSTAR, yields valuable insight into the behaviour and performance of tugs operating in ice. A practical example, considering a new series of shallow draught icebreaking tug/supply vessels for operating in the North Caspian Sea, is demonstrating this point. The paper finishes with a wrap-up and some concluding remarks.

**INTRODUCTION**

Over the past years the marine industry has shown an increasing interest in ship operations in ice and cold climate, which is fuelled by a two key developments. First, global warming potentially offers shorter routes for international trade via the Northern Sea Route and North-West Passage. Ships having the ability to operate in severe ice conditions and very low temperatures may increasingly make use of this opportunity. The second point is the increasing development of offshore oil and gas activities in the Arctic and sub-Arctic areas (e.g. Northern Russia & Canada, Okhotsk Sea), as well as in areas which experience ice during the winter season (e.g. North Caspian Sea). Tugs of all sorts play a key role in supporting these developments. Harbour tugs and offshore terminal tugs are required to assist tankers, gas carriers and cargo ships in berthing and unberthing operations, while offshore tugs and anchor handling vessels will be deployed for towage and installation of the floating offshore units. In addition, escort and salvage tugs equipped with fire-fighting systems, rescue facilities and oil recovery equipment are vital in protecting merchant ships as well the sensitive natural environment in these areas.

As a consequence of the operations in ice and cold climate, the tugs will need to be adapted for these circumstances. An example of a tug-supply vessel specifically designed for operations in ice and cold climate is shown in Figure 1.

![Figure 1: Wagenborg’s “Arcticaborg” was built by Kvaerner Masa yards in 1998 to a design of Aker Arctic in accordance with Bureau Veritas Rules.](image)

Structural reinforcement against the pressure exerted by the ice on hull, appendices and propulsion/steering units is required, as well as sufficient propulsion power to efficiently move through the ice. In addition, a degree of winterisation is needed to protect the crew and ensure that the ship’s equipment remains operational in extremely cold conditions. Last but not least, design measures are to taken to protect...
the sensitive environment against accidental pollution.

A number of safety issues related to the introduction of new ship types (double acting ships, tugs and offshore support vessels, etc.), larger ships (in particular tankers) and increased shipping activity – giving rise to increased risk of accidents & incidents – need to be addressed. In this context three basic questions require an answer:
1. Has the correct ice class (class rules & national regulations) been selected?
2. Are the existing rules and regulations valid for new ship types (with different size or shape than the current ice going fleet)?
3. How can we protect people, ships, cargoes and the natural environment?

The scope of this paper is to deal with these questions and provide support to the industry in finding satisfactory answers for their individual cases. In this context the role of a classification society is to develop rules for assessment of key safety and environmental protection parameters for ships operating in ice and cold climate (hull structure, propulsion, stability, crew safety, prevention of pollution, etc.), for which the associated requirements are refined in accordance with the prevailing ice and weather conditions as well as the applicable regulations of flag states and responsible authorities.

Within the scope of the Bureau Veritas Rules for the Classification of Steel Ships the following families of class notations are available [1]:
- **ICE CLASS** for ships operating in first year ice only;
- **POLAR CLASS** for ships operating in multi-year ice;
- **ICEBREAKER** for ships specially engaged in icebreaking and ice management activities (first year & multi-year ice);
- **COLD** for winterisation of ships

Optional additional class notations are available to recognize specific features implemented by the ship owner, such as enhanced level of comfort for people on board (noise, vibrations, protection against effects of cold weather) and enhanced level of environmental protection (in particular in sensitive marine areas) [1].

Bureau Veritas has a long experience record with the classification of ice going ships, which started with the classification of the world’s first ocean going ice breaker “Ermack” in 1898. Presently the class society has more than 1,100 ice class ships in its register.

The paper continues to describe the details of the available class notations and the associated technical requirements, including their limits of application. The following section deals with ice class selection by providing guidelines and an assessment of the level of equivalency between the different ice classes. Based on an analysis of the technical specificities of specialised ships (such as tugs) the next section introduces a methodology for the direct (first principles) analysis of ice loads & structural response. An example of the application of the method to a shallow draught icebreaking tug, making use of the Bureau Veritas IceSTAR simulation software is provided. The paper ends with some concluding remarks.

### ICE CLASS NOTATIONS & REQUIREMENTS

**ICE CLASS: first year ice (Baltic Sea)**

The ice class notations for first year ice are based on the **Finnish-Swedish Ice Class Rules (FSICR), 2008** [2]. First year ice is defined as sea ice of not more than one winter’s growth, with a typical thickness between 30 cm and 2 m. Thin first year ice (white ice) has a thickness of 30 to 70 cm thick, medium first year ice of 70 to 120 cm thick, and thick first year ice of over 120 cm thick [3]. These conditions are typically found in the Baltic Sea (for which the FSICR have been developed), as well as in other areas, such as the St. Lawrence River and Seaway.

The basic design requirement of the FSICR is a minimum speed of 5 knots in a brash ice channel. Technical requirements include the minimum propulsion power, which is calculated on the basis of the estimated hull resistance in ice. The ice resistance is a function of the characteristic hull data (including main dimensions, waterline entry angle, rake and hull form related parameters) as well as the ice thickness (selected **ICE CLASS** notation).

Hull structural reinforcements are based on the design ice pressure, which is dependent on the displacement, propulsion power, selected **ICE CLASS** notation (ice thickness) and stiffening arrangement (sideshell), and also varies between the forward, midship and aft regions. The highest pressures are obtained in the forward region under the assumption that the ship sails bow first in the ice channel, see Figure 2.

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1 Refer to Bureau Veritas additional class notation families **COMF-NOISE, COMF-VIB** and **CLEANSIP**.

2 Applicable to ships for which the building contract has been signed on 1 January 2010 or thereafter [2].
Key requirements consider the shell plating thickness, including an addition for abrasion and corrosion (or, alternatively, application of a special surface coating) and the scantlings (section modulus, and shear area) and weld connections (welding) of ice frames (longitudinal and transverse framing) and primary structural members (web frames and ice stringers). In addition some specific strength requirements are included for the bow (stem and towing arrangement), stern, bilge keels, rudder and steering arrangements.

The requirements for the propulsion machinery have been significantly amended in 2008. The first step is the calculation of design loads due to propeller-ice interaction in combination with hydrodynamic loads (load cases considering forward and backward acting forces, spindle torque on the propeller blades, thrust on the propeller, ice induced torque, ultimate blade load resulting from blade loss through plastic bending and the maximum response torque and thrust along propeller shaft line). The propulsion machinery design criteria are for operation in ice channels by considering the loads exerted on the propeller blades by ice blocks entering the propeller disc. In addition, for **ICE CLASS IA SUPER**, operation in level ice is included (by considering ramming). Both open and ducted propellers are taken into consideration. The requirements cover the selection of materials exposed to sea water & sea water temperatures. The strength requirements are based on the pyramid strength principle. That is, loss of a propeller blade shall not cause any significant damage to other propeller shaft line components. The idea behind this principle is that it is easier to replace a propeller blade (in case of damage) than a more critical and harder to replace shaft line component. Based on the calculated loads the propeller blade stresses and resistance against fatigue are checked making use of the Finite Element Method (FEM) for structural analysis. The verification of the propeller bossing and Controllable Pitch (CP) mechanism, propulsion shaft line and azimuthing main propulsors (e.g. pods) is included in the requirements, while vibrations are checked using a simplified method. A special procedure is available for the examination of alternative design procedures. Additional machinery requirements are included for the starting arrangements, sea inlets and cooling water systems to ensure safe and efficient operations in ice.

Bureau Veritas Rules includes four major **ICE CLASS** levels plus one additional level [1]:

- **ICE CLASS IA SUPER** for independent navigation in difficult ice conditions. The maximum ice thickness is 1.0 m with a 0.10 m consolidated upper layer. The maximum ice pressure height (effective contact height between ice and hull) is 0.35 m;
- **ICE CLASS IA** for navigation in difficult ice conditions, with icebreaker assistance when necessary. The maximum ice thickness is 0.8 m, while the maximum ice pressure height is 0.30 m;
- **ICE CLASS IB** for navigation in moderate ice conditions, with icebreaker assistance when necessary. The maximum ice thickness 0.6 m, while the maximum ice pressure height is 0.25 m;
- **ICE CLASS IC** for navigation in light ice conditions with icebreaker assistance when necessary. The maximum ice thickness is 0.4 m, while the maximum ice pressure height is 0.22 m;
- **ICE CLASS ID** (not covered by the FSICR) for navigation in very light ice conditions. The requirements for the fore region, rudder and steering arrangements are the same as for **ICE CLASS IC**.

A key point to note is that Ice Class vessels are not considered to be icebreakers, see the subsection **ICEBREAKER** below.

Three technical issues regarding the application of the FSICR need to be highlighted in the context of this paper. The first is related to the propulsion power. The ship resistance formulae have been validated with ice model tests. The range of parameters included in the resistance calculation for which the validity of the ice resistance has been verified is listed in Table 1 (from Annex 1 to the FSICR, [2]).

Analysis of the minimum and maximum values listed in Table 1 with typical values for tugs leads to the conclusion that the validity of the powering requirements of the FSICR is mainly focussing on larger ships (L > 65 m) with a parallel midbody of at least 25 per cent of the length. The vast majority of typical tug designs have on or more parameters outside the validity range. Hence it is difficult to assess the validity of the powering requirement for tugs. Having said that, for high bollard pull tugs there is probably not much of an issue, as the bollard pull will dictate the installed
power rather than the required engine power for ice class.

Table 1: Range of parameters used for validation of the powering requirement of the FSICR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ (waterline angle at B/4), in degrees</td>
<td>15</td>
<td>55</td>
</tr>
<tr>
<td>$\psi_1$ (rake of stem at CL), in degrees</td>
<td>25</td>
<td>90</td>
</tr>
<tr>
<td>$\psi_2$ (rake of bow at B/4), in degrees</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>L (length between perpendiculars), in m</td>
<td>65.0</td>
<td>250.0</td>
</tr>
<tr>
<td>B (maximum breadth), in m</td>
<td>11.0</td>
<td>40.0</td>
</tr>
<tr>
<td>T (ice class draught), in m</td>
<td>4.0</td>
<td>15.0</td>
</tr>
<tr>
<td>$L_{BOW}/L$ (ratio of length of bow to L)</td>
<td>0.15</td>
<td>0.40</td>
</tr>
<tr>
<td>$L_{PAR}/L$ (ratio of length of parallel midship to L)</td>
<td>0.25</td>
<td>0.75</td>
</tr>
<tr>
<td>$D_p/T$ (ratio of propeller diameter to T)</td>
<td>0.45</td>
<td>0.75</td>
</tr>
<tr>
<td>$A_{wf}/(L^2B)$ (ratio of waterline area of bow to L*B)</td>
<td>0.09</td>
<td>0.27</td>
</tr>
</tbody>
</table>

The second issue is related to ice strengthening. The requirements for the arrangement of the ice frames are difficult to apply to the flat aftbody structures typically found on tugs, as it is difficult to determine (within the context of the FSICR) whether this region is to be considered as longitudinally or transversely stiffened. In addition, the adequacy of the ice pressure is hard to judge, in particular for the case of azimuth stern driven tugs (the pods are located in the same area).

Finally, the FSICR do not consider stern first operations. Practical experience has shown that operations are often more easy while working astern in the ice by using the propellers to “milk” the ice into small pieces. This is particularly useful for tugs engaged in ice management operations (e.g. clearing ice and rubble at a terminal).

**POLAR CLASS: multi-year ice (Arctic)**

The Polar Class Rules have been developed by the International Association of Classification Societies (IACS) on the basis of commonly shared experience and technical expertise (IACS UR 11, I2 & I3, 2007) [4,5,6] and specifically considers navigation in ice-infested polar waters such as the Arctic region (e.g. the Russian Arctic and the Canadian Arctic), which includes consideration of multi-year ice down to first year ice with old ice inclusions. In this context multi-year ice is defined as old ice with a typical thickness of 3 m or more, which has survived at least two summers’ melts [2].

Technical requirements include material selection. A higher steel grade, with increased ductility, is to be selected for materials exposed to low temperatures due to the risk of brittle fracture. Structural reinforcements are required on the basis of the average ice pressure on a predefined load patch. The design ice load (bow area) is based on the concept of glancing impact, which is basically a collision between the ship and the ice edge (channel or floe) as shown in Figure 3. Figure 4 depicts the definition of the load patch, which is the (nominal) contact area between the ship and the ice. The average ice pressure can be defined as the collision force divided by the load patch area.

The basic idea is that the maximum ice load is equal to the failure strength of the ice (assuming a rigid ship hull). To this end both crushing and flexural failure of ice are taken into consideration. Crushing failure means failure under in-plane compression of the ice, while flexural failure relates to bending of the ice caused by a contact force acting perpendicular (downward) to the ice plane. Whether the ice will fail in crushing or flexural mode will largely depend on the shape of the hull at the contact location. If the ship’s side is vertical the ice can only be broken in crushing mode. If the side is inclined and there is enough available mass the ice will fail in flexural mode. As the contact force in flexural mode is generally lower than in crushing mode, icebreaking vessels normally have a special hull form in order to cause flexural failure.

Following this approach a detailed pressure distribution over the hull can be derived. Several zones are identified, as shown in Figure 5. The
reference pressure is calculated for the bow area and consequently distributed over the entire hull by means of hull area factors. The longitudinal strength is also checked by the vertical ice induced force and bending moment.

The scantling requirements for shell plating and stiffeners are based on plastic theory. This is a marked difference with the FSICR, which are based on classic elastic theory. In addition, requirements are included for the stem and stern arrangements, as well as hull outfittings (rudder and towing arrangements).

Figure 5: Hull area definition for Polar Class ships [8]

The technical requirements for the main propulsion and machinery are similar to those of the FSICR, but less detailed for fatigue. The loads due to propeller-ice interaction depend on the selected POLAR CLASS notation and the running conditions. For each of the defined load cases, for both open propellers and ducted propellers, the blade stress analysis is to be done by FEM. Figure 6 shows the load cases for ducted propellers, which is the typical case for tugs (except icebreaking tugs used for milling). In order to determined the loads and stresses the total ice torque on the propulsion line due to blade ice impacts (milling), the maximum thrust applied to the propulsion line and the propeller blade failure load are to be calculated. The propulsion line is to be designed such as to ensure sufficient fatigue strength under the calculated dynamic excitations and loads. As for the FSICR the pyramidal strength principle is applied. The propeller blade strength is to be checked for the calculated stresses and material characteristics.

Special attention is required for azimuth main propulsors, in particular in relation to ice block impacts on the propeller hub of a pulling propeller and the loads on thrusters operating at an oblique angle to the flow. In addition, requirements are given for the capability of prime movers (starting and running and emergency power) and the required capabilities for acceleration loads due to ship-ice contacts (fastening). Material requirements (exposure to sea water or low sea or air temperature) are included for machinery items as well. Finally, winterisation requirements apply to auxiliary systems, sea inlets and cooling water systems, ballast tanks and ventilation design. Alternative designs may be taking into consideration on the basis of a comprehensive design study.

Bureau Veritas Rules includes seven POLAR CLASS levels [1,8]:

- **POLAR CLASS 1** for year-round operations in all polar waters;
- **POLAR CLASS 2** for year-round operations in moderate multi-year ice conditions;
- **POLAR CLASS 3** for year-round operations in second-year ice which may include multi-year ice inclusions;
- **POLAR CLASS 4** for year-round operations in thick first year ice which may include old ice inclusions;
- **POLAR CLASS 5** for year-round operations in medium first year ice which may include old ice inclusions;
- **POLAR CLASS 6** for summer and autumn operations in medium first year ice which may include old ice inclusions;
- **POLAR CLASS 7** for summer and autumn operations in thin first year ice which may include old ice inclusions.

Even if Polar Class vessels are intended for operations in multi-year ice conditions, they are not considered to be icebreakers (see FSICR above).

Also for the Polar Class Rules some technical issues need to be addressed. The first point is that the Polar Class Rules do not contain any capability requirements, in particular in relation to the propulsion power and advance speed in ice.
This is a drawback for designers and ship owners, who receive no guidance from the rules here.

A second point is that all POLAR CLASS notations assume the presence of old ice inclusions, which makes application less suitable for areas with only first year ice.

More in general terms, the Polar Class Rules are not specific with regard to the actual ice conditions. This makes it difficult to determine the safe operating limits for a certain route during a certain period of the year (e.g. advance speed as function of the ice thickness). In addition, there is no distinction between independent and icebreaker assisted navigation in ice.

Like for the FSICR, stern-first operation in ice is not covered, which is particularly an issue for icebreaking tug-supply vessels. Re-assessment of the ice loads is required, both in relation to the hull as well as the propulsors (ice pods).

The validation calculations mainly focus on large (cargo) ships with a displacement of more than 5,000 t, which is far in excess of the size of most tugs. Having said that, it needs to be recognised that the Polar Class Rules have a stronger theoretical background than the FSICR (more rational approach), which makes the validity of their application less sensitive compared to the FSICR. Still, in combination with the difference in structural assessment philosophy (plastic theory for Polar Class Rules versus elastic theory for the FSICR), the equivalency between the POLAR CLASS and ICE CLASS notations will necessarily be only appreciative.

In order to resolve the issue regarding the ambiguity in terms of actual ice conditions Bureau Veritas has developed a capability guidance table, which is shown in Figure A1 of the Appendix. Both icebreaker assisted and independent operation have been taken into account.

ICEBREAKER: first year ice & multi-year ice
In 2010 Bureau Veritas has introduced the new additional class notation ICEBREAKER, which has been developed on the basis of the Polar Class Rules [8]. An icebreaker is defined as a ship having an operational profile that includes escort and/or ice management functions, with powering and dimensions that allow it to undertake aggressive operations in ice covered waters.

In this context icebreakers are considered to operate fully independent in ice covered and to be engaged in the following typical activities:
- Creating navigable ice channels;
- Assisting ships navigating through ice fields (e.g. oil barges);
- Clearing ice rubble (e.g. ice management at offshore gas terminal).

To accommodate for the effects of icebreaking operations the following main technical requirements of the associated Polarbreaking operations the following main technical requirements of the associated Polar Class Rules have been modified:
- Definition of hull area extents;
- Bow shape (improved ice bending capability);
- Hull area factors (modified ice pressure distribution);
- Longitudinal strength criteria (accounting for ramming).

Additional technical requirements have been introduced for the minimum propulsion power and a minimum inclination angle of vertical sides (to ensure self-freeing capability).

Bureau Veritas Rules includes seven ICEBREAKER levels [8]:
- **ICEBREAKER 1** for unrestricted summer and autumn operations in all polar waters and winter and spring operations in multi-year ice with a maximum ice thickness of 3 m;
- **ICEBREAKER 2** for summer and autumn operations in multi-year ice with a maximum ice thickness of 3 m and winter and spring operations in second year ice with a maximum ice thickness of 2.5 m;
- **ICEBREAKER 3** for summer and autumn operations in second year ice with a maximum ice thickness of 2.5 m and winter and spring operations in thick first year ice with a maximum ice thickness of 1.8 m;
- **ICEBREAKER 4** for summer and autumn operations in thick first year ice with a maximum ice thickness of 1.8 m and winter and spring operations in medium first year ice with a maximum ice thickness of 1.2 m;
- **ICEBREAKER 5** for summer and autumn operations in medium first year ice with a maximum ice thickness of 1.2 m and winter and spring operations in medium first year ice with a maximum ice thickness of 0.8 m;
- **ICEBREAKER 6** for summer and autumn operations in medium first year ice with a maximum ice thickness of 0.8 m and winter and spring operations in thin first year ice with a maximum ice thickness of 0.6 m.
In addition capability guidance is provided as shown in figure A2 of the Appendix.

**Developments**

Currently a number of developments is taking place to further improve the **POLAR CLASS** and **ICEBREAKER** notations. The first key point is stern-first operation in ice, including astern icebreaking and ice management. The second item concerns the ice pods, in particular in relation to stern working in the ice. Both items are of great importance to icebreaking tug/supply vessels.

To this end the ice load distribution on the stern needs to be re-defined for the governing load cases, with particular focus on the ice pressure, load patch dimensions and the associated hull area factors. For the ice pods a list of relevant load scenarios has been developed in cooperation with Aker Arctic, which considers both ahead and astern operations in ice, as well as longitudinal and transverse load cases. Two examples are presented in Figure 7.

![Image](image-url)

**Figure 7: Load scenarios for ice pods**

One of the key items to consider is the probability of occurrence of each load scenario. Low probability scenarios are related to extreme single events, which govern the strength of propeller blades, hull structure and supporting brackets. High probability scenarios are related to cyclic loading (dynamic impact and milling loads) and associated with fatigue considerations.

Azimuth thrusters are also in focus for the **ICE CLASS** notations. The Finnish Transport Safety Agency (TraFi, the former FMA) has initiated a joint industry project on azimuthing thrusters in ice. The goal is to improve the requirements of the FSICR. Existing load models will be analysed and new models are under development, in particular with regard to ice loads exerted on thrusters due to ice impact and ridge penetration. Validation of the models will be done using the results of full scale measurements. Bureau Veritas, along with other major classification societies (ABS, Class NK, DNV, GL, LR, RINA, RMRS), institutes (VTI, Aker Arctic) and pod manufacturers (ABB, Rolls-Royce, Wärtsilä) is participating in this project, which is expected to yield results in the autumn of 2011.

In addition, it is to be noted that the **Finnish-Swedish Ice Class Rules (FSICR)**, 2010, have been published, which are applicable to ships contracted for construction on 1 January 2012 or thereafter [9]. The main amendments are related to the hull structural requirements. Rather than changing the required strength level, their aim is to clarify the provisions and improve their applicability.

**COLD: winterisation**

Bureau Veritas Rules also include the additional class notation **COLD** (*H* t<sub>DH</sub>, *E* t<sub>DE</sub>), where t<sub>DH</sub> denotes the design temperature to be considered for the hull (H) and t<sub>DE</sub> the design temperature to be considered for the equipment (E) as specified by the designer (in degrees Celsius) [1]. The class notation implies specific consideration is given to low ambient temperatures, frozen spray (icing of ships) and reduced effectiveness of components.

The concerned functions include:

- Decks and superstructures;
- Stability (under ice accretion);
- Propulsion;
- Other essential services which are to remain in operation at the defined temperature conditions and/or which are related to the prevention of ice formation which could be detrimental to the safety of the ship or of the passengers and crew;
- Electricity production;
- Navigation;
- Crew protection and elimination of ice where necessary for safe access.

For tugs and offshore support vessels particular attention is to be paid to towing and anchor handling equipment, cranes, dynamic positioning equipment, cargo decks and accommodation spaces.

The key technical requirements related to the class notation include the selection of steel grades of exposed structures and materials selection for machinery and equipment, considering low air temperatures. The ship’s stability needs to be considered for loading conditions with ice accretion on both horizontal
and vertical surfaces. This is particularly important for tugs and anchor handling vessels, as careful attention is to be paid to the towing and anchor handling conditions. If significant ice accretion is present, the centre of gravity of the ship may increase substantially, effectively reducing the ship's stability particulars. With reference to the proposed harmonised towing stability criteria for tugs, as published by Bureau Veritas, Lloyd's Register of Shipping and the American Bureau of Shipping during ITS 2010, the designer of an ice going tug needs to consider the effects of ice accretion simultaneously with the assessment of the towline force for checking the tug's resistance against girding [10]. Similar reasoning applies to anchor handling vessels, for which stability provisions have been published by the Norwegian Maritime Directorate in 2007 and 2008 [11,12], which have been incorporated in Bureau Veritas’ Guidelines Stability during anchor handling, 2010 [13]. Another key point is to ensure that the towing equipment, including the emergency quick-release of winches is properly functioning in cold conditions.

Other requirements include temperature control for the functioning of essential equipment, such as the main engine(s), the auxiliary engines and generators, the emergency generator, the emergency fire pump and the auxiliary systems (e.g. fuel oil transfer system, lubrication oil and hydraulic oil), as well as the starting arrangement in dead ship condition.

With regard to de-icing, requirements apply regarding sea inlet(s), overboard discharge and ballast tanks (e.g. heating, circulation, bubbles and/or steam). In addition, attention is paid to ice build-up prevention of piping, vents and the fire main. The power consumption of the de-icing equipment is to be included in the electrical load balance. Finally, special equipment (e.g. de-icing tools) are to be provided for de-icing (for example of deck areas), protection of deck machinery, navigation, communication and evacuation equipment, personal protection and temperature control in the accommodation spaces (HVAC, insulation).

**ICE CLASS SELECTION**

Having introduced the available class notations for tugs operating in ice and cold climate, little guidance has yet been given with regard to the selection of an appropriate ice class. This is primarily the responsibility of the ship owner and usually based on experience with existing ships in known environments. When we move into new territories, in particular for ship owners without long term experience with operating in ice conditions, guidance may be necessary to enable the ship owner to make a rational choice. This sub-section deals with such guidance.

In principle, three questions need to be asked for selecting an ice class notation for a tug operating in ice and cold climate:

1. Where to operate?
2. When to operate?
3. How to operate?

The question where to operate relates to the actual area (port, terminal or geographical area (e.g. specific sea are or coastal area)). The question when to operate is related to the time of the year during which the tug is supposed to operate in the designated area (season; see also Figures A1 and A2 in the Appendix). The answers to the first two questions determine the ice conditions, in terms of ice type and ice thickness, to be expected, as well as the air temperature. The question how to operate is related to the anticipated duties of the tug and the required level of autonomy. For example, it needs to be clear if the tug is to be involved in icebreaking and ice management duties in addition to normal towing operations. Another matter is whether the tug needs to operate independently or if there are icebreakers in the area to assist the tug in case of heavy ice conditions. Therefore, the answer to the third question relates to the specific design conditions regarding the level of autonomy, the anticipated icebreaking and ice management activities, equipment protection (e.g. towing winch) and deck cargo (e.g. for tugs involved in supply operations).

In a different context the autonomy issue is also important in relation to the harmonised safety standards for tugs, for which the proposed service notations tug and escort tug may be completed by the additional service feature sailing time ≤ 4 h from a safe sheltered anchorage if the operational profile of the ship is such that a safe sheltered anchorage can be reached within four hours sailing time (assuming normal operation at the maximum draught) [10]. The additional service feature effectively relates to the familiarity of the crew with the operating area and the required level of autonomy of the ship in case of an emergency situation (safety equipment). It is clear that the conditions for tugs operating in ice and cold climate are generally much harsher than for vessels in more traditional operating environments. This point needs to be taken into consideration for the general design and the selection of safety equipment on board. Important issues to consider in relation to the safety and comfort of the crew are icing (slippery working areas), snow, 24 hours darkness (or daylight),
fatigue (impact on crew judgement), hypothermia, wind chill, frost bite, ultra violet radiation (sunlight), noise, vibrations and the remote location of operation. Where certain provisions may not be necessary for tugs in benign operating areas they may be required even for locally operating (terminal) tugs in ice-infested waters. In fact, it should be expected that the design standard for such vessels will be above the standard requirements of the harmonised safety standards.

Other important parameters influencing the choice of ice class are the additional steelweight for the structural reinforcements, the additional cost for providing sufficient propulsion power (capex and opex) and the potential reduction of icebreaker fees (related to higher ice class) and sometimes port dues (e.g. for Finland and Sweden).

More comprehensively, the following list of key ice parameters to be considered [3]:
- Ice conditions: e.g. level ice, floes (ice concentration), pack ice;
- Extreme level ice thickness, type and drifting speed;
- Extreme ridge size and type;
- Existence of icebergs;
- Table of ice thickness and type with associated probability of occurrence (observation);
- Ridge size classification with associated probability of occurrence (observation).

In order to support ship owners and shipyards/designers in the selection of an appropriate ice class, Bureau Veritas has issued the **Guidelines Ice reinforcement Selection in Different World Navigation Areas, 2009** [14]. The guidance note provides a description of the applicable regulatory regimes (legislation) and the available ice services. In addition, meteorological data is presented for the key navigation areas, which supports the determination of ice conditions for the following areas:
- Canadian Arctic;
- Russian Arctic;
- Baltic Sea;
- Cook Inlet and Bering Sea;
- Labrador Coast and Newfoundland;
- Saint Lawrence River and Seaway;
- Sakhalin area (Okhotsk Sea, Tartar Strait);
- Bohai Bay;
- Black Sea and Sea of Azov;
- Caspian Sea.

The guidance note also lists the related Bureau Veritas ice class notations, as well as the equivalence of these notations with national regulations (e.g. ASPPR (Canada) and RMRS).

As a simplified example we consider a project for offshore terminal tugs operating in the Kara Sea. The vessels are supposed to provide year round berthing assistance to oil tankers loading at various terminals in the area. Icebreaker assistance will be available throughout the year. In this case the tugs only need to perform light ice management duties and no heavy icebreaking. Figures 8 and 9 show the typical ice conditions the Kara Sea in February and May, respectively, while Figure 10 presents the average annual ice thickness in the same area.
From Figure 10 it becomes clear that for offshore terminals located in the eastern part of the Kara Sea the average maximum ice thickness would be about 1.6 m, see also Figure 11, while in the western part the average maximum ice thickness is less than 1.4 m. In this case the guidelines propose a minimum ice class of POLAR CLASS 4, as can be seen in Figure 12. This is consistent with Figure A1 in the Appendix for icebreaker assisted operation (maximum ice thickness 1.5 m).

The guidance note also provides levels of equivalency between the different ice classes, see Figure 12. It is to be noted that such equivalencies are only approximate. This is a consequence of differences in experience feedback as well as technical approach (e.g. plastic strength theory for Polar Class versus elastic strength theory for Ice Class).

**DIRECT ANALYSIS**

**Technical considerations**

Some technical considerations need to be made in relation to the existing rules and regulations, which are largely based on in-service experience feedback and the results of model testing with mainly merchant ships and dedicated icebreakers operating in the Baltic Sea and Arctic areas. This makes it somewhat difficult to assess the adequacy of the existing regulations for smaller and specialised ship types such as tugs and offshore support vessels, see also the comments in the section Ice Class Notations & Requirements. In addition, the present rules and regulations are quite general and do not easily allow to take into account local circumstances such as “light” ice conditions (icebreaking operations), low water salinity, shallow waters, etc.

In order to overcome these issues a more fundamental approach is needed. To this end Bureau Veritas is involved in the development of first principle strength assessment methods for ship structures under ice loading (ice-hull interaction). With such methods novel designs can be analysed, as well as stern-first operations in ice. In addition, such advanced methods – once validated – can be used to derive more practical and easy to use ice class rules.

Ice navigation is associated with the risk of ship damage due to a collision with ice floes, ridges or icebergs. Each (geographical) navigation area is characterised by its own ice types, ice conditions and, consequently, ice collision scenarios. The technical risk of an iceberg collision or ship damage during navigation in extremely severe ice conditions (e.g. grounded ridges) can be eliminated by modern ice monitoring systems and communication equipment. Consequently, the most common hazard for ships navigating in ice-infested waters is the ice pressure due to sailing in ice fields or among ice floes. To this end representative ice-ship interaction scenarios have been derived from experience feedback. The scenarios are described by a mathematical model developed through cooperative work between Bureau Veritas and St Petersburg State Marine Technical University. Generally, four scenarios
are considered as illustrated in Table 2 and Figure A3 in the Appendix.

Table 2: Ice load scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Contact</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glancing impact</td>
<td>bow, shoulder</td>
<td>moving in broken ice</td>
</tr>
<tr>
<td>reflected impact</td>
<td>bow, shoulder</td>
<td>moving in broken ice</td>
</tr>
<tr>
<td>Icebreaking</td>
<td>stern, bow, stern</td>
<td>moving in ice field</td>
</tr>
<tr>
<td>glancing impact</td>
<td>midbody</td>
<td>moving in channel, manoeuvring</td>
</tr>
</tbody>
</table>

**Mathematical model**

On the basis of these scenarios, and using a theoretical model for describing the mechanical behaviour of the intermediate layer which exists in the contact zone (observed from experiments by Russian scientists, see Figure 13), the equation of motion can be derived and solved in order to obtain the contact ice pressure, the linear intensity of ice load, the contact force and the vertical distribution of the ice pressure, as shown in Figure 14.

The basic assumptions behind the mathematical model are that the impact is non-elastic, the hull structure is rigid and that the pressure during impact is constant and equal to the ice (failure) strength. The solution of the equation of motion (application of Newton’s Second Law) takes following form [15]:

- \( p = p(b \mid \sigma = \sigma_{all}) \);
- \( p = p(v,F,M,a,f) \);
- \( b = b(v,F,M,a,f) \).

In these expressions \( p \) represents the contact pressure and \( b \) the vertical distribution of the ice pressure. The design contact pressure is a function of the vertical ice pressure distribution (height of the contact zone), taking into consideration the design strength (in terms of allowable stress) of the ship structure (\( \sigma = \sigma_{all} \)).

Both \( p \) and \( b \) are a function of the ship speed \( v \), the hull shape parameter \( F \) (depending on the angle of inclination of the sideshell and the waterline angle at the impact point), the reduction mass \( M_r \) (characterized by ship and ice floe mass and the impact direction) and the parameters \( a \) and \( f \) representing the physical and mechanical properties of the ice, respectively.

The main parameter influencing the choice of a vessel’s ice class and consequently the level of ice reinforcement is the ice thickness \( H \). Relating the vertical projection of the total contact force to the ice flexural failure force yields the ice pressure as function of the vertical ice pressure distribution for constant ice thickness: \( p = p(b \mid H = \text{constant}) \).

Application of the model enables to estimate the safe ice thickness given the ship’s hull strength and (design) speed, as well as the safe speed given the ship’s hull strength and the momentary ice thickness. This is illustrated in Figure 15, showing the ice pressure as function of the contact zone height for the design structural strength of the ship (\( p = p(b \mid \sigma = \sigma_{all}) \)) and several curves representing the ice pressure as function of the contact zone height for constant ice thickness (\( p(b \mid H = \text{Const}) \), for three levels of ice thickness). The intersection of the curves provides the limiting values for either design or operation.

Both \( p \) and \( b \) are a function of the ship speed \( v \), the hull shape parameter \( F \) (depending on the angle of inclination of the sideshell and the waterline angle at the impact point), the reduction mass \( M_r \) (characterized by ship and ice floe mass and the impact direction) and the parameters \( a \) and \( f \) representing the physical and mechanical properties of the ice, respectively.

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A more detailed description of the method is given by De Jong, Le Garrec and Dudal (2009) and Dudal, Yakimov and Tryaskin (2010) [15,16]. Further background information is also provided in the Bureau Veritas Guidance Note Ice Characteristics and Ice/Structure Interactions, 2010 [3]. Detailed information regarding the classification of ice is provided (considering ice age, form and crystallographic description), as well as an overview of the mechanical properties.
of ice (tensile and compression strength, flexural strength, etc.). In addition, the issue of ice-structure interaction is considered. Different ice failure modes (crushing, bending, buckling and splitting) are described together with their characteristic features and the interaction between failure modes.

One of the key points is the angle of inclination of the hull at the contact zone and the (reduction) mass. For an inclined hull (relative to the ice) the ice first fails in crushing mode, as the contact area is still small. Once the contact area has reached a critical value the bending moment on the ice is high enough to enough the ice will fail in flexural mode. This process is illustrated in Figure 16. It is to be noted that tugs and offshore support vessels generally have vertical sides (in the midbody area) and limited own mass (relatively small ships). This makes flexural failure of the ice relatively difficult to realise. Consequently, high ice crushing pressures are to be expected.

**IceSTAR software**

In close cooperation with St Petersburg State Marine Technical University the simulation software IceSTAR has been developed, which is an efficient tool for the application of the direct analysis method. The software is able to calculate the ice pressure and dimensions of the contact area (load patch) at any point on the hull surface with high degree of accuracy by taking into consideration the actual ship characteristics (hull geometry, mass, etc.) and ice characteristics. All relevant ice load scenarios can be studied for both moving ahead and moving astern (stern working). The gyration, heeling angle and drifting angle can be included in the description of the ship’s motion, as well as a number of parameters influencing the ice impact process. In addition to calculating the ice load distribution the programme is also able to produce the so-called allowable speed curve (as function of the ice thickness), see Figure 17.

The description of the ice properties encompasses many parameters, including the ice cover thickness, ice concentration (floes), density, flexural strength and dynamic crushing strength, Young's modulus and Poisson ratio, edge rounding radius and opening angle. In addition, consideration can be given to summer/autumn and winter/spring navigation.

With IceSTAR it is therefore possible to obtain a much more accurate and detailed ice load distribution compared to the existing rules, which only define the ice load acting on the lower part of the ship’s hull as a percentage of the ice load acting at the level of the summer waterline. This is particularly useful for novel designs (in relation to ice navigation) and navigation areas with special characteristics (ice properties).

The output data of ice load calculations – in terms of ice pressure and load patch dimensions – can be transferred onto a finite element model (FEM) of the structure in order to verify the structural resistance of the ship. This process can be executed for a number of relevant loading conditions (draught, trim) and load scenarios (motion description, including speed) for the expected ice conditions (navigation area, season).

**Application: icebreaking offshore tug**

In order to illustrate the direct analysis methodology, the example of a series of shallow draught icebreaking tugs (50 t bollard pull) is presented. The operating area is year-round in the North Caspian Sea (Kashagan field). The design icebreaking capability of the tugs is 0.6 m level ice thickness. The series of five vessels, with an overall length of about 66 m, have been designed by Aker Arctic (ARC 104) and are built...
by STX RO Offshore (Braila, Romania) for managing owners Caspian Offshore Construction in Kazakhstan. A picture of the second ship of the series, delivered in October 2010, is shown in Figure 18.

The characteristics of the operating area are as follows:
- Extremely shallow water (< 5m water depth);
- Ice formation in winter/spring season (first year ice only);
- Up to 80 cm level ice thickness;
- High flexural ice failure strength due to low salinity of seawater (about 0.5 MPa).

The icebreaking capability of the design has been assessed in two ways. First, model testing has been conducted at the Aker Arctic ice tank facilities in order to verify the hull form and the propulsion arrangement (installed power and pod configuration) in relation to the required capabilities for bollard pull, icebreaking and ice management, as shown in Figure 19. Secondly, a direct assessment of icebreaking capability of the ship has been made by applying IceSTAR simulations and finite element analysis (FEA). Moving in an ice field and in ice channel have been studied (icebreaking and manoeuvring, with consideration of ice floes in the channel). In addition, an analysis of drift angle and speed variation has been made (30 cases), see Figure 20, where the influence of the angle of inclination of the hull at the impact location can be clearly observed.

The results of the above mentioned studies, which provide a comprehensive insight in the ship's behaviour in the expected ice conditions, have been utilised to support the design review within the scope of classification.

**CLOSURE**

With the offshore oil and gas industry advancing further into areas with ice and cold climate, tugs and offshore support vessels need to be adapted to the associated challenges. The key to a successful ice-going tug design is in the proper understanding of the ship’s operational profile in terms of the operating area, time window (season), the required duties and the required level of autonomy.

The existing rules and regulations provide for the class notations **ICE CLASS** (first year ice), **POLAR CLASS** (multi-year ice), **ICEBREAKER** (first year ice and multi-year ice), as well as the **COLD** notation (winterisation). Guidance for the selection of the appropriate ice class notation, which should be based on the operating profile, is provided through the **Guidelines Ice Reinforcement Selection in Different World Navigation Areas, 2009** [14].

With regard to winterisation issues particular attention is to be paid to the harmonised safety standards for tugs [10]. The harsh operating conditions in ice and cold climate impose special consideration with regard to the general design and the selection of safety equipment in order to provide an adequate level of safety and comfort for the crew.

Some limitations with regard to the validity and applicability of the general rules and regulations to tugs and offshore support vessels have been identified, which need to be further addressed.
particular, there is a need for further development regarding stern-first operations and ice pods. To this end, several rule development programmes have been initiated, in which Bureau Veritas is an active partner.

The in-house developed IceSTAR software has been designed for direct assessment of ice loads and ship capabilities (e.g. speed as function of ice thickness). The programme is based on a rational mathematical ice-structure interaction model, making use of specific data regarding both the ship as well as the anticipated ice conditions. This enables the calculation of a detailed ice load distribution over the hull surface, for which the ship structure can be checked against by finite element analysis. This methodology supports the assessment of novel designs, as well as the development of more simplified technical requirements for areas currently insufficiently covered.

The ongoing developments are part of a comprehensive technical approach towards reducing the technical risks associated with tug operations in ice and cold climate, including icebreaking and ice management activities, which opens the way for a new generation of properly reinforced and winterised tugs.

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APPENDIX

<table>
<thead>
<tr>
<th>POLAR CLASS</th>
<th>Icebreaker assisted operations</th>
<th>Independent operations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Operations</td>
<td>Ice description (2)</td>
</tr>
<tr>
<td>POLAR CLASS</td>
<td>Year-round</td>
<td>all multi-year ice</td>
</tr>
<tr>
<td>1</td>
<td>Year-round</td>
<td>all multi-year ice</td>
</tr>
<tr>
<td>2</td>
<td>Year-round</td>
<td>second-year ice which may include multi-year ice inclusions</td>
</tr>
<tr>
<td>3</td>
<td>Year-round</td>
<td>thick first-year ice which may include old ice inclusions</td>
</tr>
<tr>
<td>4</td>
<td>Year-round</td>
<td>medium first-year ice which may include old ice inclusions</td>
</tr>
<tr>
<td>5</td>
<td>Summer/Autumn</td>
<td>medium first-year ice which may include old ice inclusions</td>
</tr>
<tr>
<td>6</td>
<td>Summer/Autumn</td>
<td>thin first-year ice which may include old ice inclusions</td>
</tr>
</tbody>
</table>

1. Proportion of sea covered by the ice, expressed in tenths.
2. Based on World Meteorological Organization (WMO) Sea Ice Nomenclature.

Figure A1: Bureau Veritas capability guidance table for POLAR CLASS [8]

<table>
<thead>
<tr>
<th>ICEBREAKER</th>
<th>Independent operations in summer/autumn</th>
<th>Independent operations in winter/spring</th>
<th>Design ramming speed in ice (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ice description (1)</td>
<td>Maximum ice thickness (m)</td>
<td>Ice description (1)</td>
</tr>
<tr>
<td>1</td>
<td>without restrictions</td>
<td>3.0</td>
<td>second-year ice</td>
</tr>
<tr>
<td>2</td>
<td>multi-year ice</td>
<td>3.0</td>
<td>medium first-year ice</td>
</tr>
<tr>
<td>3</td>
<td>second-year ice</td>
<td>2.5</td>
<td>thin first-year ice</td>
</tr>
<tr>
<td>4</td>
<td>thick first-year ice</td>
<td>1.8</td>
<td>medium first-year ice</td>
</tr>
<tr>
<td>5</td>
<td>medium first-year ice</td>
<td>1.2</td>
<td>thin first-year ice</td>
</tr>
<tr>
<td>6</td>
<td>medium first-year ice</td>
<td>1.0</td>
<td>thin first-year ice</td>
</tr>
<tr>
<td>7</td>
<td>medium first-year ice</td>
<td>0.8</td>
<td>thin first-year ice</td>
</tr>
</tbody>
</table>

1. Based on World Meteorological Organization (WMO) Sea Ice Nomenclature.

Figure A2: Bureau Veritas capability guidance table for ICEBREAKER [8]

Figure A3: Graphical representation of ice load scenarios