Arctic Marine Operations Challenges & Recommendations
Volume 5  Marine Icing on Arctic Offshore Operations - Pilot Project

Final report of the Arctic Operations Handbook Joint Industry Project
Version 15-12-2013
EXECUTIVE SUMMARY

The Arctic Operations Handbook Joint Industry Project (JIP) was launched in February of 2012 supported by a number of companies and knowledge institutes. The JIP was initiated by a number of Dutch companies in the framework of the Maritime Innovation Program (MIP) and was awarded a subsidy from the Dutch Ministry of EL&I (Economic affairs, Agriculture & Innovation). With it the JIP participants committed to issue an open source document to ensure that the work from the JIP is offered to the international arctic offshore community and the general public for further use.

The participating companies have the ambition to execute projects in arctic areas, such as installation and operations of oil and gas production facilities. The term arctic as used here refers to areas where ice, permafrost and low temperatures may influence offshore operations, field development and decommissioning.

Currently, there is no specific standard for companies operating in arctic offshore areas. To support this industry and to ensure services can be provided in a safe manner with minimum environmental impact, it was proposed to prepare guidance/standards for such operations. This project has taken an important step in gathering existing rules & regulations, identifying the areas which require additional guidance, and has taken some steps in defining guidance. The focus is on the operational activities for installation of fixed, floating and subsea units, dredging, trenching, pipe laying and floating oil/gas production. Detailed design of facilities & equipment was not covered in this JIP as it is already supported through ISO 19906 for Arctic Offshore Structures.

The development of guidelines and regulations in modern industry are expected to be functional, goal based, as much as possible relying on procedures and technology already in general use and, in this case, focused on arctic operations.

As part of the work scope the JIP has taken the initiative to liaise with Class Societies, Arctic Governmental Authorities and international standards organizations such as ISO. A diversified group of Dutch operators and knowledge centers have assessed deficiencies in existing standards and it is therefore considered useful and beneficial for the ISO TC67 SC 8 and SC 7 to use this report when preparing their new ISO norms.

This Arctic Marine Operations Challenges & Recommendations Report presents existing rules & regulations, identifies the areas which require additional guidance, and in those cases where possible defines recommendations for arctic operations. The index used in this report is based on ISO 19901-6; Petroleum and natural gas industries — Specific requirements for offshore structures — Part 6: Marine operations. The index has been adjusted and complemented with aspects specific for arctic operations.
The following key observations/guidance have been gathered within the scope of this Joint Industry Project;

- It was noted from the gap analysis that there was limited (ISO) guidance for pipe lay, trenching and dredging operations, let alone for the arctic areas. It was therefore chosen to provide a number of best practices for these operations, considering the arctic environment. The efforts concentrated on the aspects that would be new in the arctic when comparing with open water operations in non-arctic areas.
- Site specific operations should be considered when planning and carrying out operations.
- Considerable effort was performed to align the knowledge on weather conditions and in particular on the requirements for monitoring and forecasting as well as the requirements for decision based tools.
- For the transportation & logistic aspects input relied heavily on the existing guidance for arctic shipping which is further developed and was evaluated and transferred to recommendations for the specific services of this guide.
- This report provides guidance as required specifically for contractors expecting to work in arctic areas on the aspects of health, safety, training and also stakeholder mapping.
- A framework is provided to perform environmental impact assessments both in early as well as detailed stages of design in order to ensure that impacts can be managed and mitigated.
- Specific attention was given to the evaluation of the loads on and the operation of disconnectable floating production units.

The other volumes of this report contain results of the gap analysis performed in the project as well as relevant results of the pilot projects of the Arctic Operations Handbook (AOH) JIP;

- The IceStream – Pilot project, described in volume 3, has shown that the egg code (which is a method to describe characteristics of ice fields), when used as a basis to establish a visualization of the ice field, can serve as input to numerical models with which ice loads can be predicted on floating structures. More field data is required to support development of new analytical models.
- The Environmental Impact – Pilot project, described in volume 4, has developed an enhanced approach (interaction of linked sensitivities) for understanding the environmental impact of operations in an early project stage in a semi-quantitative manner. Application of such an approach is recommended to assess, evaluate and reduce the environmental impact of operations in arctic areas.
- A state of the art review for marine icing on vessels has been performed and has been documented in volume 5, Marine icing on arctic offshore operations – Pilot project. It highlights that although there are many approaches, there is no common approach and no industry standard for marine icing calculations. It strongly recommends more field observations and improved prediction models to determine sea spray formation and icing accretion.
Key recommendations from the Arctic Operations Handbook JIP are:

- Prepare more detailed operational standards including waiting on weather and ice, uptime and risk and hazard management.
- Develop equipment standards especially for the niche operations in this report.
- Prepare ice management guidelines, in concert where possible with the ISO TC67 SC 8 Work group 4, ice management.
- Guidance text for marine operations in arctic conditions has been prepared in this report. It is recommended that this can be incorporation into ISO 19901-6, or other ISO documentation.
- Implementation of an operational ice level into the ISO documentation for defining the ice action at which the (vessel) position may no longer be retained, due to structural or station keeping capability.

List of participants

The following companies have participated in the Arctic Operations Handbook JIP;

Allseas Engineering B.V.
American Bureau of Shipping
Bluewater Energy Services B.V.
Canatec Associates International Ltd.
Delft University of Technology
Deltas
GustoMSC B.V.
Heerema Marine Contractors B.V. [Project Coordinator]
Huisman Equipment B.V.
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IntecSea The Netherlands
MARIN
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Royal Boskalis Westminster N.V.
Shell Global Solutions International B.V.
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Impact of Marine Icing on Arctic Offshore Operations

Pilot Project, Volume 5 of Arctic Marine Operations Challenges & Recommendations Report
Title:
Impact of Marine Icing on Arctic Offshore Operations

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Abstract:
This report is intended to give designers a state-of-the-art review on the sources and distribution of ice accretion on ships. The goal is to develop an understanding of the subject, and to develop a guideline on ice accretion based on the best information available. Sea spray and atmospheric precipitation are the two principal sources of ice accretion. Most sea spray occurs up to 15 - 20 m above the sea surface and forms about 50 to 90% of the icing on ships, the remaining being atmospheric sources, depending on the world's geographic location. The main international code containing provisions for marine icing is ISO19906 (ISO 2010), which gives guidance on icing as a function of structure height and icing density, but no indication of the environmental factors giving rise to these icing parameters. Prediction of icing build-up rate is very complex. The physical processes of superstructure icing vary spatially and temporally on a ship, and icing rate is qualitatively related to ship size, speed, headway, temperature, and sea state. Today, modeling of sea spray and atmospheric precipitation are still in its development phases. Several methods are yet available for icing mitigation and removal, such as thermal, coating, chemical or mechanical. Vessel design for anti-icing may increase design and construction cost, but can significantly increase workability and has potentially minimal operational costs.
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1 Report Overview

1.1 Introduction

Ice accretion on fixed or floating offshore structures is a potential concern for operations in cold climates and can lead to a variety of problems. Even light ice accretion can lead to many operational difficulties: slippery decks, ladders, and handrails can be safety hazards; equipment such as winches, derricks, and valves can be rendered useless, causing delays in operation; ice on radar antennas can interfere with operations, creating a safety hazard; life-saving and firefighting equipment can be rendered unusable. For ground-based structures, heavy ice accretion can be a serious concern because of the increased size of structural members. This can lead to higher lateral wave and wind forces than anticipated. For floating structures and vessels, the effects are more serious, in that ice accretion can increase the draught, reduce the freeboard, and raise the center of gravity of the vessel, thereby compromising stability.

This report is intended to give designers a state-of-the-art review on the sources and distribution of ice accretion on ships. The goal is to develop an understanding of the subject, and to develop a guideline on ice accretion based on the best information available. It is not intended, however, to provide detailed methods for estimating ice accretion loads for all types of vessels or structures for all environmental conditions, as such technology is simply not yet available.

1.2 Report Scope

The chapters of this report are divided into the following subject areas:

- Chapter 2 covers the fundamentals of sea spray and atmospheric icing. It provides an overview of ice accretion observations to date (historical and current), and summarizes the available theoretical ice accretion models.
- Chapter 3 presents a review of applicable Rules, Codes and Standards, starting with the most recent International Standard (ISO 19906), followed by the Russian Rules for sea going ships, MODUs and FOPs. This leads to a discussion of the main national standards (Canadian, US, and Norwegian), and the classification society guidelines (principally DNV and ABS). This chapter concludes with a comparison of icing provisions for potential users of the Arctic Operations Handbook, and then uses the information in a comparative assessment for two different vessel types.
- Chapter 4 provides an overview of the available models for theoretical and deterministic prediction of icing accretion prediction, and draws some principal recommendations.
- Chapter 5 summarizes the available knowledge on the mitigation and removal of icing, and presents some recent information on effective for anti-icing.
- Chapter 6 presents general conclusions and recommendations for future work.

1.3 Report Authors

Dr. Gus Cammaert of Delft University of Technology (TUDelft) was the prime author of this report. Technical assistance and review was provided by Benny van der Vegte of IntecSea. Research assistant for this study was Marijn Abrahamse (BSc student) of TUDelft.

The management of this pilot study was undertaken by IHC Merwede (Robert Plat and Frank Renting).
2 Sources of Ice Accretion

Ice accretion on ships and offshore structures has two principal sources:

- **Sea spray** - this type of ice accretion occurs when the air temperature is below the freezing point of seawater (approximately \(-2^\circ\text{C}\)) and air-borne brine droplets impact a structure and partially freeze. Sea spray is mainly generated by wave-structure impact and the wind convects spray to portions of the structure downstream of the source. Sea spray can also be generated by strong winds that shear off the tops of wave crests (referred to as “spindrift”) and by bubbles bursting in breaking waves. For offshore structures, sea spray from wave-structure interactions is usually the dominant source of ice accretion because of the large flux of seawater past the structure.

- **Atmospheric precipitation** - these sources include freezing rain, super cooled fog, and pellets of wet snow or ice. Freezing rain is the term for water droplets that are cooled below 0\(^\circ\text{C}\) ("super cooled") in the atmosphere and partially freeze on impact with a structure. This ice accretion source tends to produce “glaze” ice, which is clear ice with a density of approximately 900 kg/m\(^3\). Supercooled fog is the term for highly super cooled water droplets that freeze completely on impact with a structure and produce a porous white deposit known as “rime” ice, which has a density of 100 to 600 kg/m\(^3\), depending on the air temperature and wind velocity. Pellets of wet snow or ice (which can include ice flakes) adhere to a structure on impact and produce a layer that is a mixture of snow and water. Compaction of the snow layer by the wind may produce a density of approximately 350 kg/m\(^3\), which is greater than that of wet snow falling on the ground.

2.1 Fundamentals of Sea Spray Icing

Sea-spray generated ice, or superstructure ice, has a greater impact on vessels, especially vessels of supply boat size and smaller, than does atmospheric ice. Superstructure ice forms when drops are created from waves splashing against the structural elements of rigs and vessels, typically below main deck level. For smaller vessels, spray originates from bow/wave interaction, and is carried over the ship by wind after the spray rises above the deck if the rails are open, or above solid bulwarks. Most sea spray occurs 15 to 20 m above the sea surface, but it can be lofted as high as 30 to 60 m (Figures 2.1 and 2.2). However, liquid water content at the greatest heights will be low and thus presents less of a hazard.

Russian studies indicate that, in most parts of the world, sea spray forms about 90% of the icing on ships. However, in the Arctic, sea spray is only about 50% of the source for icing, the remaining being atmospheric sources. In addition, there is little evidence that freezing rain is a significant hazard to vessels and platforms. Minsk (1984) indicates that freezing rain occurs only about 4% of the time in the Barents and Chukchi Seas. Large vessels generally are not moving and hence the effects of sea spray on FPSOs, for example, is expected to be much less than on smaller ships.

Limited information is available on icing observations for larger vessels, and as such is only available for ships in transit. A very severe case was documented in 1991 (Figure 2.3). A 120-m container ship left a European port with a 0.2-m trim by the stern and reached port at Quebec City with a trim by the bow of approximately 4.0 m. A heel of five degrees developed and the
vessel became directionally unstable. The ship master was totally unaware of the serious icing forward until a boarding pilot reported the developing condition. It is clear from the figure that icing in the bow area appears to be at its highest value (no thickness measurements were reported), but at the stern the thickness of icing is minimal - it was progressively thinner with distance from the bow. Ships with containers stacked on the forward end are particularly vulnerable to ice accretion on the forecastle deck structure and adjacent areas. Large quantities of ice accumulation may develop and remain unnoticed even during daylight hours, since observation of that part of the ship from the bridge may be obstructed.

For stationary vessels the only data that appears to be available is for drilling rigs. Typically, the majority of icing of drilling rigs is caused by sea spray (Figure 2.4). Because drill rigs are stationary (except when in transit), sea spray typically is found in greatest concentration from 5 to 7 m above the sea surface, to 10 to 20 m above the sea surface. Most of the literature indicates that splashing of a stationary rig is less intense than splashing of a ship, and that spray rarely carries more than 5 to 10 m above the sea surface.

Most investigators agree that sea-spray icing on superstructures is typically the greatest threat to safety for stationary platforms, causing slippery decks, ladders, handrails, icing on helicopter platforms, deck cargo, winches, and other equipment, causing operational delay and additional costs. Ice on antennas cuts communications and distorts radar signals for navigation. Ice-coated windows, rescue equipment hatches, winches, and cranes reduce safety. Added weight during icing decreases stability and buoyancy, and additional sail area causes heeling (Figure 2.5). Bridge windows become covered with ice; winches, windlasses, boats, life rafts, firefighting equipment and valves, and radar domes become ice-covered and inoperable (Figures 2.6, 2.7 and 2.8).

### 2.2 Fundamentals of Atmospheric Icing

The expression “atmospheric icing” comprises all processes where drifting or falling water droplets, rain, drizzle or wet snow in the atmosphere freeze or stick to any object exposed to the weather.

Unlike other meteorological parameters such as temperature, precipitation, wind and snow depths, there is generally very limited data available about atmospheric ice accretion. The wide variety of local topography, climate and icing conditions make it difficult to standardize icing actions.

The best source of information on atmospheric icing is the ISO standard (ET ISO 12494). The standard states that the lack of available data requires urgent comparisons between collected data and the exchange of experiences, since this will be a way to improve knowledge and data necessary for a future comprehensive International Standard for atmospheric icing. Detailed information about icing frequency, intensity, etc. should be collected. The following methods may do this.

Atmospheric icing is traditionally classified according to two different formation processes - precipitation icing and in-cloud icing. The maximum amount of accreted ice will depend on several factors, the most important being humidity, temperature and the duration of the ice...
accretion. A main precondition for significant ice accretion are the dimensions of the object exposed and its orientation to the direction of the icing wind.

2.3 Ice Accretion Observations

Observations of ice accretion on offshore structures are scarce; however, there are a few publications that give some idea of the potential for ice accretion as a function of environmental conditions. Kelly and Karas (1989) provide environmental and icing data for the semi-submersible Ross Rig operating in the Barents Sea during the winter of 1987–88. There are also reports of ice accretion observations on offshore rigs for the semi-submersibles Ocean Bounty in Alaska (Nauman and Tyagi, 1985), Sedco 708 on the North Aleutian Shelf (Minsk, 1984), Bow Drill 3 off the east coast of Canada (Mitten, 1987), and Sedneth II off the east coast of Canada (Agnew, 1985). A detailed review of these observations is presented in Chung and Lozowski (1996). In addition, Brown and Horjen (1989) present information on ice thickness profiles and estimates of ice mass for several ice accretion incidents involving offshore structures.

More recently, icing was observed in the Norne and Draugen fields in the Norwegian Sea, but no measurements are reported (Teigen, 2012).

2.4 Ice Accretion Models

Estimates for total ice accretion loads on offshore structures fall into two categories: modeling and field observations/measurements. Numerical models for estimating ice accretion combine the spray generation rates discussed above with the thermodynamics and heat transfer processes associated with freezing. The modeling is complex because seawater does not freeze completely (resulting in concentrated brine pockets within the ice and brine drainage from the ice layer) and the ice layer develops large surface irregularities that augment the ice accretion process.

Further discussion on accretion models is provided in Chapter 4 of this report.
Figure 2.1 Ice accretion zones
(after Ryerson, 2008)

Figure 2.2 Icing on Russian vessel
(unknown source)
Figure 2.3 - Icing buildup on containership in the Gulf of St. Lawrence (from Transport Canada, 2009)

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Figure 2.6  Icing build-up on evacuation equipment  
(after Loset, 2012)
Figure 2.7 Icing build-up on ship deck (from DNV)

Figure 2.8 Icing build-up on Norwegian icebreaker (after Loset, 2012)
3  Review of Rules, Codes and Standards

3.1  Introduction

The main international code containing provisions for marine icing is ISO19906 (ISO 2010). ISO has also published a comprehensive code for atmospheric icing (see references). This section also provides a summary of the Russian, Canadian, US and Norwegian codes as well as DNV and ABS guidelines. It concludes with a comparison of the marine icing provisions of all relevant standards.

3.2  International Standard ISO 19906

The ISO Standard on Arctic Structures gives a short section on marine icing and its effects in Sections A.6.3.5.3 - Marine Icing (ISO, 2010). The code points out that:

“The extent of ice accretion from sea spray, freezing rain or drizzle, freezing fog or cloud droplets shall be considered in the design and operability of the structure. Ice accretion can increase the diameter of structural components and can lead to a substantial increase of actions caused by wind and self-weight, particularly for long slender structure such as flare towers. Ice accretion also affects operations and personnel safety.”

The discussion on icing covers both atmospheric icing and sea spray icing (or marine icing). Atmospheric icing is described in terms of what type of phenomena this is, where it will occur on the structure and under what conditions. For marine icing ISO19906 also discusses the phenomena, the most usual conditions causing it to occur and the “typical” severity (in mm/h) of icing as a function of temperature and wind speed.

According to the code sea spray is formed in two ways. The most important with regard to icing is sea spray generated by the vessel or structure as it interacts with waves. The second form is created when the wind blows droplets of water off wave crests and depends on the form and steepness of the waves and wind speed.

The code states that sea spray icing begins to occur at wind speeds of 8 m/s to 10 m/s. The stronger the wind, the higher the spray is lifted. While the height of sea spray icing is usually limited to 15 m to 20 m above the sea surface, there have been reports of sea spray icing at up to 60 m above the sea surface.

Certain ranges of air temperature, water temperature and wind speed are required to cause a significant accumulation of superstructure icing. These conditions are

- an air temperature less than the freezing point of seawater (depending on the salinity of the water)
- a wind speed of 10 m/s or more;
- a seawater temperature colder than 8 °C.

A strong wind, cold air, and cold seawater all contribute to greater accumulations of ice. In Arctic and cold regions seas, icing can occur throughout the year. Icing is most likely at the end of autumn or in winter when air temperatures are below zero and there is no ice cover on the sea surface. Generally, from mid-winter to mid-summer, salt water icing is unlikely. From end of
summer to mid-winter, marine icing accounts for about half of all cases of icing; most of the remainder are mixed icing, simultaneous marine and atmospheric.

The code classifies icing by its intensity as slow, fast, or very fast. Broadly speaking,

- Slow icing (ice accumulation of less than 10 mm/h) occurs when air temperature is between 0 °C and -3°C and any wind speed, or with air temperatures of -3°C or lower and a wind speed of less than 7 m/s;
- Fast icing (ice accumulation between 10 mm/h and 30 mm/h) occurs with air temperature between -3°C and -8°C and wind speeds of 7 m/s to 15 m/s;
- Very fast icing (ice accumulation greater than 30 mm/h) occurs with air temperature at or below -8°C and wind speed of more than 15 m/s.

The rate of ice thickness accumulation also depends on the structure and the height above water. The duration of the icing phenomenon exceeds 12h in three quarters of reported cases; its maximum duration is seven days. During the period prior to freeze-up, the occurrence rate of slow icing is 20% to 40% in the coastal areas and 50% to 70% in the central parts of the Arctic seas. The occurrence rate of fast icing ranges from 1% to 5% in the southern parts and up to 10% in the northern parts of the Arctic seas. These values increase by about 10% in the latter part of this period. Icing can also accumulate through a series of independent icing events. Much depends on the degree of melt and loss of adhesion between events as well as possible countermeasures.

The topic of icing is also covered in other sections:

- Measurement of icing mass is covered briefly under Section 8.3.1.2.1 (Ice accumulation-general)
- The application of ice-phobic coatings are described in Section A.13.8.1.3.

The ISO standard gives guidance on icing as a function of structure height and icing density, but no indication of the environmental factors giving rise to these icing parameters.

### 3.3 RMRS Rules for Sea Going Ships

Under RMRS Rules for the Classification, Construction and Construction of Sea-Going Ships, “for ships navigating within winter seasonal zones, stability with due regard for icing shall be checked in addition to the main loading conditions”.

Under Section 2.4 (Allowance for Icing) the mass of ice per square meter of the total area of horizontal projection of exposed decks shall be assumed to be 30 kg (equivalent to 33 cm of ice build-up at a density of 900 kg/m³). The mass of ice per square meter of wind age area shall be assumed to be 15 kg (equivalent to 17 cm of icing).

The rules for sea-going ships do not include variation of ice accretion with vertical height.

### 3.4 RMRS Rules for MODUs and FOPs

RMRS Rules for MODUs and FOPs also stipulate that a unit must be checked for ice and snow accretion if the unit is operating within a winter seasonal zone.
In Section 2.5.5 guidelines are given on ice and snow accretion. For units operating within winter seasonal zones to the north of latitude 66° 30’N, as also in winter in the Bering Sea, the sea of Okhotsk and in the Tatar Strait, the specified mass of ice per square meter of the total area of horizontal projection of exposed decks shall be assumed to be 30 kg if those decks are located at a height up to 10 m above the water line, 15 kg if the height is from 10 m up to 30 m, and if the height is above 30m the mass of ice may be neglected.

The specified mass of ice per square meter of the wind age area of the structure shall be assumed 15 kg if those decks are located at a height up to 10 m above the water line, 7.5 kg if the height is from 10 m up to 30 m, and if the height is above 30m the mass of ice may be neglected.

For some other regions the accumulation is provided as a ratio of the rates described above. The code also contains guidelines for the snow load. The mass of snow per square meter shall be 100 kg for unmanned units and 10 kg for manned units.

3.5 Canadian Standard CSA S471

*(note – the Canadian code may have been withdrawn and replaced by ISO19906 provisions, but for the time being the discussion below will be retained for discussion purposes)*

The Canadian code CSA S471 (General Requirements, Design Criteria, the Environment and Loads) gives only a short discussion on snow and ice accretion" in Section 5.2.3 of the code:

- Ice accretion from sea spray, freezing rain or drizzle, freezing fog, or cloud droplets shall be considered in the design. In the absence of specific information, the ice that can form on the structure may be assumed to have a density of 900 kg/m³.

It also refers to Annex I of the code for more guidance on ice accretion.

Estimates for total ice accretion loads on offshore structures fall into two categories: modeling and field observations/measurements. Numerical models for estimating ice accretion combine the spray generation rates discussed above with the thermodynamics and heat transfer processes associated with freezing. The modeling is complex because seawater does not freeze completely (resulting in concentrated brine pockets within the ice and brine drainage from the ice layer) and the ice layer develops large surface irregularities that augment the ice accretion process. Two ice accretion models have been developed specifically for offshore structures.

Observations of ice accretion on offshore structures are scarce; however, there are a few publications that give some idea of the potential for ice accretion as a function of environmental conditions. Kelly and Karas (1989) provide environmental and icing data for the semi-submersible Ross Rig operating in the Barents Sea during the winter of 1987–88. There are also reports of ice accretion observations on offshore rigs for the semi-submersibles Ocean Bounty in Alaska (Nauman and Tyagi, 1985), Sedco 708 on the North Aleutian Shelf (Minsk, 1984), Bow Drill 3 off the east coast of Canada (Mitten, 1987), and Sedneth II off the east coast of Canada (Agnew, 1985). A detailed review of these observations is presented in Chung and Lozowski (1996). In addition, Brown and Horjen (1989) present information on ice thickness profiles and estimates of ice mass for several ice accretion incidents involving offshore structures.
As a final note, the CSA code states “a designer should obtain as much environmental data as possible for the region of operation, including data from climatic atlases, ship measurements, site measurements from rigs operating in the area, and coastal stations.” (more to come)

### 3.6 US Standard API RP2N

The standard contains two sections on icing:

- **Section 4.3.5:** “Icing of structural members can result from fog, freezing rain or wind driven seawater spray. Data for estimating icing potential may be found in Searby (1977). A predictive method for calculating structural icing is given in Wise (1980), Makkonen (1989) and Labelle (1983). Information on icing in the Bering Sea can be found in McLeod (1977) and Pease (1986).”

- **Section 10.3.4:** “Accretion of ice on the superstructure of vessels or floating construction equipment can cause local over stressing, construction equipment malfunction, and reduction of overall stability. A stationary structure’s icing rate under marine conditions is addressed in Itagaki (1984). A prediction methodology that accounts for atmospheric and spray icing in the Bering Sea is discussed in Zakrzewski (1986). Topside icing, due to bow spray of naval ships in the Bering Sea, is discussed in Thomas (1992). Where built-up ice may break off and fall, personnel and equipment should be protected. Measures such as clean surface design and heating can minimize ice build-up. Consideration should be given to methods of icing removal after reaching a critical mass or volume. This especially applies to moored vessels where a change in direction is not practical. Icing can also occur on the mooring lines above and below the waterline which may increase the mooring load on the vessel.”

Furthermore, the standard states in several places that ice and snow loads should be taken into account in the design of the structure but no design method or values are given.

### 3.7 Norwegian Standard NORSOK N-003

The only Norwegian Standard that currently provides guidelines for ice accretion on offshore structures is NORSOK N-003. In this standard, ice accretions due to sea spray and atmospheric icing are considered separately, and ice accretion thickness and density are specified for various elevations on the structure. Compared to previous mentioned codes it has a slightly different approach to which areas of the structure are subject to icing and prescribes a linear reduction in the ice accretion between 10 m and 25 m above sea level. For ice accretion due to sea spray only, there are guidelines on ice thickness for various latitudes. However, these guidelines have been developed for Norwegian coastal regions only.

### 3.8 DNV Classification Rules for Ships

*(note – this section to be replaced by updated version)*

A part of the DNV Classification Rules for Ships (Part 5, Chapter 1 – Ships for Navigation in Ice), ships with class notation WINTERIZED COLD will fulfil certain additional requirements.
Part of these requirements relate to Section C203 which gives the additional ice load to be included in the loading conditions and satisfying applicable stability requirements:

- For decks, gangways, wheelhouse tops and other horizontal surface, the values found in Table Error! No text of specified style in document..1 below;
- For projected lateral area of each side of the vessel above the water plane: 7.5 kg/m².

The projected lateral area of discontinuous surfaces of rail, sundry booms, spars (except mats) and rigging of vessels having no sails and the projected lateral area of other small objects shall be computed by increasing the total projected area of continuous surfaces by 5% and the static moments of this area by 10%.

**Table** Error! No text of specified style in document..1: **Icing load (kg/m²) to be applied to decks, gangways, wheelhouse tops and other horizontal surfaces**

<table>
<thead>
<tr>
<th>Distance from Forward Extremity</th>
<th>From 0 to 50 m Aft of F.P.</th>
<th>From 50 to 100 m Aft of F.P.</th>
<th>&gt; 100 m Aft of F.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 18 m from WL</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>&gt; 12 to 18 m from WL</td>
<td>40</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>&gt; 6 to 12 m from WL</td>
<td>80</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>0 to 6 m from WL</td>
<td>120</td>
<td>60</td>
<td>30</td>
</tr>
</tbody>
</table>

1 For surfaces with active anti-icing systems, the icing weight load in that area may be set to 30 kg/m².

Note that there is no allowance for reduction of icing weight on vertical planes with height as there is in the RMRS and NORSOK formulations.

Furthermore the code includes some general information on anti-icing and de-icing methods in Sections B 100 and B 200 subsequently.

### 3.9 ABS Guide for Vessels Operating in Low Temperatures

To assist the marine industry, ABS issued the Guide for Vessels Operating in Low Temperature Environments (ABS, 2010). Included in this Guide are the ABS criteria that are intended to assist in the design, operation, and maintenance of vessels when operating in either continuous or occasional operation in ice.

Throughout the guide it is clearly described that icing should be taken into account in the design of the vessels but the only reference to ice accretion is found in Appendix 3, Figure 1 of the Guide, which is a grouping of icing nomograms developed by the United States National Oceanic and Atmospheric Administration (NOAA) from actual icing reports from fishing, U.S. Coast Guard and towing vessels operating in Alaskan waters. These reports were based on icing events that lasted anywhere from 1 to 26 hours but averaged 3 to 6 hours.

Appendix 3, Figure 2 of the Guide provides information on ice accretion versus wind velocity for air temperatures ranging from -34°C to -7°C. The source of this information is the US Navy Cold Weather Handbook for Surface Ships (May 1988).
The ABS Guide also specifies the ABS requirements and criteria for obtaining the optional notation of DE-ICE, which is a notation available for vessels occasionally operating in low temperatures subject to ice accretion.

Furthermore the guide addresses several anti-icing and de-icing methods in the Section 5.1.7 and Section 10.

3.10 Comparison of Icing Provisions in Various Codes and Standards

The following table (table 3.2) provides a comparison of the marine icing provisions of the various standards and rules presented above. The study team did not have access to the Russian rules, however, and relied on summary reports by others for the discussion in Sections 3.3 and 3.4.
Table 3.2 (Part 1): Comparison of Icing Provisions in Various Codes and Standards

<table>
<thead>
<tr>
<th>Country</th>
<th>ISO 19906 Arctic Structures</th>
<th>RMRS Rules for Sea Going Ships</th>
<th>RMRS Rules for MODUs and FOPs</th>
<th>CSA S471 Canadian Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year published</td>
<td>2010</td>
<td>2009</td>
<td>2005</td>
<td></td>
</tr>
<tr>
<td>Vessel types</td>
<td>All types</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max size (mt)</td>
<td>no restriction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational area</td>
<td>worldwide</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accounts for sea spray icing (yes/no)</td>
<td>yes</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Accounts for atmospheric icing</td>
<td>yes</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Air temp range (1)</td>
<td>&lt; freezing (1)</td>
<td></td>
<td></td>
<td>&lt; -2°C</td>
</tr>
<tr>
<td>Water temp range (1)</td>
<td>&lt; 8°C (1)</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Wind speed range (1)</td>
<td>&gt; 10 m/s (1)</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Max icing thick. (mm)</td>
<td>NS (1)</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Icing load hor. surfaces; hor. height range (m) &amp; load range (kg/m²)</td>
<td>(2)</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Icing load (kg/m²) lateral area each side and height range</td>
<td>(2)</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Icing load (kg/m²) windage area and height range</td>
<td>(2)</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Icing density (kg/m²)</td>
<td>850 to 500</td>
<td></td>
<td></td>
<td>If unknown 900; rime 100 to 600; compacted snow: 350</td>
</tr>
<tr>
<td>Snow load (kg/m²), unmanned units</td>
<td>NS</td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Snow load (kg/m²), manned units</td>
<td>NS</td>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

(see notes end of part 2 of table)
Table 3.2 (Part 2): Comparison of Icing Provisions in Various Codes and Standards

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max size (mt)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Year published</td>
<td></td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Max size (mt)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Year published</td>
<td></td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Vessel types</td>
<td>Offshore concrete, steel and hybrid structures</td>
<td>All types of offshore structures</td>
<td>All vessel types</td>
<td></td>
</tr>
<tr>
<td>Year published</td>
<td>USA 2007</td>
<td>Norway 1999</td>
<td>International 2005</td>
<td>USA 2010</td>
</tr>
<tr>
<td>Operational area</td>
<td>Arctic and sub-arctic regions</td>
<td>Focus on Norwegian waters</td>
<td>Arctic and Antarctic regions</td>
<td></td>
</tr>
<tr>
<td>Accounts for sea spray icing</td>
<td>yes</td>
<td>yes</td>
<td>no (3)</td>
<td></td>
</tr>
<tr>
<td>Accounts for atmospheric icing</td>
<td>yes</td>
<td>yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Air temp range (1)</td>
<td>NS</td>
<td>NS</td>
<td>Ranging from -7°C to -34°C</td>
<td></td>
</tr>
<tr>
<td>Water temp range (1)</td>
<td>NS</td>
<td>NS</td>
<td>-1.5°C to 3°C</td>
<td></td>
</tr>
<tr>
<td>Wind speed range (1)</td>
<td>NS</td>
<td>NS</td>
<td>0 - 50 m/s</td>
<td></td>
</tr>
<tr>
<td>Icing load horizontal surfaces; horizontal height range (m) &amp; load range (kg/m²)</td>
<td>NS</td>
<td>No distinction is made between surface orientation or location</td>
<td>&gt;18, 30 12 - 18, 40 - 30 6 - 12, 80 - 30 0 - 6, 120 - 30</td>
<td>NS</td>
</tr>
<tr>
<td>Icing load (kg/m²) lateral area each side and height range</td>
<td>NS</td>
<td>See above</td>
<td>7.5</td>
<td>NS</td>
</tr>
<tr>
<td>Icing load (kg/m²) windage area and height range</td>
<td>NS</td>
<td>See above</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Icing density (kg/m²)</td>
<td>NS</td>
<td>0 m to 10 m 850; 10 m to 25 m: linear from 850 to 500</td>
<td>900</td>
<td>NS</td>
</tr>
<tr>
<td>Snow load (kg/m²), unmanned units</td>
<td>NS</td>
<td>0.5 kPa</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Snow load (kg/m²), manned units</td>
<td>NS</td>
<td>0.5 kPa</td>
<td>NS</td>
<td></td>
</tr>
</tbody>
</table>
Notes to tables

1) The code describes three different icing rates: slow icing (10 mm/h), fast icing (10 to 30 mm/h) and very fast icing (faster than 30 mm/h):
2) slow icing; air temperature is between 0°C and −3°C and any wind speed, or with air temperatures of −3°C or lower and a wind speed of less than 7 m/s,
3) fast icing; air temperature between −3°C and −8°C and wind speeds of 7 m/s to 15 m/s,
4) very fast icing; air temperature at or below −8°C and wind speed of more than 15 m/s.
5) No mention is made of surface orientation or location. An example (location off Norway) is given in which icing thickness depends on latitude.
6) The code also describes wind and wave conditions (depending on ship length) needed to cause severe icing (assuming cold air and water temperatures).
4 Prediction of Accretion Rates

4.1 Introduction

The prediction of how much icing will build up in a period of time is a very complex subject. The physical processes of superstructure icing vary spatially and temporally on a ship, and icing rate is qualitatively related to ship size, speed, headway, temperature, and sea state. This includes the dynamics of how, hypothetically, ice could be forming on one portion of a ship, and eroding on other portions (Ryerson, 2013).

4.2 Factors Effecting Ice Accretion

The size and design of a ship has a major effect upon the rate of super-structure spraying during icing conditions, and the subsequent growth of topside ice. Smaller vessels are immersed with spray more frequently than larger ships because of their lower freeboard and greater ship motions. Also, bow spray clouds are more likely to cover the entire superstructure of a small ship with a large spray flux than large ships. This is related to the size distribution of drops in spray clouds. Larger drops have greater fall velocities than small drops. Droplet sizes in spray events can range from less than 10 μm to 3 mm diameter at the bow. As the bow jets break up into drops and they are accelerated by the wind over the ship, they begin to fall. Large drops have higher terminal fall velocities than small drops, but the time, and distance, required to reach terminal velocity is greater for large drops than for small drops (Ryerson, 2013).

The distance that spray moves aft, the portion of the ship that is wetted, is a function of the relative wind speed and the height of the spray jet. The height of the spray jet is a function of true wind speed, ship speed, and ship heading according to Zakrzewski et al. (1988a, b). They also state that wetting of the superstructure is greatest when spray crosses 60 to 70° off the bow because the water source is now closer to the superstructure (Zakrzewski, 1987). Drops originating over the bow in head seas potentially must travel farther to reach the superstructure. Head seas may be more likely to allow drops to be carried farther aft, if the spray jet is high enough, because the trajectory will be directly aft. However, ship heading also influences where ice forms on a ship. Quartering seas, or their approximation, cause spray to be carried across the deck and may actually cause more impingement on the opposite side of the ship from where the spray originated than on the near side (Chung and Lozowski, 1999).

Hull shape also influences the amount of spray lofted over the superstructure. Ships with greater freeboard in the bow area and greater bow flare tend to deflect spray away and reduce entrainment of drops into the relative wind. Sapone (1990), in tow tank experiments, found that bows with increased flare (tested from 35 to 55° flare angles) reduce the wetted area of decks. Greater flare also reduced the volume of spray liquid water reaching decks, reduced the distance spray travelled aft, and produced finer drops at the deck edge than did bows with less flare angle.

Superstructure spray icing occurs when sea water is delivered to the ship superstructure and sufficient heat can be removed from the spray droplets in flight and from the water film on the superstructure after the droplets have collided and splashed, that the water can freeze. Air supercools drops in their first few seconds of flight, but if the sea is too warm, even very cold air
may be insufficient to cool drops sufficiently that they freeze after collision. The water may run off the ship without freezing.

Generally, sea temperature must be lower than 5°C for superstructure icing to occur according to Guest (2005; DeAngelis, 1974). The US Navy indicates that the critical sea water temperatures for superstructure icing in the Gulf of Alaska, the Aleutian Islands, the Bering Sea, and the Arctic is between -2.2 and 8.9°C (Fett et al., 1993; Sechrist et al., 1989). Brown and Agnew (1985), in assessing about 1000 ship icing reports in Canadian water from the 1960s to the 1980s, found that water temperatures were typically 0 to 2°C during icing events.

Winds may also contribute significantly to icing. Wind helps carry spray over the ship, and may create the seas that cause the spray when the bow pitches into them. In addition, the wind increases convective cooling of the drops. The Navy Forecasting Handbooks indicate that faster wind speeds generally see more ice forming (Fett et al., 1993; Sechrist et al., 1989). Brown and Agnew (1985) find winds associated with icing to be typically 26 to 31 m/s off the Canadian east coast, and 15 to 20 m/s in the Arctic. Ryerson (1991) found mean wind speeds of 16 m/s in ship icing off of the Canadian east coast, though speeds did range up to 33 m/s.

Wave heights are also important generators of spray. Without waves, bow plunging would not occur to create spray jets and spray clouds. However, ships of different size interact with sea states differently, with smaller vessels creating spray in lower sea states than larger ships because of their greater pitch angle and pitch frequency, and typically lower freeboard. The database analyzed by Brown and Agnew (1985) in Canadian waters includes ships ranging in size from fishing trawlers to cargo ships. They found icing to be associated with seas of 2 to 4 m off the east coast of Canada and in Hudson Bay, but seas of 1 to 12 m in the Scotian Shelf area, the Grand Banks, and off Newfoundland. Seas of 6 to 8m accompanied icing in the Gulf of St. Lawrence, Labrador Sea, and eastern Arctic. The western Arctic had seas of less than 2.5 m during icing. Ryerson (1991) found that waves averaged about 1.6 m high, and swells 1.8 m off the Canadian east coast during icing.

Sea spray ice accretion rates vary considerably with location on a ship (Ackley 1985). Ice accretion rates are determined by the balance of heat delivery by spray, both sensible and latent, and atmospheric heat removal processes. Figure 4.1 illustrates three icing zones that often occur on all sizes of ships. The maximum accretion zone is where spray delivery matches the atmosphere’s ability to remove sensible and latent heat from impinged water at a sufficient rate for all spray to freeze (although some spray remains trapped as brine within the ice). Maximum accretion may take place at bow locations maximally exposed to the wind, such as at the top of the bow and windlass located on the forecastle of the fishing trawler shown in Figure 4.2. However, during heavy spraying, much ice may also accumulate amidships, where the spray flux is smaller and the rate of heat removal by the atmosphere is still large (Figure 4.1). This is demonstrated by the wheelhouse roof and areas immediately aft of the wheelhouse on the trawler (Figure 4.2).

Thermally limited accretion (Figure 4.1) takes place where the spray water delivered exceeds the atmosphere’s ability to remove its sensible and latent heat. Thus, ice accretion rates are smaller than water delivery suggests. Large spray fluxes, and thus thermally limited accretions, are normally only found on the bow areas of large ships, even though large volumes of spray can reach farther aft on smaller ships.
Guest (2005) provides guidelines relating vessel length, significant wave height, and wind speed to threshold icing conditions (see Table 4.1).

**Table 4.1 Threshold wind speeds for icing to occur on various length ships**
(from Guest, 2005)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>15 meters</th>
<th>30 meters</th>
<th>50 meters</th>
<th>75 meters</th>
<th>100 meters</th>
<th>150 meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel Length (feet)</td>
<td>49</td>
<td>98</td>
<td>164</td>
<td>246</td>
<td>328</td>
<td>492</td>
</tr>
<tr>
<td>Significant wave height - $h_{1/3}$ (meters)</td>
<td>0.6</td>
<td>1.2</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Wind Speed at 200 km (108 nmi) fetch (meters/second)</td>
<td>5.0</td>
<td>7.4</td>
<td>9.8</td>
<td>12.5</td>
<td>15.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Wind Speed at 200 km (108 nmi) fetch (knots)</td>
<td>9.7</td>
<td>14.4</td>
<td>19.0</td>
<td>24.3</td>
<td>29.3</td>
<td>38.9</td>
</tr>
</tbody>
</table>

Note: This is only a rough guide for ships steaming into the wind and waves. The actual potential for icing depends on the type, load, and handling characteristics of a particular ship. Any captain or bridge officer who is familiar with a ship should be well aware of the wind speeds which cause sea spray to reach the deck and superstructure, and should base their assessment on the potential for icing on this knowledge.

Icing rates, the result of seas, wind, spray, and cold, are either expressed as a thickness or mass accumulation with time, and are usually expressed for the entire ship. Icing rates suggest how quickly ships may become dangerously loaded with ice. Even small amounts of ice on a ship can reduce the safety of personnel operating on decks, and also degrade optical systems, sensors, and antennas. Icing rates are usually indicators of how quickly seaworthiness may deteriorate, but they are also an indication of the deterioration of ship operations and safety (Ryerson 2013).

### 4.3 Theoretical and Deterministic Models

Two theoretical ice accretion models have been developed specifically for ships and offshore structures:

ICEMOD was developed in 1986 at the Norwegian Hydrotechnical Laboratory by Horjen and Vefsnmo (1986a, 1986b) and modified in 1987 (Horjen and Vefsnmo, 1987) and 1988 (Horjen et al., 1988). RIGICE was developed in 1987 (Roebber and Mitten, 1987) in response to a request from government regulatory agencies to determine icing norms and extremes for offshore structures operating in Canadian coastal waters; recently, some modifications have been made to RIGICE, particularly with regard to spray generation (Lozowski et al., 2002). Brown and Horjen (1989) and Chung and Lozowski (1996) compare these two ice accretion models. It should be noted that neither model has been completely verified quantitatively by field measurements of ice accretion on structures, but the models can still be used for comparative purposes.
The deterministic predictor model suggested by Overland et al (1986) is the following

\[ PR = \frac{V_A(T_F - T_A)}{1 + \Phi(T_W - T_F)} , \]

where

\[ V_A = \text{wind speed (m/s)} \]
\[ T_F = \text{freezing point of seawater (°C)} \]
\[ T_A = \text{air temperature (°C)} \]
\[ T_W = \text{water temperature(°C)} \]
\[ \Phi = 0.4 \] (empirical constant)

The equation gives the following prediction of icing rates (Table 4.2):

**Table 4.2 Prediction of icing rates**
from Overland (1986)

<table>
<thead>
<tr>
<th>Icing rate (cm/h)</th>
<th>Light</th>
<th>Moderate</th>
<th>Heavy</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predictor PR (°C/m)</td>
<td>&lt; 0.7</td>
<td>0.7 - 2.0</td>
<td>&gt; 2.0</td>
<td>&gt; 5.0</td>
</tr>
</tbody>
</table>

Overland re-derived his 1986 algorithms in 1990, but stated that the 1986 algorithms were operationally performing well (Overland 1990). The new derivation accounts for super cooling of drops in flight when sea water temperatures are lower than 2 to 3°C. This required reclassifying icing rates into four categories (Table 4.3).

**Table 4.3 Prediction of icing rates by various authors**

<table>
<thead>
<tr>
<th></th>
<th>Light</th>
<th>Moderate</th>
<th>Heavy or very severe</th>
<th>Very severe, extreme, very heavy</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overland et al. (1986)</td>
<td>&lt;0.7</td>
<td>0.7 - 2.0</td>
<td>&gt;2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overland (1990)</td>
<td>&lt;0.7</td>
<td>0.7 - 2.0</td>
<td>&gt;2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lundquist and Udin (1977)</td>
<td>0.04-0.17</td>
<td>0.25-0.75</td>
<td>&gt;1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sawada (1973)</td>
<td>&lt;0.5</td>
<td>0.5 - 2.0</td>
<td>&gt;2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kachurin et al. (1974)</td>
<td>—</td>
<td>—</td>
<td>1.8</td>
<td>4.2</td>
<td>—</td>
</tr>
<tr>
<td>Mertins (1968)</td>
<td>0.04-0.125</td>
<td>0.17-0.25</td>
<td>0.29-0.56</td>
<td>&gt;0.625</td>
<td>—</td>
</tr>
<tr>
<td>Wise and Comiskey (1980)</td>
<td>0.09-0.21</td>
<td>0.21-0.42</td>
<td>0.42-0.63</td>
<td>0.63-1.06</td>
<td>&gt;1.06</td>
</tr>
</tbody>
</table>

Wise and Comiskey (1980) used Mertins’ earlier (1968) nomograms and combined them into one based on additional icing reports from the northeast Pacific Ocean. They also included
climatologies of the north-eastern Pacific Ocean and the north-eastern Atlantic Ocean (Feit, 1985).

It should be kept in mind however that these models are limited by the following:

- No variation with vessel geometry,
- No input of sea spray properties
- Steady state assumption
- Thermally limited scenarios

### 4.4 Real Time Mapping of Icing Severity

NOAA uses the algorithms developed by Overland (as discussed above) that relate icing to wind speed at a height of 10 m, the sea water freezing temperature, air temperature at 2 m, and sea surface temperature. Designed from a database of “58 carefully selected cases of trawlers 20 to 75 m in length”, the prediction algorithms generate three classes of icing rates. Forecasts are made at 3-hour intervals for 6-hour forecast periods on a 1° latitude by 1° longitude grid globally. Icing rates are predicted in three intervals: light is 0.3 to 2.0 cm of ice in 3 hours, moderate is 2.0 to 6.1 cm of ice in 3 hours, and heavy is greater than 6.1 cm of ice in 3 hours (see also Table 4.2). Forecast maps show areas where each category could occur over 6-hour periods, with forecasts created every three hours for one week ahead. These rates are defined as the “maximum sustained rate for typical Alaskan vessels, 20- to 75-m length, which are not actively avoiding icing through heading downwind, moving at slow speeds or avoiding open seas” (Overland 1990). See examples of typical icing maps in Figure 4.3 and 4.4.

Forecast maps of icing are available directly from the Internet for the November-May Northern Hemisphere icing season. The National Centers for Environmental Prediction (NCEP), Ocean Modeling Branch (OMB), has a web site with icing maps for the North Atlantic, North Pacific, Eurasian and off the U.S. East Coast (“NOPP Demonstration Area”). This site is also sponsored by the US Department of Commerce, The National Oceanographic and Atmospheric Administration (NOAA) and the National Weather Service (NWS).

www.weather.nps.navy.mil/~psguest/.../predict.html

### 4.5 Numerical Models

Several research teams have recently applied computational techniques to simulate icing accretion rates on various types of vessels.

The MARICE project is a multi-year effort by DNV, the Norwegian University of Science and Technology (NTNU), Statoil and the Research Council of Norway (NFR) to study the ice accretion issue. A three-part system was designed to study the amount of water lifted from different types of ship bows in different weather conditions and estimation of the movement of droplets over, and their impingement with, the superstructure of vessels, neglecting the possibility of droplet break-up or coalescence.

An ATC paper by Shipilova et al. (2012) describes the MARICE model of sea spray dynamics, based on published models of spray generation, fluid dynamics based simulation of droplet movement subjected to reasonable simplifying assumptions, and a simple mechanism of droplet freezing and runoff. The model was applied to two different vessels of similar size and profile -
the Geosund shown in Figure 4.5 has a helicopter deck impeding airflow over the top of the vessel. Freezing rate estimates were compared to experimental measurements conducted in cold conditions on Svalbard.

The authors state that modeling of sea spray generation is the most challenging subject in marine icing. The amount of spray, its density, duration and frequency depend on the ship design, speed and heading with respect to the waves. Few data are available in published literature on this issue.

Figure 4.6 shows the calculated airflow for the initial wind speed of 25 m/s for the Geosund in the plane along the vessel centerline. The maximum flow velocity reaches 46.6 m/s in the entire domain. As it can be seen the helicopter deck on the Geosund forms a shelter above the bridge. Thus, it is expected that the main part of the spray droplet cloud will end in the very front of the hull.

To analyze the results on the ice accretion the authors have chosen to divide the vessel superstructure into three main areas: Front, Bridge and Rear. Figure 4.7 shows the icing rate on the Geosund for the total vessel, as well as for the three major areas of the ship, as functions of air temperature for the cases (in the left-hand column) where the droplet temperature is the same as the air temperature and (in the right-hand column) where the droplet temperature is the same as the seawater, +5°C.
Figure 4.1 Ice accretion zones on a ship during spray-generated events (from Ryerson, 2008)

Figure 4.2 Ice accretion zones on trawler in the Bering Sea
Ryerson 1990)
Figure 4.3 Icing prediction for North Pacific areas  
(from NOAA)

Figure 4.4 Icing prediction for Barents Sea areas  
(from NOAA)
Figure 4.5  Example of complex superstructure – the Geosund supply vessel
Shipilova et al, 2012

Figure 4.6  Velocity field over Geosund superstructure, 25 m/s wind speed
Shipilova et al, 2012
Figure 4.7  Computed ice accretion rate for Geosund
Shipilova et al, 2012

The technology innovator.
5 Icing Mitigation and Removal

5.1 Introduction

Platforms operating in cold regions are protected primarily by designs that reduce ice accretion, coupled with the selective use of heat. A variety of de-icing and anti-icing technologies have been tested on offshore platforms and boats, but with mixed overall success. New technologies and modern versions of old technologies, now used successfully in aviation, the electric power industry, and on transportation systems in general, may be transferable to the offshore environment.

A report by published by the US Army Corps of Engineers (Ryerson, 2008) has identified, explained, and reviewed fifteen classes of de-icing and anti-icing technologies, as well as numerous ice detection technologies. This report has been the main source of information used for this Appendix.

The report by Ryerson addresses the superstructure icing threat to offshore oil structures and supply vessels by assessing how sea spray icing and atmospheric icing affect operations and safety. It also indicates how selected technologies can help improve safety on offshore structures, and reduce the magnitude of the additional loads on the vessel and the superstructure.

Only those methods which have potential for large-scale anti-icing or de-icing applications on board offshore vessels are reviewed here. These methods fall under the following categories:

- Thermal Methods
- Coatings and Chemicals
- Other De-icing Methods

“Design” is treated here as a mitigation method as well.

The reader is referred to the original Ryerson report for further information.

5.2 Thermal Methods

There are two methods of preventing icing. One is to prevent liquid water from reaching the surface to be kept ice-free. The other is to heat the surface sufficiently so that it is anti-iced, or heated periodically after icing to induce de-icing. Though costly in energy, heat is often the best and most cost-effective approach (Ryerson, 2008).

For anti-icing or de-icing, sufficient heat must be applied to at least cause melting at the ice/substrate interface. Or, heat must be sufficient to prevent latent heat from being released from the water, causing ice. Water releases 334 J/g (334 W/cm^3) to freeze at 0°C. Therefore, an anti-icing system must supply a sufficient amount of heat to prevent even a small volume of water from freezing. Much less energy is required for de-icing if melting only a thin layer of water is necessary to release ice from the substrate.

Heat is provided by a wide variety of technologies for many different applications. Provided here is a review of electrothermal, hot air, and hot water de-icing.
Electrothermal Heating

Electro-thermal heating results from heat from electrical resistance heating. Not considering the source of electrical power, resistance heating is 100% efficient - all of the energy conducted through the wires is converted to heat. Typically, Nichrome wires as found in electric heaters that are controlled by thermostats, or materials such as carbon layers, which vary in thickness with location and are self-healing and self-regulating, are used. Ships commonly use heating cables to prevent icing of walkways, hatches and bulkhead doors (Figure 5.1).

Another source of heat for de-icing and anti-icing is hot air. The automobile windshield defroster is a classic example of de-icing using hot air, and illustrates well the relatively modest ability of air to transfer heat to solids. Obviously, this type of systems would have rather limited application for a large offshore vessel.

Hot Water

Hot water has recently been used to deice aircraft where the use of chemicals needs to be controlled. In a series of experiments, hot water at a temperature of 60°C was applied to plates contaminated with ice in air temperatures as low as -9°C at wind speeds of 2.8 m/s. De-icing was considered successful if a surface experiencing an ice accretion rate of 0.25 cm/cm²/hr would de-ice and remain de-iced for 3 min or longer. Hot water performed acceptably, similarly to Type I de-icing fluids under the same conditions. However other experiments have indicated that water could refreeze on drained surface where no icing had previously formed.

Infrared De-icing

Infrared de-icing is a well-proven heating technology and it has had some application for de-icing. Infrared may be considered a sub-application of de-icing technologies using heat. However, it is unique because it is a remote technology; objects are heated through absorption of infrared energy from an emitter that has a temperature allowing it to radiate in the infrared portion of the electromagnetic spectrum. However the technology has not been applied to ships, as far as is known.

5.3 Coatings and Chemicals

Coatings

According to the CRELL report, “coatings are materials applied to the surface of ice-accreting substrates to reduce the adhesion strength of ice to the substrate”. Also according to the report there is a common notion that ice phobic coatings (coatings that have reduced adhesive strength with ice) will prevent or reduce icing. Because ice phobic coatings also are often hydrophobic, they do have the potential to reduce icing amounts. However, ice phobic coatings typically do not prevent icing and, in general, hydrophobic coatings (those that repel water) are not necessarily also ice phobic.

Development and testing of ice phobic coatings is one of the most active areas of anti-icing/de-icing research. Coatings are attractive because an ideal coating would prevent icing, would be easily applied over any substrate, would be inexpensive, would require little or no maintenance,
and because of its passive nature would require no power. In reality, most hydrophobic coatings have little ice phobicity, most do not have longevity (thus requiring frequent maintenance or cleaning to maintain the low adhesion characteristics, especially after numerous icing events), and many are not easily applied and require frequent reapplication.

Coating technology varies widely in material properties, chemistry, and design. Most coatings are of a single chemical compound that is applied to surfaces by spraying or brushing. Or, they are materials such as plastics that can be structural materials themselves. As a solid material, Teflon has been found to have nearly the lowest ice adhesion strength of all materials. Polyethylene has an adhesive strength similar to Teflon. However, Teflon is soft and is not generally a durable structural material. Other non-durable materials that have demonstrated very low adhesion values include silicone grease and lithium grease. But grease typically readily washes from surfaces, and is often removed with the ice, making it a nondurable coating.

Despite these remarks however, some new coatings show promise. The lowest adhesion strength ever measured at CRREL (US Army Cold Regions Research and Engineering Laboratory) was a silicone by NuSil Technology (see references in CRREL report, p. 59). Compared to Teflon’s average adhesion strength of 238 kPa, NuSil R-2180 has an average adhesion strength of 37 kPa. Another material, Phasebreak B-2, has an average strength of 117 kPa. Even after roughening with sandpaper and weathering to simulate thermal and humidity cycling and salt spray, the adhesion strength of NuSil R-2180 was always lower than that of unweathered Teflon.

In many cases, coatings that only reduce ice adhesion are insufficient. Coatings also require easy field application and often require abrasion resistance. Several companies have proposed developing coatings that are ice phobic and abrasion-resistant. However, only one such coating is in development. Further details are not available at this time.

Researchers are still seeking a coating that will prevent ice formation, and at least two approaches have been taken. The first is a nanotechnology approach to embed capsules of anti-icing compound within an ice phobic coating material (Microphase 2008). Microphase Coating, Inc. has created a coating with low ice adhesion that is erosion-resistant and renewable, and has high adhesion to substrates. The coating is composed of epoxy, silicate mesh, and freezing-point depressants in embedded nano-capsules. As the coating erodes, the capsules break and slowly release freezing point depressant at the ice-coating interface, thereby intending to reduce ice accretion rates. A company in Norway (Re-Turn AS, www.re-turn.no) is carrying out similar research.

**Chemicals**

De-icing and anti-icing chemical development is probably the most active area of ice control research with regard to new products and investment capital. This is because dry and wet chemicals are used in large volumes and at great cost for highway and runway ice and snow control and for airframe de-icing and anti-icing.

The most widely used de-icing chemicals are sodium chloride, calcium chloride, magnesium chloride, potassium chloride, calcium magnesium acetate, and urea. Sodium chloride (NaCl), rock salt, has been used heavily since the 1940s. Sodium chloride is most effective at temperatures warmer than -10°. However, the large volumes of material that may need to be
used are of concern because of potential problems with environmental impact and metal corrosion.

5.4 Mechanical Methods

Manual methods are still the primary technique for removing ice from smaller vessels and marine structures, even in recent years. In the mid-1980s, de-icing was still largely accomplished with wooden baseball bats, fire axes, hammers, and crowbars, as was done a century earlier on whalers and other craft (Ryerson, 2008). However, mechanical methods are slow and laborious, expose crew to dangerous conditions, and can damage marine equipment and components such as machinery and windows. These methods can chip paint and damage newer composite materials that are not resilient to impacts.

5.5 Other De-Icing Methods

Electrical Techniques

Recently several innovative de-icing technologies have been developed using electrical techniques that cause ice to melt in a thin layer at the ice/substrate interface, melt through the entire ice thickness, or cause erosion of the ice, thereby physically disconnecting it from the substrate. Methods also have been developed for electrical control of ice adhesion to substrates, causing it to either decrease or increase at will.

Three fundamental electrical techniques have been developed to modify the adhesion strength of ice to substrates. The techniques are 1) application of a DC voltage to the ice/substrate interface, 2) pulse electothermal de-icing, or 3) ice dielectric heating. These inventions evolved from basic research funded by US government agencies, as well as by private industry. Because the more recent engineering work is privately funded, many details are proprietary and are therefore unavailable.

The research up to the present time is largely experimental, and has only been used in small-scale applications like helicopter or wind turbine blades.

Hydraulic and Steam Lances

Hydraulic de-icing involves the use of high pressure water jets to remove ice from surfaces. Some researchers have concluded that high-pressure lances for de-icing of ships are a viable method that is safer and less expensive than alternatives. It has generally been concluded that the water jet approach, though high in initial cost, deserved additional investigation.

An experimental high pressure (75 to 125 psig) flash flow system for de-icing that operated between 122°C and 133°C, has been demonstrated in the US. The concept was that such a system could operate from the ship fire mains and use a portable heater to raise water temperature (Fig. A-6), but not convert the water to steam. Therefore, seawater could be used. The result is a two-phase flow with about 10% steam that, in experiments, removed ice faster than a 4000-psi water jet. Tests showed the ability to remove ice 10 cm thick and up to 186 cm² of ice per second. Recommendations were to construct a prototype system for shipboard testing. However it is unknown whether this was done.
Steam lances also were commonly used at sea in the past because of the ready availability of steam from engine boilers. Løset (1985), for example, recommends steam as a method of removing ice from ships and drill rigs.

All de-icing with high pressure hydraulics is still experimental. There are no systems known to be sold as high pressure hydraulic de-icing systems (Ryerson, 2008).

5.6 Safe Vessel Operations in Icing Events

Det Norske Veritas (DNV), an independent Norwegian foundation, manages risk, similar to Lloyds of London and the American Bureau of Shipping. Because superstructure icing and snow produce ice on decks and superstructures, they can affect the stability, safety, and general operation of vessels. Ice covering navigational equipment and deck mechanical equipment reduces safety (Koren 2007). Therefore, DNV has developed the class notation DEICE to ensure operational safety by providing anti-icing requirements for equipment and areas of a ship where continuous operation is required, such as navigational equipment and fire lines, and de-icing requirements for equipment and areas where ice accumulation is acceptable (Magelssen 2005). However, the ship must be equipped to de-ice within 4 to 6 hours of accumulation. DNV’s concerns are impairment of stability, impaired navigation caused by inoperable antenna and radar equipment, and icing of wheelhouse windows. Deck equipment, such as rescue equipment, lifeboats, and life rafts may be sufficiently iced that davits are inoperable. Vents and anchors may be ice covered and inoperable, and gangways and railings may be ice-covered, making it dangerous to operate safely on deck. DNV’s standards are intended to encourage vessel operators to operate more safely in icing conditions.

Equipment and areas that DNV requires to be anti-iced include the following (Magelssen, 2005):

1. Communication equipment and antennas.
2. Radars.
3. Wheelhouse windows.
5. Cooling water systems.
6. Firefighting equipment.
7. Anchor equipment.
10. Lifeboats, davits, rafts, man overboard boats, and launching areas.
11. Escape exits.
12. Storage lockers or rooms for lifesaving or de-icing equipment.
13. Cargo system emergency shutoff or venting valves.

Equipment and areas the DNV requires to be de-iced within 4–6 hours of the end of an icing event include the following (Magelssen, 2005):

1. Open deck and extra cargo areas.
2. Gangways, stairways and access to bow.
4. Railings.
5. Outdoor piping.
7. Deck lighting.
8. Protected locations with heating.

5.7 Design for Anti-Icing

Improved design of vessels and topsides can be a significant method of reducing superstructure icing. Of the methods for preventing icing, preventing water from freezing, or preventing liquid water from striking the superstructure, the overall effect is that design reduces water from striking the superstructure and freezing to it. Also, as stated in the Ryerson report “optimal design is a passive technology that has minimal operational cost if it does not cause inefficiencies, though it may possibly increase design and construction cost”.

Numerous examples can be drawn from reports for other types of vessels that may be relevant for the design and operation of an FPSO. A report for de-icing of drilling vessels typically recommended including an enclosed derrick, heated walkways, wind walls, additional heating facilities, and temporary local shielding around working areas. As well as standard de-icing equipment another source recommends a system to constantly flush the deck with warm seawater during icing conditions. The overall design must be as “clean” as possible, with few small-diameter elements, enclosed systems, and freeboard sufficient to reduce splashing of deck and other working areas.

Figure 5.3 shows a well-enclosed topsides (in this case, for the Goliat Development off northern Norway. Figure 5.4 shows a very efficient bow (the Ullstein X-bow) design that would minimize icing problems over the rest of the vessel in that sea spray is interrupted from reaching the rest of the vessel, and icing that does form could be flushed away with warm sea water.
Figure 5.1 - Example of electric resistance elements for walkways

Figure 5.2 - Portable-icing system for ships
Figure 5.3 - Platform design for efficient anti-icing

Figure 5.4 - Polarcus Adira with Ulstein X-bow design
6 Conclusions and Recommendations

6.1 General Conclusions

The main conclusions arising from the current report are as follows:

- Despite many years of observations, and the development of empirical and analytical models, marine icing remains a serious operational issue for small and large vessels alike.
- The catastrophic capsize of smaller vessels is still taking place, with subsequent loss of life.
- For larger vessels ice accretion can lead to serious safety hazards and loss of usability.
- Sea spray icing remains the predominant threat for vessels of all types. Limited observations are available for icing of larger vessels.
- As offshore operations are expected to continue in Arctic regions, the threats to life and safety will inevitably increase.
- Though the Arctic is warming sufficiently to cause significant warm season sea ice retreat, sea surface temperatures will largely remain within a few degrees of freezing, and the increase in fetch and the high frequency of storms and moderate to strong winds will make superstructure icing a greater danger.
- Work is continuing on national and international codes and standards, but there is little agreement between them, and they mostly rely on observations in specific geographic regions.
- Icing codes and standards usually only give estimates for the total amount of icing that may occur, and most do not give specifics on longitudinal and vertical variations in icing buildup.
- Empirical models for ice accretion rely mostly for smaller vessels, and extrapolation to the larger vessels used in oil and gas operations are questionable.

6.2 Recommendations

Recommendations related to marine icing can be divided into practical operating guidelines, and issues regarding codes and standards. With respect to operational issues:

- Icing due to ice spray can be reduced by selection of a new course, adaption of a reduced speed or avoiding open seas or heading into ice if practical.
- Nearly all ship de-icing is now done manually, with some ship-specific technological help such as deck heating systems. Modern technology should be used for de-icing and anti-icing to a greater extent.
- Technologies that do not require crew to be on deck in severe weather, at night, and on slippery surfaces would be of value.
- Decks on the forward part of the ship, but also including lifeboat launch should be given highest ice protection priority. This will remove considerable weight, improving vessel seaworthiness and stability, and provide a safe topside operating environment.
- Measures like heat traced lifeboat hatches and davits are recommended and vessels should be equipped with arctic life rafts which have trace heating installed inside them.
• De-icing or anti-icing electronics, mooring and navigation, safety and boat launch hardware will improve safety and allow greater operating success.

• Vessel design for anti-icing may increase design and construction cost, but can significantly increase workability and has potentially minimal operational costs.

With respect to prediction of sea ice accretion rates in particular:

• There is a need for more field observations of sea spray formation and icing for all types of vessels

• Systematic procedure should be developed to determine sea spray formation and air flows for particular types of vessels.

• New prediction models should be developed that are relevant for larger vessels based on actual observations and measurements.
APPENDIX A – REFERENCES

A1 CODES AND STANDARDS


DNV (2013). Classification Rules for Ships, Part 5, Chapter 1 – Ships for Navigation in Ice


A2 RESEARCH REPORTS AND PAPERS

Note this list is not meant to be exhaustive; it focuses on field measurements and observations, and empirical rather than theoretical models


Corps of Engineers, Engineering Research and Development Centre, Report ERDC/CRREL TR-08-14.
