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Abstract

The purpose of this report is to investigate the phenomenon of vessel icing in general and examine the problem for the Shtokman FPSO, which is now being designed to operate in severe conditions in the Barents Sea. Ice properties, icing conditions and intensity, geography of possible vessel icing are studied in details.

Another aim is to develop theoretical models of the FPSO icing considering its dimensions and design features. The goal is to analyze all known anti – icing strategies, deicing and ice detection technologies for application and workability in the certain case of the Shtokman field. Finally possible affects of ice presence and icing on the FPSO productivity and stability are studied. The results of the work might be taken into account in further vessel's design improvements and for efficient anti – icing strategies.

One of several major features of the FPSO from icing point of view is sophisticated deck geometry with a number of deck structures of different height and width. Another issue is a presence of different equipment and engines that may act as sources of heat. This problem hasn't been studied yet due to its specificity.

The work combines both theoretical research basing on the new proposed mathematical model and numerical calculations of icing on the FPSO according to different international rules and standards. Results of this comparison are very promising and show potential for other work in this direction.

Key words: icing, vessels, Barents, FPSO, offshore, marine, production.

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Introduction

The phenomenon of vessel icing is usually represented by an accumulation of a significant layer of ice on the vessel’s above-water body, deck, topsides, bridges, life boats, pillars and equipment. Ice damages and breaks down ship-radio communication, reduces coefficient of stability, causes changes in draft and deteriorates its controllability. Vessel icing is known to be a serious threat for the vessel’s stability and the possibility of carrying out marine operations in cold regions at high latitude. One of the main concerns is that because the center-of-gravity position is rising up the ship’s stability reduces and risk of capsizing occurs - and there is lot of records of such accidents from the very ancient times up to recent. One of possible reasons that the Kolskaya jack-up capsized as it is discussed now was icing on the platform together with harsh environment conditions [3].

Despite of the fact that the phenomenon of vessel icing has a long record in history, it is not well studied and even discussed. The answer to this is the fact that first knowledge of vessel icing was presented by fishermen and marine explorers. And it is quite obvious that they didn’t stay in the area where the vessel was subjected to icing – on the contrary the only rational action to escape was to leave to another location. Nowadays when world-growing demand of hydrocarbons calls for exploration and production in severe Arctic regions, the problem of vessel icing has received new lights. After the start of the oil exploration in the cold regions of Norway and Alaska and with an increased number of marine operations understanding the icing problem became vital for the oil and gas industry. Point here is that during exploration and all the more so for production operations, we merely can’t leave the location (depends on type of activity, for some of them the time of planned work is up to 50 years). In condition of icing superstructure icing makes these marine operations more difficult and dangerous and can delay the operation in time. It means that new methods of icing prevention and de-icing should be invented which is completely impossible without clear understanding of the mechanisms of the icing process.

Statistically the threat of vessel icing is pressing for small displacement ships with low freeboard. Almost 80% of vessels lost because of icing during last 80 years were less than of 100 meters length. Those were harvesting and small transport vessels presenting fishing industry in areas associated with the possibility of vessel icing for 6 months a year. For example, in nearshore zone of Greenland icing threat is almost for 9 months, and in the Barents, Bering and the Sea of Okhotsk it’s 8 months [9].

Unfortunately there is no good and up-to-date reliable statistics for ship icing (although there special agencies investigating such events). But according to [10] every year the world fleet loses 10 vessels because of icing and dozens get in critical conditions. For instance, only in 1968 near west coast of Kamchatka and Kuril Islands 56 ships were exposed to icing within weather conditions of minus 10-12 degrees Celsius of air temperature, wind speed 15-20 m/s and wave height more than 3 meters [8].

But what’s important here is to understand that most statistical data of vessel loss due to icing problems don’t account for near loss of ships and icing accidents [5]. It also does not cover all potential safety issues caused by iced superstructures and top-sides. Although there is a number of marine organizations that request data about any icing accident.

A lot of work regarding ship icing was carried out in the former Soviet Union in order to provide ice-defense of fishing catchers. In 1970s there were series of researches devoted to icing in Russian Far East, Baltic and Northern seas.

Based on this experience and studies of Russian Fishing industry standards and rules [11] were developed for vessel acting in the areas with potential threat for icing. These rules restricted any work for vessels of certain type and limited work (work and transit to the site only in groups or with guidance) for others. It also called for permanent presence of supply vessels. It’s obvious that those recommendations were applicable only for the fishing industry with small trawlers, and were focused only at post-actions and didn’t try to control icing itself.

However further study of icing with means of theoretical researches, field studies of the vessels and model experiments are needed. The last of these are complicated by the fact that objective principles of icing are not available and criteria of similitude for modeling of the process are unknown. Modeling of ship icing in laboratories is therefore difficult. Despite of it some supplementary experiments have been carried out in the United Kingdom, Island and in other countries that have helped to change the construction rigging of fishing ships. In the former Soviet Union icing was studied in the laboratories of Arctic and Antarctic Research Institute (AARI), Polytechnical Institute in Leningrad, Moscow State University and Hydrometeorological Institute in Leningrad [2,6,7]. These investigations consisted of:

- conditions of icing generation and based on it, the corresponding development of a prediction system and warning about the threat of icing;
- characteristics of ice generated at the vessel;
- development of technical equipment against icing;

- influence of icing on the seagoing performance of the vessels, consideration of icing for stability and minimum free board rule-making
- ship maneuvering in conditions of icing.

Different specialists in physics, termothecnics, meteorology, hydrology, ship theory and ship design participated in those studies.

Nowadays physics of icing is actively studied and special means and methods are developed to protect vessel from icing which can be divided into: active methods – ice removal, changes in ship design etc., and passive – prevention of icing and predicting. Active methods can be mechanical (simple removal), physical (usage of thermal, ultrasonic and electrical methods for ice removal and its prevention), physical-chemical (usage of dissolving agents or agents to reduce temperature of icing) and integrated.

All new researches in this field methods should take into account the experience gained before but unfortunately this is a hard task because the problem of vessel icing is not studied properly, and the results of experiments and works carried out twenty and more years ago are almost impossible to find (even in the Libraries with printed materials).

The high priority research needs for development and practical interest are now focused at:

- specification of areas exposed to icing and investigation of vessel’s navigation with different amount of icing;
- investigation of ice distribution at the ship’s topsides;
- changes of sailing performance dependent on accumulated mass of ice;
- analysis of efficiency of different agents and methods to fight icing;
- determination what type of vessels are exposed to icing.

The work in the field of vessel icing is to assess all the potential hazards and threats of icing and to develop methods and techniques to mitigate the effect of icing for safe and operational processes. The protection technologies should be efficient and reliable, following the rule of “keep it simple” to provide sustainable work for long time.

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1. Geography of vessel icing

The latitude limits areas with favorable hydro meteorological conditions for vessel icing. In the Arctic the northern border for possible spray icing is the edge of unbroken ice because continuous ice bodies prevent generation of waves at the sea surface. The southern border coincides with the isothermal line of - 1.5 °C for considerable time of a year.

In winter areas of potential vessel icing expand further and cover northern seas: the Greenland sea, the Norwegian, the Barents, the Baltic, the Bering, seas of Japan, Chuckchee and Okhotsk.

Most often severe vessel icing occurs in the following areas: from the northern coast of Norway and the Kola Peninsula to the Spitsbergen in the Barents sea; in the Northern Atlantics near shore of Island and Canada; in the sea of Okhotsk and in the northern part of the Japan sea; in the Bering sea near shore of Alaska; near the Kuril Islands and Kamchatka [9].

Statistically from [9] we can see how vessel icing is distributed among the seas (See Table 1).

Table 1 Distribution of vessel icing among the seas [1]

Area	Percentage
The Barents and Norwegian Sea	34.5%
The Bering Sea	25.5%
The Sea of Okhotsk	18.0%
Westen Pacific Ocean	10.5%
The Sea of Japan	8.1%
The Baltic Sea	2.4%
The Black and Azov Seas	1.0%

Another source [12] gives us a number of emergencies occurred by vessel icing in different seas during the period from 1950-1971 (See Table 2).

Table 2 Distribution of vessel icing among the seas [12]

Area	Number (%)
The Barents and Norwegian Sea	877 (38.6%)
The Bering Sea	571 (25.2%)
The Sea of Okhotsk	437 (19.3%)
Westen Pacific Ocean	182 (8%)
The Sea of Japan	140 (6.2%)
The Baltic Sea	44 (1.9%)
The Black	18 (0.8%)

In the work [5] we can find timing of possible vessel icing in different seas (See Table 3).

Table 3 Timing of possible vessel icing in the seas [5]

Area	Timig
North-West Atlantics	15 Dec – 15 Mar
The Norwegian and Greenland Sea	15 Dec – 31 Mar
Northern Atlantics	15 Jan – 15 Apr
The Barents Sea	1 Dec – 15 Mar
The Baltic Sea	15 Dec – 1 Mar
The Baffin and Hudson Bay	1 Dec – 31 Mar
Newfoundland	1 Jan – 15 Mar
The Arctic Seas (The Kara, the Laptev, the East Siberian and the Chuckchee Seas)	15 June – 15 Nov
The Bering Sea	1 Dec – 31 Mar
The Sea of Okhotsk	1 Dec – 31 Mar

Icing can develop in different synoptic situations: in back and front areas of cyclones and anti-cyclones. Most often (in 55%) it is developed in back areas of big cyclones. Less often (in 37%) it is observed in front areas of cyclones. Sometimes icing can develop near the center of cyclone [11].

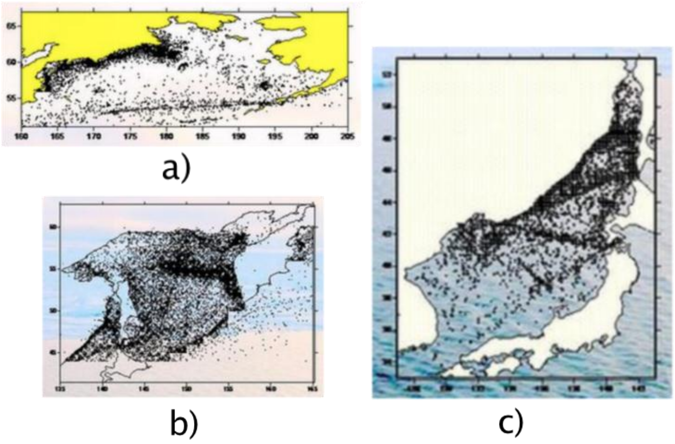
Referring to the Atlas of vessel icing in the Russian Far East Seas we can build a table of icing accidents for different types (See Table 4). Unfortunately there is no full version on the web but from Internet source [2] we can take the up to date table of vessel icing emergencies in the Russian Far East Seas (the Bering Sea, the Sea of Okhotsk and Japan).

Table 4 Number of meteorological observations and number of icing accidents [2]

Month	**1**	**2**	**3**	**4**
October	261753	83	62	0
November	223964	1704	1142	72
December	201971	4426	2648	314
January	204055	7843	3731	738
February	204326	9037	2681	1038
March	234999	7682	1552	1041
April	227658	2647	461	456
May	250342	1291	71	275
June	248642	776	14	202
Total	2057710	35489	12362	4136

Where 1 – total number of meteorological observations at vessels; 2 – total number of registered icing accidents; 3 – number of slow icing accidents; 4 – number of rapid icing accidents.

In the same work [2] we can find a number of vessel icing accidents happened in the Seas of Russian Far East approximately in the period from 1968 to 2008 and maps with coordinates of: all icing accidents (See Fig. 1), slow icing accidents (See Fig. 2) and rapid icing accidents (See Fig. 3).



a)

b)

c)

Fig. 1. Coordinates of all icing accidents in the Seas of Russian Far East [2]

a) The Bering Sea. Total number of icing accidents 6742 since 1960 to 2005;
b) The Sea of Okhotsk. Total number of icing accidents 23210 since 1968 to 2008;
c) The Sea of Japan. Total number of icing accidents 5527 since 1968 to 2005.

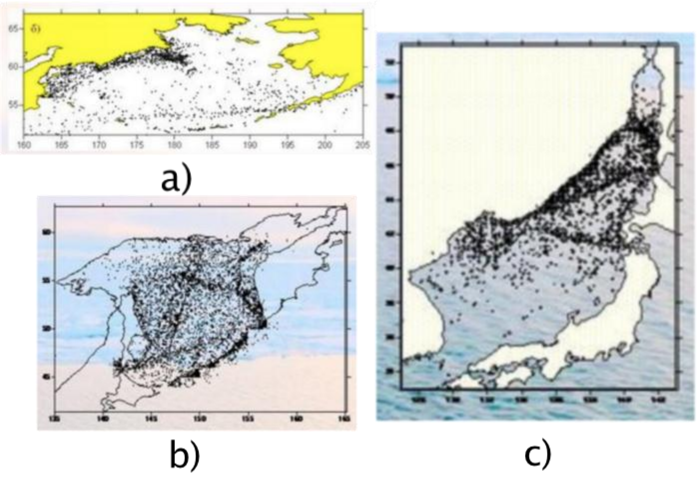


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Fig. 2 Coordinates of slow icing accidents in the Seas of Russian Far East [2]

a) The Bering Sea. Total number of icing accidents 2344 since 1960 to 2005;
b) The Sea of Okhotsk. Total number of icing accidents 7062 since 1968 to 2008;
c) The Sea of Japan. Total number of icing accidents 2956 since 1968 to 2005.

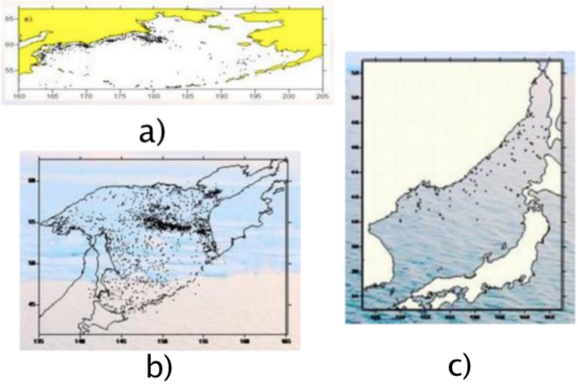


Fig. 3 Coordinates of rapid icing accidents in the Seas of Russian Far East [2]

a) The Bering Sea. Total number of icing accidents 972 since 1960 to 2005;
b) The Sea of Okhotsk. Total number of icing accidents 2817 since 1968 to 2008;
c) The Sea of Japan. Total number of icing accidents 347 since 1968 to 2005.

In addition to this info we can use the map of locations of icing events on Soviet ships published by V. Panov at the AARI in 1979 (See Fig. 4). Surprisingly, there are not so much icing accidents along the Northern Sea Route but most of them took place in the Russia-Norway border area and in the Okhotsk Sea. Both of these locations are a high vessel activity areas at the moment due to emerging hydrocarbon development and sea trade (the Okhotsk Sea). It means that vessel icing can be a potential threat for a significant number of vessels operating there.

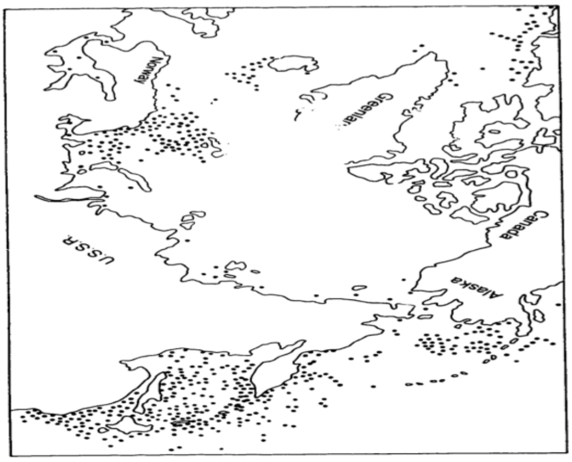


Fig. 4 The locations of icing events on Soviet ships (after V. Panov, 1979)

Referring to the Atlas guide for vessel icing in Russian Far East Seas [2] we can also discuss frequency of vessel icing accidents dependent on: water temperature (See Fig. 5), wave height (See Fig. 6) and air temperature (See Fig. 7).

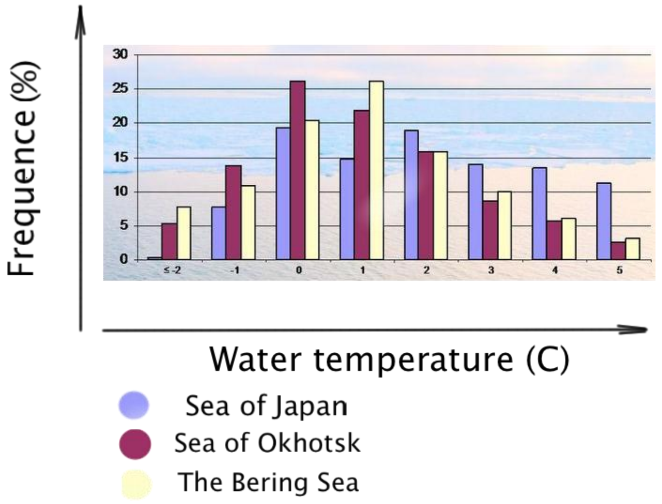


Fig. 5 Frequency of vessel icing in Russian Far East Seas dependent on water temperature [2]

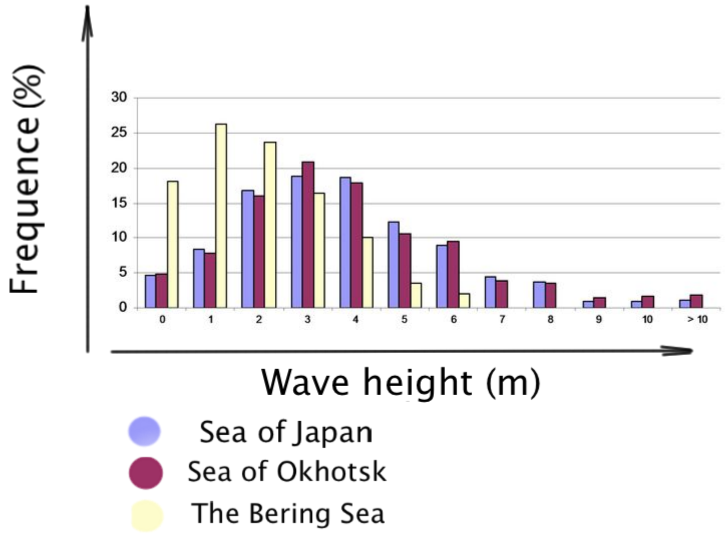


Fig. 6 Frequency of vessel icing in Russian Far East Seas dependent on wave height [2]

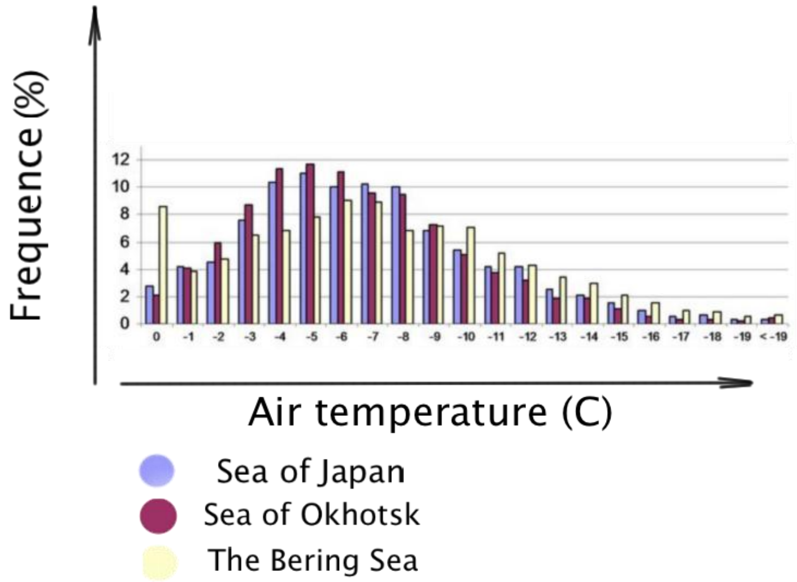


Fig. 7 Frequency of vessel icing in Russian Far East Seas dependent on air temperature [2]

Based on such data, special charts of vessel icing probability can be drawn for each of seas in different time of year. Just for example, chart of vessel icing for northern part of the Pacific Ocean [8] (See Fig. 8).

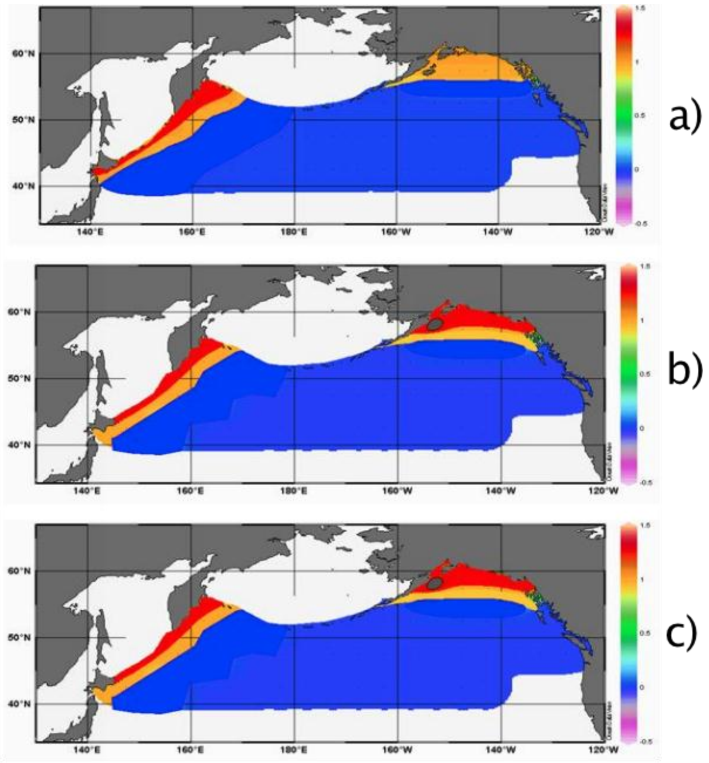
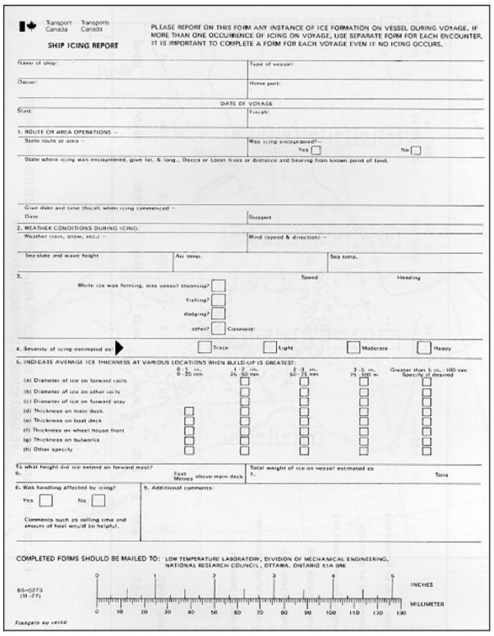


Fig. 8 Charts of vessel icing in the Northern Pacific [8]

Where blue – probable vessel icing; yellow – hazardous vessel icing; red – extremely hazardous vessel icing. a) January; b) February; c) March.

We need data analysis in order to estimate vessel icing (See Fig. 9) and draw charts of possible icing emergencies. Unfortunately at the moment there is still no uniform report database that covers all icing accidents. Nevertheless in 1980 Stallabrass published a comprehensive report of icing accidents on fishing trawlers on the east coast of Canada [7]. He developed a simple questionnaire (See Fig. 10) that would allow all types of vessels to collect and describe observed instances of icing and report them to the National Research Council of Canada (NRC). This data collection program was highly successful and a large amount of data on actual icing conditions was collected. The data obtained from the reports helped to establish relationship between the icing and environmental conditions, geographical, extent of the icing occurrence, and statistics on the icing severity in the Canadian East coast [10]. Subsequently, Brown and Agnew [3] and Brown and Robber [4] characterized and summarized the ice accretion in Canadian coastal region using the regular ship icing observations and icing reports.

Fig. 10 Icing on K/V Nordapp, 27.02.1987 (Soure: Loset,1999)



Transport Canada Transports Canada

SHIP ICING REPORT

PLEASE REPORT ON THIS FORM ANY INSTANCE OF ICE FORMATION ON VESSEL DURING VOYAGE. IF MORE THAN ONE OCCURRENCE OF ICING ON VOYAGE, USE SEPARATE FORM FOR EACH ENCOUNTER. IT IS IMPORTANT TO COMPLETE A FORM FOR EACH VOYAGE EVEN IF NO ICING OCCURS.

Name of ship:
Type of vessel:
Owner:
Home port:

DATE OF VOYAGE

Start:
Finish:

1. ROUTE OR AREA OPERATIONS –
State route or area –
Was icing encountered? – Yes ☐ No ☐
State where icing was encountered, give lat. & long., Decca or Loran fixes or distance and bearing from known point of land.
Give date and time (local) when icing commenced –
Date
Stopped

2. WEATHER CONDITIONS DURING ICING:
Weather (rain, snow, etc.) –
Wind (speed & direction) –
Sea state and wave height
Air temp.
Sea temp.

3. Speed Heading
While ice was forming, was vessel steaming? ☐
fishing? ☐
dodging? ☐
other? ☐ Comment:

4. Severity of icing estimated as: ☐ Trace ☐ Light ☐ Moderate ☐ Heavy

5. INDICATE AVERAGE ICE THICKNESS AT VARIOUS LOCATIONS WHEN BUILD-UP IS GREATEST:

	0 - 1 in. 0 - 25 mm	1 - 2 in. 25 - 50 mm	2 - 3 in. 50 - 75 mm	3 - 5 in. 75 - 100 m	Greater than 5 in. - 100 mm Specify if desired
(a) Diameter of ice on forward rails		☐	☐	☐	☐
(b) Diameter of ice on other rails		☐	☐	☐	☐
(c) Diameter of ice on forward stay		☐	☐	☐	☐
(d) Thickness on main deck	☐	☐	☐	☐	☐
(e) Thickness on boat deck	☐	☐	☐	☐	☐
(f) Thickness on wheel house front	☐	☐	☐	☐	☐
(g) Thickness on bulwarks	☐	☐	☐	☐	☐
(h) Other specify	☐	☐	☐	☐	☐

6. To what height did ice extend on forward mast? Feet Metres above main deck
7. Total weight of ice on vessel estimated as Tons

8. Was handling affected by icing?
Yes ☐ No ☐
Comments such as rolling time and amount of heel would be helpful.

9. Additional comments:

COMPLETED FORMS SHOULD BE MAILED TO: LOW TEMPERATURE LABORATORY, DIVISION OF MECHANICAL ENGINEERING, NATIONAL RESEARCH COUNCIL, OTTAWA, ONTARIO K1A 0R6

85-0273
(11-77)

Français au verso

Fig. 10 Vessel Icing Report [7]

These reports should cover all vital data about the accident:

- The General information about the source of data, vessels on which the icing was being observed, date of the voyage and geographic location at which icing was being observed;
- Weather and Sea Ice Conditions category that provides information on weather conditions (snow, rain, fog, snow flurries, light spraying, wind speed and direction, air temperature) and sea state (fair sea, large waves, rough sea, sea temperature, water salinity, wave height and frequency);
- The Icing Thickness and Location category that provides information on the average ice thickness and total ice weight on the vessel, as well as information on average ice thickness at various vessel locations.

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2. Conditions of ice formation at the vessel

2.1 Icing classification

There are several classifications of icing. Some of them are based on physical processes of ice formations, others – how ice affects on ship stability and the third group combines these two principles.

When speaking about the origin of icing, one divides this into two main types:

- spray icing when sea water splashes at negative air temperatures;
- icing caused by precipitation of supercooled atmospheric water (rain or snow) and the influence of cold air, saturated with vapor (mist, steam and fog). This type is also often referenced as fresh-water icing. In real life these two types of icing very often exist simultaneously.

Traditionally fishermen of different countries distinguish between two types of atmospheric icing: “dark” and “light”. The “dark” icing appears when mist steam or mizzle layers freeze above the bridge and ice appears most intensively at the upper parts. If the super cooled mist layers spread near the sea surface the icing is called “light”. In this case the ship hull is exposed to icing.

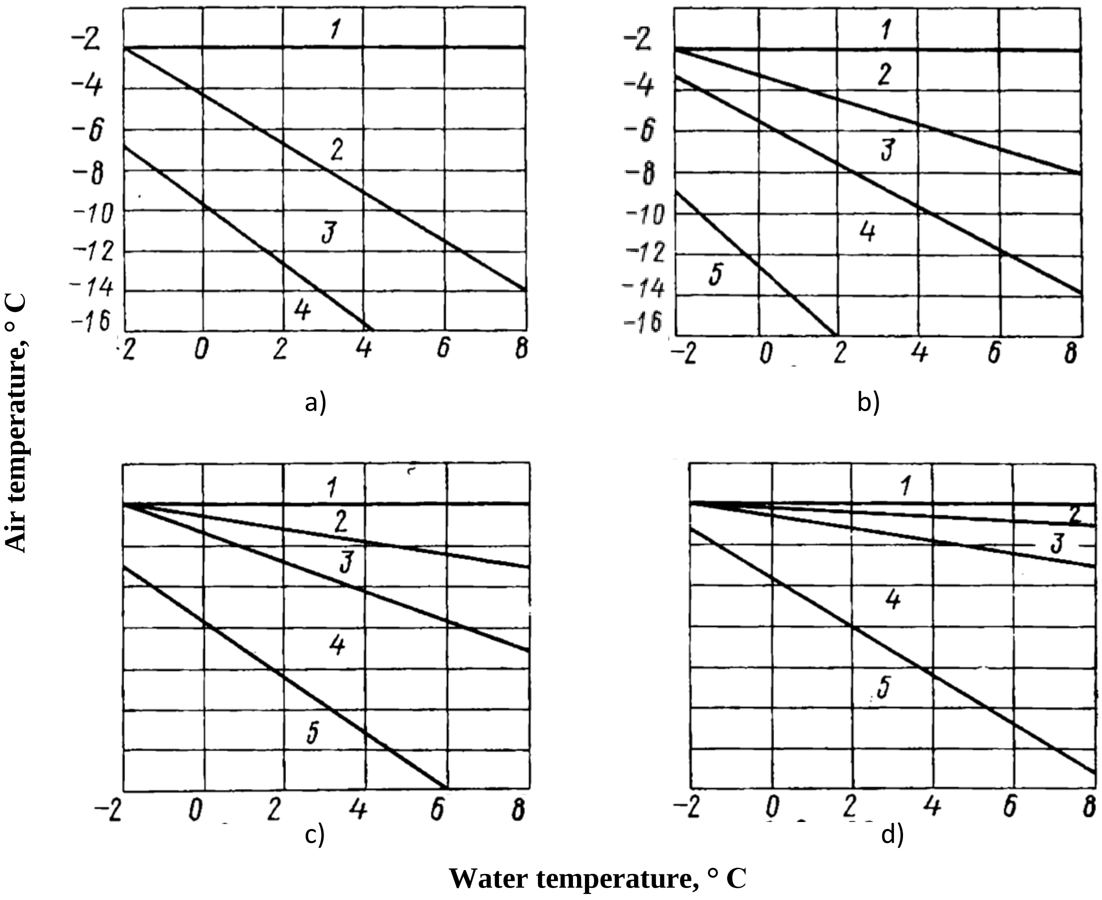
It is obvious that “dark” icing is more dangerous because the center of gravity lifts up and the ship loses stability. Besides in this case there is a danger for the top-side facilities.

According to statistics, wave splashing and washing cause icing. The hydro-meteorological service of the USSR studied this question with the help of special check-list questionnaires for the vessels [11]. The analysis of fishing ships icing in the North Atlantics and the Far East was caused in 89.9% by splashing. Co-action of splashing and mist, rain or mizzle was observed only in 6.4%, while only mist, rain and fog – 2.7%. Splashing and snow was found only in 1.1% of cases.

In arctic seas the distribution differs [11]. For splashing it was 50%, splashing and precipitation – 41%, pure precipitation – 6%, and fog – 3% of the studied cases. Certain decrease of the splashing effect can be explained by the fact that sea ice limits wave sizes in this area.

There is a well-known icing classification based on the ice accumulation speed. This classification has 3 scales: weak icing – up to 2 cm/day, medium with 2-6 cm/day and strong with more than 6 cm/day. This criterion was taken from the air aviation because of no scientific data about vessel icing existed at that time. Nowadays it is out of use.

Mertins [10] (See Fig.11) suggested the following 5 range scale of icing speed: 1 – no icing; 2 – weak icing (1-3 cm/day); 3 – medium icing (4-6 cm/day); 4 – strong icing (7-14 cm/day), 5- very strong icing (more than 15 cm/day) [3]. The scale of icing is determined as a function of three arguments: wind speed, air temperature and water temperature.



a)

b)

c)

d)

Fig. 11 Icing diagram according to Mertins [10]. a) – wind speed 6-7 in Beaufort scale; b) – wind speed 8 in Beaufort scale; c) wind speed 9-10 in Beaufort scale; d) wind speed 11-12 in Beaufort scale. Where 1,2,3,4,5 – icing severity scale

Mertin’s icing diagram requires significant corrections because it is based on the assumption that there is no icing when the air temperature is below -18 ° C [3].

Considering the fact that the speed of icing varies on different parts of the vessel, the grading systems are imperfect. The same disadvantage appears when the classification criterion is based on the total mass of ice accumulated on the vessel – the influence on the vessel’s stability depends on the ship’s part that is iced. Besides in this case one should take into account the size of the vessel or in other words the iced area.

2.2 Conditions of icing and ice properties

The main hydro meteorological conditions of icing in different basins are almost identical.

Icing is possible at negative air temperatures and water temperature below + 6.8 ° C. Icing appears within different combinations of these factors and usually with wind and waves. The conditions of icing are summarized in reference [7] in several meteorological complexes (blocks) that are shown in the Table 5.

Table 5 Meteorological complexes causing vessel icing

Complex number	Air temperature, ° C	Wind speed, m/s
1	≤ 0 (precipitations, mist)	≤ 7.0
2	From 0 to -3.0	7.1 – 15.0
3	From 0 to -3.0	> 15.0
4	From -3.1 to -8.0	7.1 – 15.0
5	From -3.1 to -8.0	> 15.0
6	> -8.1	7.1 – 15.0
7	> -8.1	> 15.0

* Complex #1 describes atmospheric icing, others – spray icing.

In real life vessel icing was observed at air temperature from 0 to -26 ° C, at wind speed from 0 to 55 m/s, and with decreasing air temperature and increasing wind speed the probability of icing and its intensity increase.

There is a statement [3] that there is no spray icing when the air temperature is below -18 ° C because water droplets freeze in the air during their flight, turn into little ice crystals and don’t stick to the vessel’s constructions. But in practice there were a lot of cases of severe vessel icing when the air temperature was below -18 ° C [7].

Changes in air temperature affect the adhesive force of the ice to stick to constructions. The mechanism of this influence depends on the physic-chemical properties of the construction material exposed to icing. So, the ice adhesive (with some special anti-icing coatings) increases with lower temperatures and reaches maximum value at around -15 ° C. Further decrease of temperature results in decrease of the adhesive force. [6].

Icing at temperatures of +5,6 °C is also possible. In this case water droplets freeze to ice temperature in the air due to energy loss.

It should be said that different authors estimate the effect of water temperature differently. But it is a common opinion that the closer water temperature is to the icing temperature the heavier is the icing [5].

Seawater salinity is also an important factor (See Fig. 12). Within the same hydro-meteorological conditions the amount of ice accumulated at the vessel is bigger when the seawater salinity is higher [4].

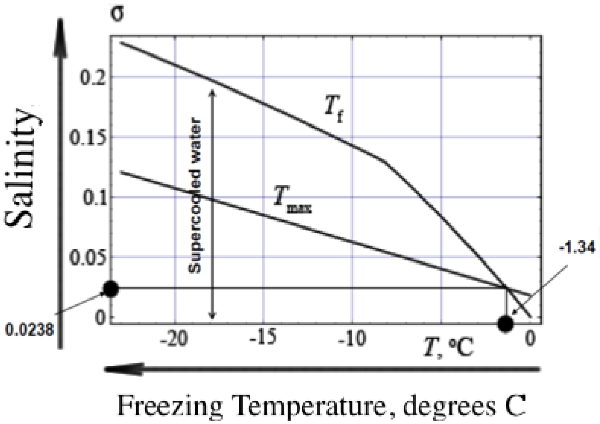


Fig. 12 Dependence of freezing temperature and temperature of max. density on water salinity [14]

Fig. 12 represents two curves – dependence of water freezing temperature on water salinity T_f and temperature of maximum density of ice. We can see that the freezing temperature reduces significantly with increase of water salinity. It means that brine has lower potential to cause icing.

Spray icing is significantly affected by wave size and steepness. With increase of wave size and steepness icing severity and intensity is also increased. In near shore areas hydro-meteorological conditions, and particularly bigger waves, cause icing more often than in open seas. It is found out that water splashing is increased 2-4 times in near shore areas [12]. This fact explains that the number of vessels lost due to icing near shore is 71% while vessels loss in open sea is only 26% [8].

As mentioned above icing depends on a number of factors but most of all on air temperature, seawater temperature and wind speed. In real life they can be met in different combinations. For practical evaluation of icing the possibility in certain hydrodynamic situation we can set a criterion for convenience.

For example, in work [13] special criterion of "weather severity" S is introduced:

$$S = W * (T_a + T_w)$$

Where W – wind speed, T_a – air temperature, T_w – water temperature.

Physical and mechanical properties of ice accumulated on a vessel depend on hydro meteorological conditions of icing and the part of vessel where it is accumulated and the time.

Ice density usually varies from 0.71 to 0.96 t/m^3. It is recommended to take the average ice density as 0.94 t/m^3 according to [2 and 12]. Ice generated from seawater usually has less mechanical resistance and melting temperature than fresh water ice. Melting temperature of sea ice depends on the salinity as it was discussed above.

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3. Icing intensity

The icing intensity is usually estimated by the mass of ice accumulated at a vessel during 1 hour. The efficiency of de-icing methods is also determined with respect to intensity. Back in the day of maritime practice, the icing intensity was estimated visually but now special measurement technologies of ice detection and monitoring are implemented. These techniques will be discussed further in the repost. Nevertheless in the literature of that time [5] it is mentioned that skilled captains can visually estimate the ice mass at the vessel with an accuracy of 1-1.5 tons. Of course this practice might work at small fish trawlers but not at big production facilities with dimensions of hundreds of meters. And obviously these visual methods can't be classified as strict methods of measurements.

There are a lot of methodologies to describe the icing intensity but all of them are based either on visual measurements or weather severity factors. Russian marine scientists have developed different diagrams to estimate icing intensity and possible threat of icing for vessels. But they are suitable for small fishery trawlers only and can't be used for big production vessels as FPSOs. Nevertheless some of them look interesting from stability point of view. What concerns modern icing intensity measurements and monitoring, these technologies will be studied further in the work.

Analytically the intensity of icing at the vessel can be determined by the formula [8]:

$$I = \alpha \frac{t_i - t_z + 2.6p^{t_{ev}}(E_{ta} - E_{ti})}{t_{cr+}C_i(t_a - t_i) + C_w(t_i - t_z)} \tag{1}$$

where **α** – coefficient of heat transmission which depends on the wind speed and the form of the surface exposed to icing**;** **t_l** – temperature of the ice, °C; **t_z** – temperature of water particles in the atmospheric cloud or in the sea spray which is dependent on air and water temperature, the time of the droplet's flight and its size, °C**;** **2.6** – coefficient with dimension of $g*grad*cal^{-1}$; **t_{ev}** – evaporation heat of the ice which depends on water salinity and t_l, °C; **p** – standard pressure at the sea surface, Pa; **E_{ta}** – elasticity of water vapor at the sea surface temperature, $kg*s/cm^2$; **E_{tl}** – elasticity of water vapor at the icing temperature, $kg*s/cm^2$; **t_{cr}** – solidification temperature dependent on water salinity and t_l, cal/(g*°C); **t_a** – air temperature, °C; **c_w** – specific heat of water dependent on temperature and salinity, cal/(g*°C); **c_i** – specific heat of ice which depends on water salinity and **t_l**, cal/(g*°C);

The formula describes the intensity of icing on an area of 1 cm^2 oriented perpendicular to the spray. This equation was obtained through studying the heat balance of the surface exposed to icing and works both for spray and atmospheric icing.

The minimal intensity is usually observed during atmospheric icing. Even under very severe conditions of air temperature (-15 °C to -25 °C) and wind speed up to 22 m/s intensity of atmospheric icing does not exceed 0.1 g/hour at 1 cm^2 of the vessel's area. Such intensity doesn't create any threat even for small vessels [4]. However, specialized equipment can get dysfunctional due to small amounts of icing.

Intensity of the spray icing depends on the so-called capture coefficient. This coefficient is determined as a relation of the accumulated mass of ice to the total mass of water that gets at the vessel [2]. The value can vary in a big range from 1/100 to 1/10000. It depends in general on the air temperature and the total mass of water at the vessel. With reduced air temperature and reduced amount of water the coefficient increases. That is why within spray icing the total mass of ice accumulated at the vessel is more than within deck flooding.

The total mass of accumulated ice depends according to [8] directly on the splashing frequency. The splashing frequency in its turn depends on the relative wave period, i.e. on the encounter frequency between waves and vessel hull. An empiric dependency between these values was described in [7]:

$$\mathrm{n} = 15.78 - 18.04\mathrm{e}^{-\frac{4.26}{\tau_k}} \qquad (2)$$

where **n** – splashing frequency; $\boldsymbol{\tau_k}$ – wave encounter period, sec.

Expression (2) was developed for wave encounter $\boldsymbol{\tau_k}$ from 3.5 to 15. From formula (2) we can see that when $\boldsymbol{\tau_k = 15}$ sec we will have two splashes in one minute and ten splashes when $\boldsymbol{\tau_k = 3.5}$ sec. So splashing is more intensive for short waves and less for long.

It is known that for small and medium fishing trawlers sea splashes get onto the vessel topsides when actual wind speed is more than 5–6 m/s [8]. Of course it also depends on the heading angle of the vessel.

The splashing frequency depends according to [8] on wave height, heading angle and speed of wave propagation. We can see that each wave height has its own worst heading angle when the splashing frequency is maximum and therefore having the maximum icing intensity (See Fig. 13, where n – number of splashes in one minute). With a decreased wave height the worst heading angle is increased.

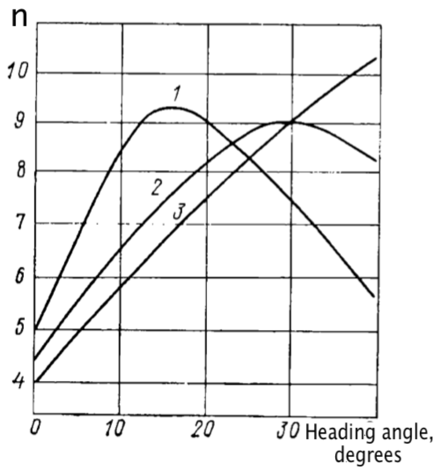

Fig. 13 Splashing frequency's dependence on wave height H_w and heading angle [8]

Where 1: $\mathbf{H_w}$= 3–3.5 m; 2: $\mathbf{H_w}$= 2–2.5 m; 3: $\mathbf{H_w}$= 1–1.5 m.

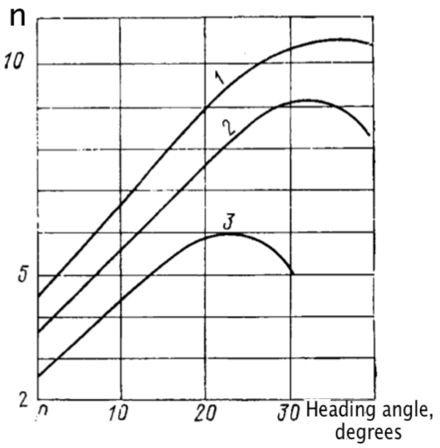

Fig. 14 Splashing frequency's dependence on heading angle and vessel speed, V_v [8]

1: $\mathbf{V_v}$= 8.5 knots; 2: $\mathbf{V_v}$= 7 knots; 3: $\mathbf{V_v}$= 5.5 knots.

With the same heading angle the splashing frequency increases with increased speed of the vessel. At high speeds the heading angle also increases and the splashing frequency is maximum (See Fig. 14).

The pattern of icing also changes with ship sitting. An iced vessel is exposed to stronger wave hits and the waves themselves go higher and cove ra bigger area of the vessel.

The highest splashing and therefore spray icing is observed when resonance occurs, i.e. when the encounter period is equal to pitch period, which can be calculated as in [7] for a vessel simplified as a rectangle (See Fig. 15).

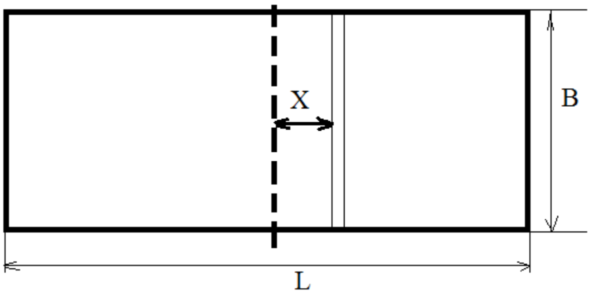

Fig. 15 Simplified vessel approximation

Area moment of inertia:

$$\boldsymbol{I_{AL} = \int_{-\frac{L}{2}}^{\frac{L}{2}} B\,x^2 dx = \frac{BL^3}{12}} \tag{3}$$

$$\boldsymbol{BM_L = \frac{I_{AL}}{\nabla} = \frac{\frac{BL^3}{12}}{BLd} = \frac{L^2}{12d}} \tag{4}$$

Mass moment of inertia:

$$\boldsymbol{I_{ML} = \int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{M}{L} x^2 dx = \frac{ML^3}{12L} = \frac{ML^2}{12}} \tag{5}$$

$$\boldsymbol{T_p = \frac{2\pi}{\sqrt{12}} \frac{L}{\sqrt{GM}} = 0.6 \frac{L}{\sqrt{GM}}} \tag{6}$$

So pitch period

$$T_p = 0.6 \frac{L}{\sqrt{GM_L}} \tag{7}$$

For a rough calculation one can use [3]:

$$\boldsymbol{T_P \approx k * \sqrt{d} \approx 2.4\sqrt{d}} \tag{8}$$

The wave encounter period can be measured directly as the time between two wave crests or calculated by the formula:

$$\tau_k = \frac{\lambda}{1.25\sqrt{\lambda}+0.514 \cdot V \cdot cos\varphi} \qquad (9)$$

where **λ** – wave length, m; **V** – vessel speed (or wave propagation speed if the vessel is static), knots; **q** – heading angle (See Fig.16).

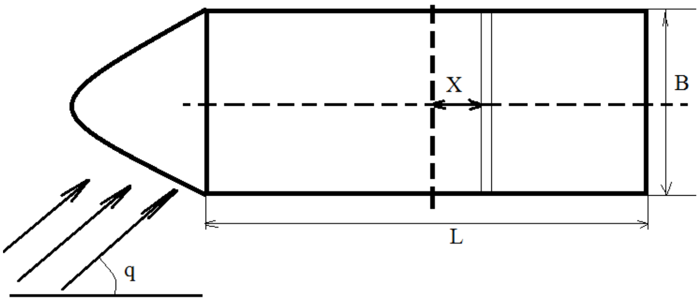

Fig. 16 Heading angle

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4. Shtokman Project and the FPSO General Information

JSC Gazprom and its partners are studying the development of the Shtokman gas condensate field in the Russian sector of the Barents Sea. The complete field will be developed by means of subsea production systems tied back to floating production facilities (Offshore Ice-Resistant Process Platforms) or FPSO. One variant is that the produced gas will be conditioned onboard the FPSO and further transported to the Russian mainland via a subsea pipeline, after which it will be exported into the onshore transportation network or processed to liquefied natural gas (LNG) at an LNG plant in Teriberka village for further transport to end users' locations. Condensate will be exported directly from the FPSO by means of shuttle tankers (See Fig. 17).

The Shtokman field location is approximately 550 km from the Teriberka village, which is the proposed site for the onshore facilities.

The Shtokman site is characterized by harsh environmental conditions including the potential of developing ice cover, passing of icebergs, winter darkness and arctic lows. Water depth at the location is approximately 340 m.

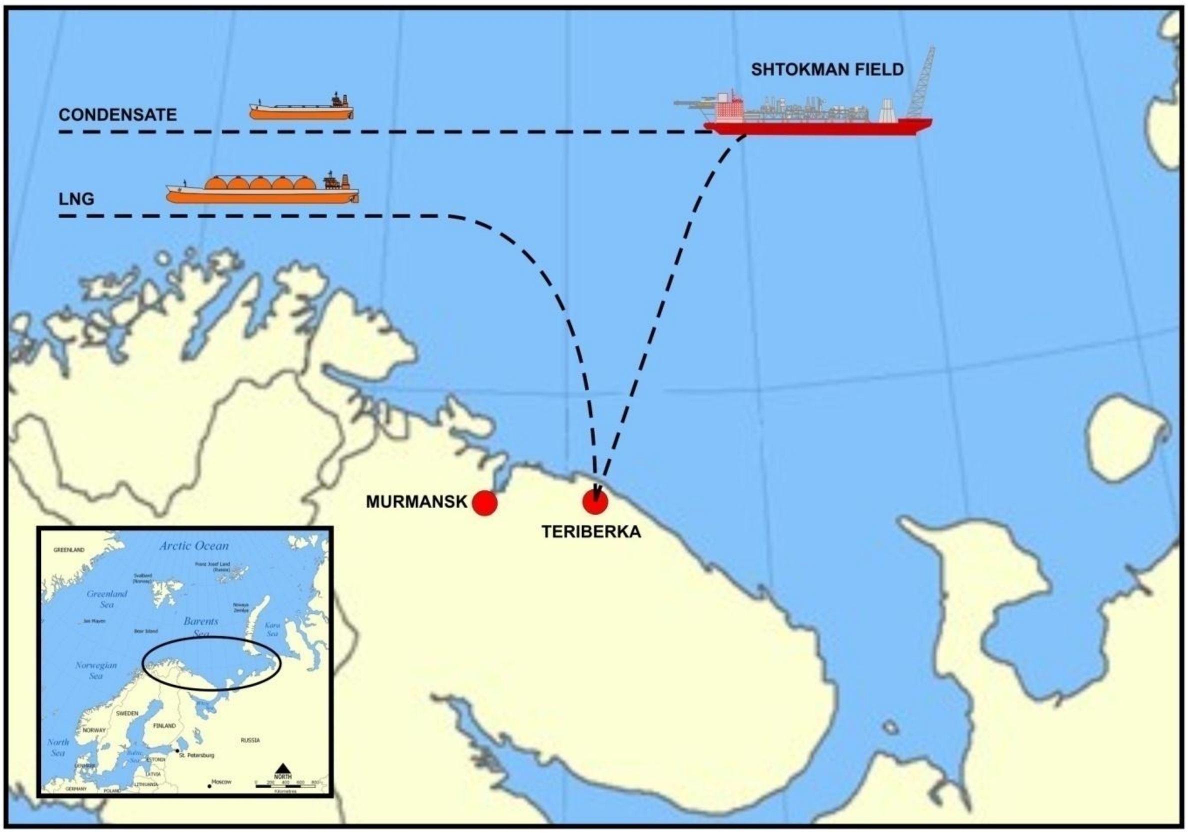

Fig. 17 The Shtokman Field Location area

4.1 FPSO Facility Requirements

The FPSO shall be moored at the production site, connected to the subsea production to receive the field raw gas, produce condensate through the on board process system and for the variant described, store the condensate in condensate storage tanks located in the hull of the FPSO and offload the condensate by a tandem offloading system to export tankers.

The FPSO shall be designed with respect to the following main principles:

- The FPSO shall be designed to store produced condensate;
- The FPSO shall be equipped with an internal turret moored for weathervaning and icevaning capabilities;
- The FPSO shall be self-propelled;
- The FPSO shall be designed with main ice resistance capability on the moored and free;
- The FPSO shall be designed with disconnectable turret so it can go off location in case of threatening ice load.

4.2 Winterization

The FPSO arrangement shall be suitable for all the cases of operation with extreme temperatures.

In order for the hull to obtain the ARC 5 RMRS notation [Chapter 7.12], the hull shall be designed for the winterization temperatures.

FPSO hull design shall comply with requirements from RMRS for the granting of ANTI-ICE, WINTERIZATION (-40) notation with the appropriate design temperatures as required by the RMRS Regulations.

5. Meteorological and climatic Conditions of the Shtokman site

The Shtokman site is characterized by harsh environmental conditions due to high waves, strong wind and currents including the potential for sea ice and ice bergs.

5.1 Sea Water Density

Average annual sea water density on the surface is 1028 kg/m^3.

5.2 Sea Water Temperature

Season variations are typical: maximum average monthly temperature is in August, and minimum average temperature is in March-April. Absolute maximum temperature is 9.0 °C, absolute minimum temperature can be below 0°C up to -1°C on sea surface. From February to May the temperature profile is rather uniform and negative. Then the temperature decreases through the depths from 2 – 8°C on the surface to 0°C or below at depths over 200 m (See Table 6) referring to [1]:

Table 6 Average Month Sea Water Temperature (°C) at Specified Depths [1]

Depth	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
Surface	-0.5	-0.2	-0.81	-0.45	1.83	3.75	7.72	6.59	3.6	2.2	1.7	2.31
10 m	-0.57	-0.2	-0.75	-0.46	0.87	3.6	7.6	6.49	3.62	2.61	1.54	2.21
20 m	-0.56	-0.3	-0.75	-0.48	1.92	3.45	6.11	6.52	3.62	2.6	1.7	2.17
30 m	-0.54	-0.32	-0.94	-0.48	1.89	1.7	4.5	5.75	3.59	2.58	1.39	1.74
50 m	-0.59	-0.56	-0.93	-0.52	0.68	2.54	2.6	3.2	3.34	2.55	1.29	1.24
75 m	-0.62	-0.93	-0.94	-0.58	0.07	1.88		2.07	1.1	2.61	1.29	0.6
100 m	-0.63	-0.94	-0.94	-0.58	0.05			1.15	0.29	1.73	0.6	0.08
125 m	-0.65	-0.97	-0.95	-0.7	-0.24				-0.17	1.26	0.62	-0.23
150 m	-0.67	-0.97	-0.95	-0.77	-0.3				-0.48	0.8	0.5	-0.36
200 m	-0.76	-0.97	-0.95	-0.89	-0.43	-0.7				0.25	0.4	-0.51
250 m	-0.92	-1	-0.97	-0.93					-0.95	-0.11	-0.78	-0.81

5.3 Sea Water Salinity

The sea water salinity depends on the following factors: evaporation, quantity of precipitation, salt transfer by sea currents, processes of ice formation and thawing.

Average month salinity is from 34.75 to 35 units. In the summer (See Table 9), i.e. from July to September, the surface salinity decreases and achieves the minimum value of 33 units in September (See Table 10). In winter sea water surface salinity increases (See Table 7) and is equal to the salinity at deep waters (34.8 – 34.9 units). For conditions during the spring, see Table 8. Near the seabed the water salinity is from 348 to 35.1 units at any time of the year (See Table 11) [11].

Table 7 Sea water salinity for the Shtokman site (winter),‰ [11]

Depth	Min	Date Min	Mean	Max	Date max
0	34,78	31.12.59	34,90	34,99	26.02.58
10	34,78	31.12.59	34,91	34,99	26.01.57

Table 8 Sea water salinity for the Shtokman site (spring),‰ [11]

Depth	Min	Date Min	Mean	Max	Date Max
0	34,80	04.05.85	34,89	35,03	04.04.41
10	34,80	04.05.85	34,89	34,99	26.05.38

Table 9 Sea water salinity for the Shtokman site (summer),‰ [11]

Depth	Min	Date Min	Mean	Max	Date Max
0	34,72	19.08.55	34,83	34,96	17.06.71
10	34,74	19.08.55	34,83	34,96	17.06.71

Table 10 Sea water salinity for the Shtokman site (autumn),‰ [11]

Depth	Min	Date Min	Mean	Max	Date Max
0	34,68	04.10.72	34,81	34,86	27.10.70
10	34,69	04.10.72	34,80	34,86	27.10.70

Table 11 Sea water salinity for the Shtokman site during observations 1992 – 1995 years at 3.5 m depth [17]

Year	Parameter	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1992	**Mean**	-	-	-	0	34,87	35,01	34,89	34,8	34,76	34,84	34,95	35,02
	Max.	-	-	-	50	34,95	35,15	35,05	34,93	35,12	34,99	35,12	35,37
	Min.	-	-	-	50	34,82	34,83	34,66	34,71	34,63	34,72	34,81	34,59
1993	**Mean**	35,09	35,13	35,15	35,09	34,7	34,55	34,69	34,86	34,87	34,6	34,73	34,9
	Max.	35,34	35,40	35,26	35,26	35,41	34,72	35,06	34,98	34,96	34,97	35,01	35,17
	Min.	34,95	35,00	34,96	34,8	34,47	34,38	34,37	34,69	34,75	33,02	34,42	34,42
1994	**Mean**	35,08	-	-	-	-	35,65	35,44	35,36	35,41	35,53	35,64	-
	Max.	35,23	-	-	-	-	35,79	35,65	35,47	35,55	35,75	35,73	-
	Min.	34,91	-	-	-	-	35,33	35,25	35,23	35,26	35,36	35,57	-
1995	**Mean**	-	35,6	35,64	35,52	35,28	35,25	35,2	35,19	35,19	35,24	35,37	35,45
	Max.	-	35,76	35,79	35,75	35,49	35,47	35,35	35,33	35,35	35,42	35,68	35,60
	Min.	-	35,47	35,52	35,34	35,12	35,06	35,07	35,08	35,03	35,12	35,24	35,32

Let’s look at the diagrams of sea water salinity at the Shtokman site dependent on depth for: winter (See Fig. 18), spring (See Fig. 19), summer (See Fig. 20) and autumn (See Fig. 21).

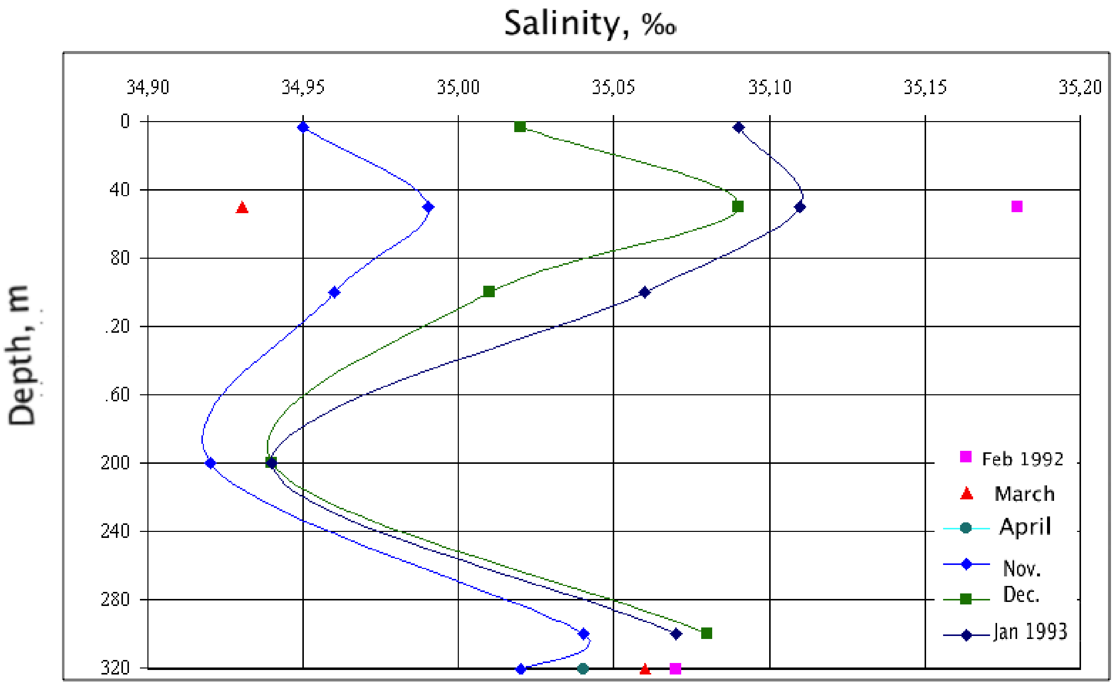

Fig. 18 Sea water salinity monthly profiles (‰) for winter season (Feb – Apr, Nov, Dec 1992, Jan 1993) for the Shtokman site [17]

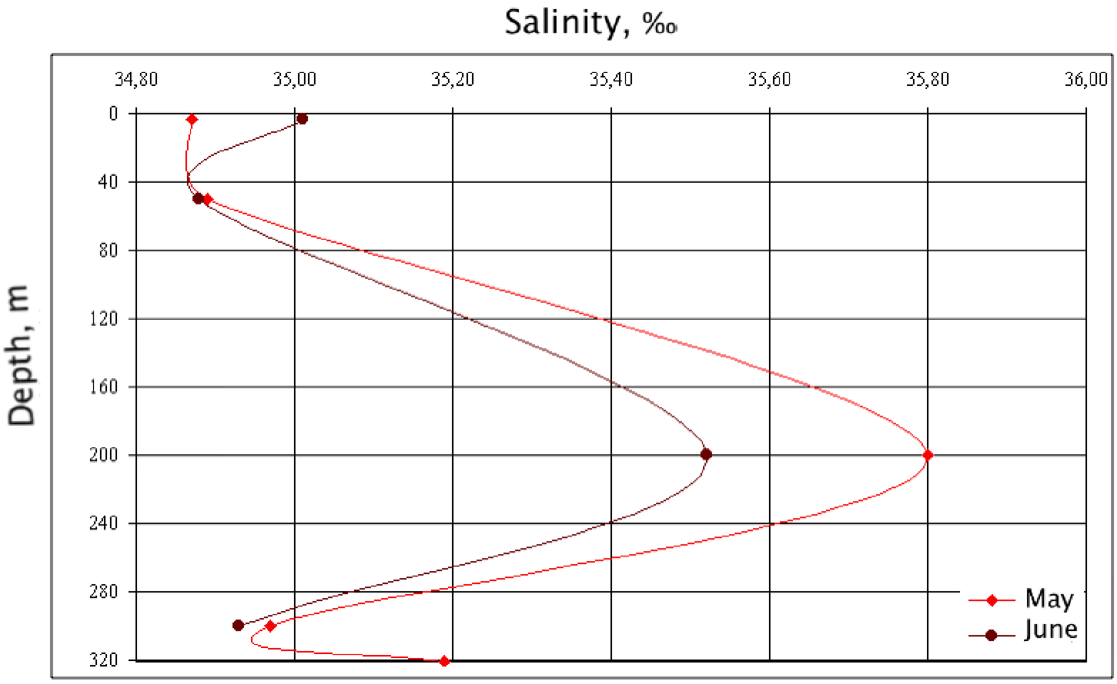

Fig. 19 Sea water salinity monthly profiles (‰) for spring (May – June 1992) for the Shtokman site [17]

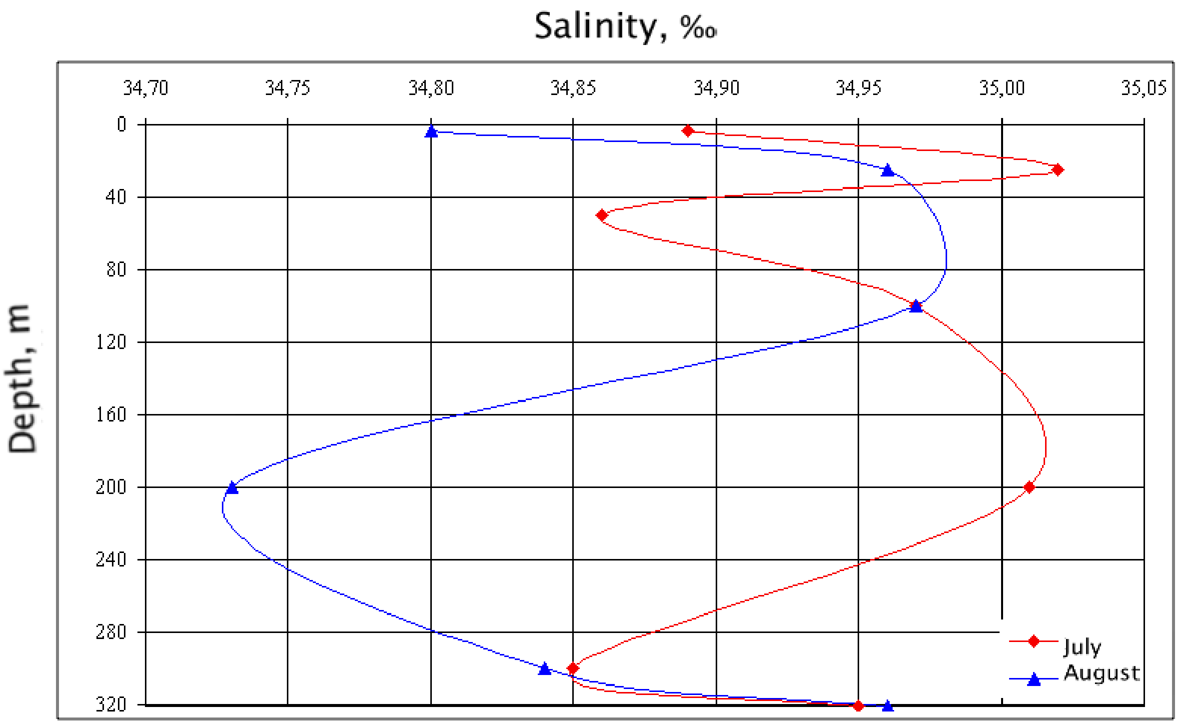

Fig. 20 Sea water salinity monthly profiles (‰) for summer (July – August 1992) for the Shtokman site [17]

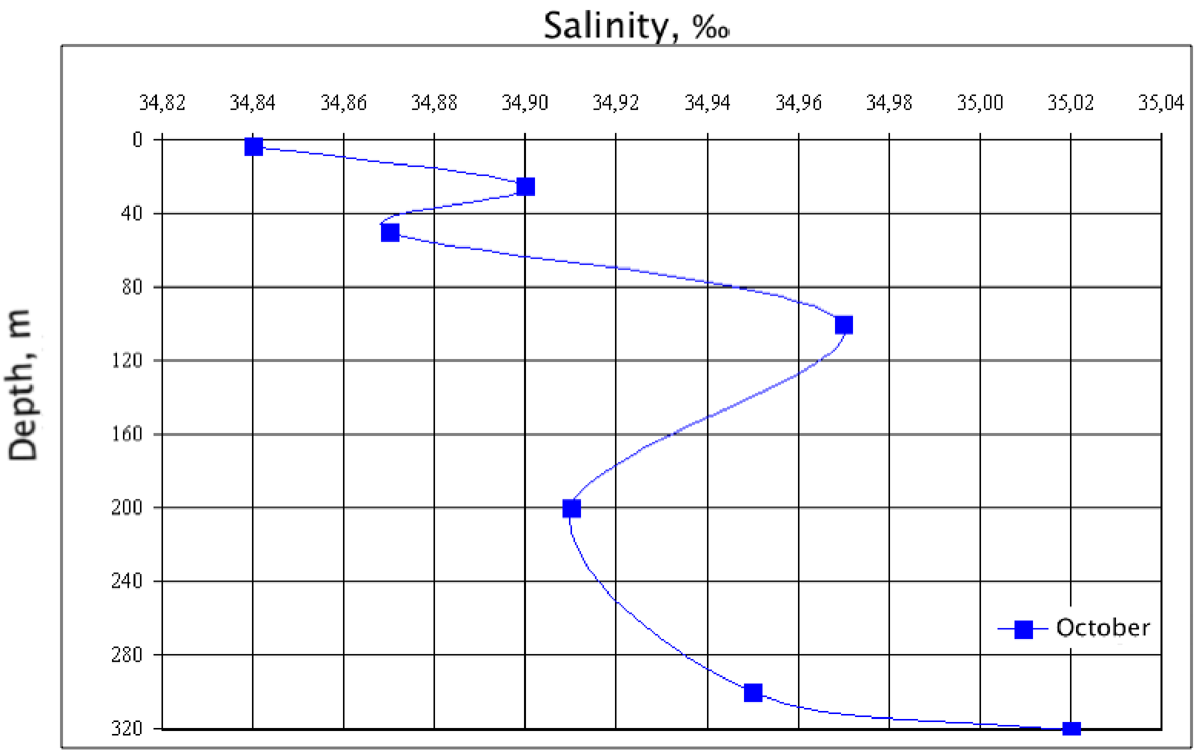

Fig. 21 Sea water salinity monthly profiles (‰) for autumn (October 1992) for the Shtokman site [17]

Next step in describing the hydrological conditions of the Shtokman area is to prepare so called T-S diagrams of the sea water. These diagrams show the dependence of the sea water salinity on temperature for: winter (See Fig. 22) and summer (See Fig. 23).

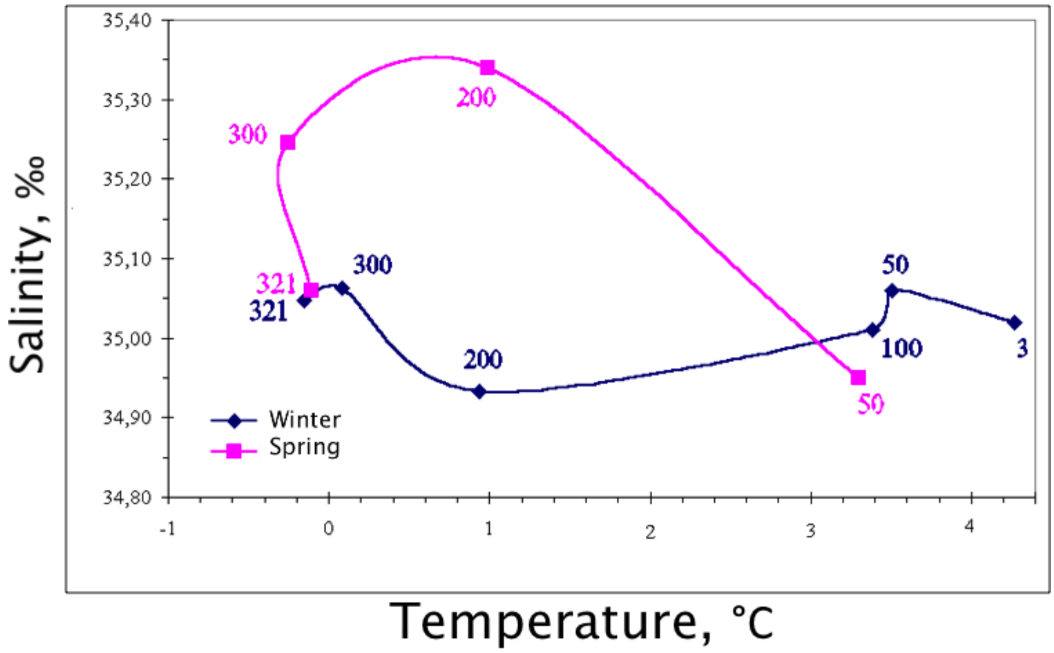

Fig. 22 T-S diagrams for sea water at the the Shtokman site for winter (Feb – Apr1992) and spring (May-June 1992) conditions [17]

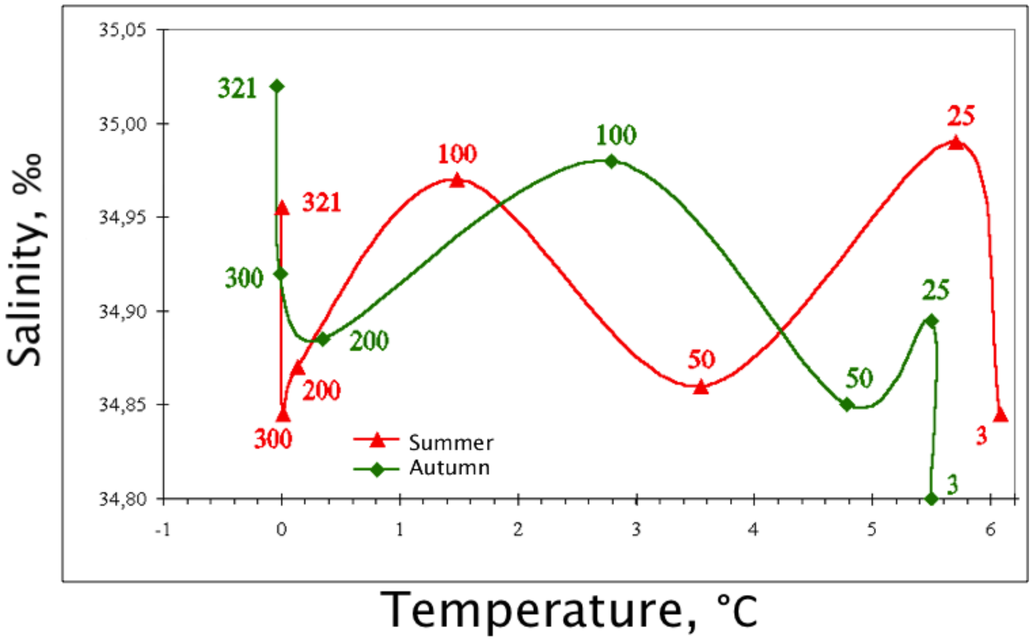

Fig. 23 T-S diagrams for sea water at the Shtokman site for summer (July – August 1992) and autumn (September- October 1992) conditions [17]

5.4 Air Temperature and Relative Humidity

Minimum air temperature at the Shtokman site is -38 ^{o}C with return period 100 years.

Let’s look at the distribution of maximum air temperature at the Shtokman site in different months with different return periods (See Table 12).

Table 12 Extreme Maximum Air Temperature at the Shtokman site [17]

Month	Maximum Air Temperature, °C		
	Return Period, years		
	1	10	100
Jan	4	5	6
Feb	4	6	7
Mar	4	6	7
Apr	5	6	7
May	6	7	8
Jun	9	11	12
Jul	12	14	15
Aug	12	13	15
Sept	10	11	12
Oct	8	9	10
Nov	5	6	7
Dec	4	5	6
Year	12	14	15

For atmospheric icing two parameters are very important: air temperature and air humidity. The distribution of the values of these parameters for a year with different return periods is given in the Table 13 and the design temperature for the most cold 5 days – in Table 14.

Table 13 Extreme Minimum Day Air Temperature and the Relative Humidity at the Shtokman site [17]

Month	**Minimum Air Temperature, °C**					**Relative Humidity, %**				
	Return Period, years					**Return Period, years**				
	1	5	10	50	100	1	5	10	50	100
Jan	-11	-15	-18	-23	-26	89	85	82	77	74
Feb	-13	-21	-24	-33	-36	87	79	76	67	64
Mar	-15	-23	-27	-35	-38	85	77	73	65	62
Apr	-12	-17	-19	-24	-25	88	83	81	76	75
May	-5	-9	-11	-16	-19	66	53	89	84	81
Jun	0	-2	-2	-3	-3	80	75	74	71	70
Jul	3	2	2	1	1	88	86	85	83	83
Aug	4	3	2	2	1	92	88	87	85	84
Sept	2	0	0	-1	-1	85	81	80	78	77
Oct	-3	-6	-7	-8	-9	70	62	60	55	53
Nov	-7	-10	-10	-12	-13	59	51	90	88	87
Dec	-10	-13	-15	-17	-19	51	87	85	83	81
Year	-15	-23	-27	-35	-38	85	77	73	65	62

Table 14 Design Temperature of the Most Cold 5 Days and the Relative Humidity at the Shtokman site [10 and 17]

Month	Minimum Air Temperature, °C					Relative Humidity, %				
	Return Period, years					Return Period, years				
	1	5	10	50	100	1	5	10	50	100
Jan	-10	-14	-16	-20	-22	51	86	84	80	78
Feb	-15	-22	-24	-30	-32	85	78	76	70	68
Mar	-9	-17	-20	-28	-32	54	83	80	72	68
Apr	-11	-16	-17	-21	-22	89	84	83	79	78
May	-3	-6	-8	-13	-16	70	62	57	87	84
Jun	1	-1	-1	-2	-3	83	78	76	73	71
Jul	4	3	2	2	2	91	88	87	85	85
Aug	4	4	3	3	3	93	91	90	89	88
Sept	3	1	1	0	-1	89	84	83	80	78
Oct	-2	-5	-6	-8	-9	73	66	63	56	53
Nov	-5	-7	-8	-10	-10	64	58	56	51	90
Dec	-7	-10	-11	-12	-13	58	50	89	88	87
Year	-15	-22	-24	-30	-32	85	78	76	70	68

Referring to general icing (both sea spray and atmospheric icing) we should also know the number of days with air temperature below zero (See Table 15) in order to evaluate possible patterns of vessel icing in these conditions.

Table 15 Number of Days with Air Temperature below 0°C at the Shtokman site [4 and 17]

Month	Quota in % per period	Number of days
Jan	91%	28.2
Feb	91%	25.7
Mar	85%	26.4
Apr	85%	25.5
May	68%	21.1
Jun	10%	3
Jul	0%	0
Aug	0%	0
Sept	1%	0.2
Oct	42%	13.2
Nov	68%	20.3
Dec	86%	26.7
Year	52%	190.34

5.5 Wind, Waves and Currents

Other important meteorological parameters to estimate vessel icing are: waves (height, speed), winds as they generate sea spray and blow it onto the vessel (speed, direction and duration) and sea currents (See Table 16).

Table 16 Extreme values for all direction at the Shtokman site [1,6,11 and 17]

	Return Period			**Prevailing Direction**
	100 years	**10 years**	**1 year**	
Waves				From West
Hmax, m	23.3	20.4	17.5	
Hs, m	12.5	10.8	9.0	
Tp, s	17.2	16.1	15.0	
Wind Velocity at Height 10 m, m/s				No Prevailing Direction
$\mathbf{V}_{1h}$	31	28	26	
$\mathbf{V}_{10min}$	34	31	28	
$\mathbf{V}_{1min}$	38	34	32	
$\mathbf{V}_{3s}$	44	39	36	
Current, cm/s				In N-E Direction
$\mathbf{U}_{surface}$	88	76	64	
$\mathbf{U}_{bed}$	39	36	32	
Crest Height	14.2	12.3	10.5	
Storm Surge	1.1			

Where: **H**max – maximum wave height;

Hs – significant wave heights;

Tp – spectral peak period.

5.6 Precipitation

Maximum amount of precipitation is from October to February; the average monthly value is 70 mm. Minimum precipitation in summer is 35 mm per month.

From December to March snowfall is 50 cm/month. Major part of snowfall is from October to May.

Potential average monthly snow accumulation is calculated based on the precipitation quantity and is included in Table 17. It should be noted that 1mm of precipitation is equal to 1cm of snow.

Table 17 Potential Average Month Snow Accumulation at the Shtokman site [3 and 13]

Snow, cm	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
Aver.	67	63	50	35	25	4	-	-	-	28	45	62	-

At temperatures above zero the snow melts or converts to wet snow.

In winter the precipitation in combination with winds from North and East practically in all cases is in form of snow. Precipitation distribution at the Shtokan site is given in Fig. 23.

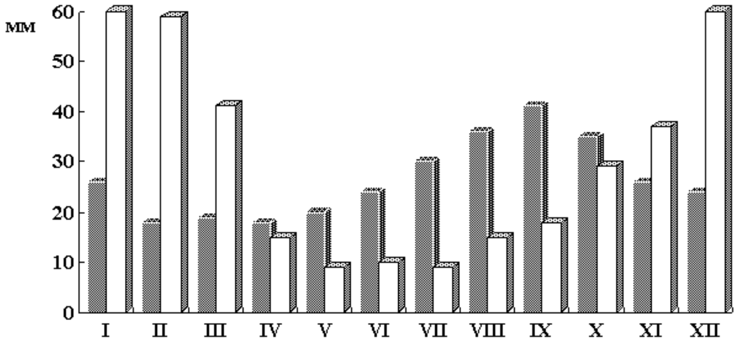

Fig. 23 Precipitation distribution (mm) for months at the Shtokman field (while columns) and Malyi Karmakyli on the Novaya Zemlya Islands (dark columns) [17]

All meteorological conditions of the Shtokman site are presented in the joint Table 18.

Table 18 Joint table of meteorological conditions at the Shtokman site [1,2,11 and 17]

Parameter	Value
Wind speed (at 10 m above the sea surface) in 100 years for:	
10 min	34,2
2 min	37,1
2 sec (gusts)	43,7
Air temperature:	
-absolute Max.	+24^{0}C
-absolute Min.	-25^{0}C
days with fogs:	
Max in month	19 (in Aug)
Minimum in month	1 (in Jan, Feb, Mar, Apr)
Precipitation, max	60 mm (in Dec, Jan)
Snow level, min./mean./max./	30/35/46 cm
100 years wave height	
0,1%	23,7
1%	19,5
13%	13,1
Mean	8,2
100 years wave period	
0,1%	15,8
1%	15,5
13%	14,4
Mean	13,8
Wave length in 100 years	
0,1%	391
1%	377
13%	326
Mean	295
Water temperature	
Min/Max. at surface	-1,7/8,2 ^{o}C
Min/Max. at bottom	-1,7/0,88 ^{o}C

5.7 Sea spray icing at the Shtokman site

Based on ship observations the frequency of occurrence of sea spray icing was computed for three classes of icing. The data for the Shtokman field are given in the following Table 19.

Table 19 Frequency of Occurrence of Sea Spray Icing within the Shtokman Field area[17]

	Month											
Icing class	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Slow					15-20					10	>20	>35
Fast				5–10							5–10	5–10
Very fast	5–10	10–15	5–10									

The values of sea spray ice thickness in the next table are rounded values (See Table 20). Ice density is given as 900 kg/m^3.

Table 20 Estimated Sea Spray Ice Thickness at the Shtokman with 100 Year Return Period [3]

Ice caused by extreme sea spray icing	
Height above sea level, m	**Thickness**
5 – 10	1.0 m
10 – 15	Linear reduction from 1.0 m to 0 m

The atmospheric icing is estimated using the expected thickness of the accreted ice on a vertical cylinder with diameter 10 mm (See Table 21). Estimates are obtained for extremes with a 5-year return period. A 20% increase in the values is added in order to get an estimation of the 100-year value. A 20% increase is equivalent to the difference between the 1-year and the 100-year wind speed at the Shtokman field. Estimated snow accumulation at the site for all year months is presented in Table 22.

Table 21 Estimated Atmospheric Icing at the Shtokman Field with 100 Year Return Period [13]

Height above sea level, m	10	20	30	40	50	60	70	80	90
Thickness, mm	15	23	31	36	38	42	45	50	53

Table 22 Mean Monthly Potential Accumulation of Snow at the Shtokman Field [17]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Snow, cm	67	63	50	35	25	4	-	-	-	28	45	62

References for Chapter 5:

[1] *Atlas for wave and wind conditions at the seas of USSR.* Register of USSR. Leningrad. Marie Transport, 1965;

[2] *Atlas of the Artic*, USSR State Committee for Hydrometeorology and Natural Environment, Moscow, 1985;

[3] Borthwick, I., N. Riley, P. Strass and S. Løset. *Ice Accretion in the Barents Sea - Instrumentation of the Ross Rig*. Proceedings of the International Conference on Technology for Polar Areas (Polartech), Vol. 2, pp. 423-434. Trondheim, 1988;

[4] *CALMS (Climate Assessment from Multisensor Satellite) data*, 1998

http://clams.argoss.nl;

[5] Davidan I.N., Lopatoukhin L.I., Rozhkov V.A. *Winds in the world ocean.* Gidrometeoisdat. Leningrad, 1985;

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[8] Haring R.E., Osborne A.R., Spencer L.P. *Extreme wave parameters based on continental shelf storm wave records*. Proc. 15tg Coastal Engineering Conference. Honolulu, 1976;

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[12] *ISSC. International Ship Structures Congress. Reports of Committee 1, Environmental Conditions.* 1967-1982. IMO;

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[15] Otter group. *Oseberg Conceptual Study, Estimation of Loads due to platform icing*, Trondheim, 1983;

[16] *Rules for the design construction and inspection of offshore structures. Appendix A: Environmental conditions*. – DNV Recommended Practice DNV-RP-C205, Det Norske Veritas, 1977;

[17] Sarpkaya T. and Isaacson M. *Mechanics of Wave Forces on Offshore Structures*, Van Nostrand Reinhold. New York, 1981;

[18] *Technical Report on the Barents Sea conditions*, INFOMAR. Moscow, 1997;

[19] *World Wave Atlas*. Oceanor. Norway, 1996. Htttp://www.oceanor.com/Services/wwa_info/.

6. Review of Rules, Codes and Standards about vessel icing

This chapter reviews various rules, codes and standards that may be applicable to the Shtokman FPSO design for icing and snow loading.

6.1 RMRS Rules for Sea-Going Ships

Under RMRS Rules for the Classification, Construction and Construction of Sea-Going Ships [12], for ships navigating within winter seasonal zones, stability with due regarding to 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/m^3). The mass of ice per square meter of windward area shall be assumed to be 15 kg (equivalent to 17 cm of icing).

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

6.2 RMRS Rules for MODUs and FOPs

The RMRS Rules for MODUs and FOPs also stipulate that a unit must be checked for ice and snow accretion [12] if the unit is operating within a winter seasonal zone.

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 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.

6.3 International Standard ISO 19906

The recent ISO standard on Arctic Offshore Structures gives a short section on marine icing and its effects in Section A.6.3.5.3 – Marine Icing.

The discussion on icing covers both atmospheric icing and marine icing. Generally speaking, no guidance is given on how to calculate the loads from either type of icing on offshore structures or ships. 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

The following Table 23 provides an example set of data for a location off Norway:

Table 23 Icing for Environmental Load Checks in ISO 19906

Height of structure above sea level, m	Action case 1			Action case 2	
	Sea spray icing			Ice caused by rain snow	
	Thickness for 56 °N to 68 °N, mm	Thickness for >68 °N, mm	Density, kg/m^3	Thickness, mm	Density, kg/m^3
5 to 10	80	150	850	10	900
10 to 25	Linear from 80 to 0	Linear from 150 to 0	Linear from 850 to 500	10	900
> 25	0	0	500	10	900

(Original Source: NORSOK Standard N-003, Actions and Action Effects, [11])

According to ISO9906 sea spray icing on ships 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 the 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, that is simultaneous marine and atmospheric icing.

6.4 Canadian Standard CSA S471

The Canadian code gives only a short discussion on “snow and ice accretion” in Section 5.2.3:

“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/m^3.”

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.”

6.5 Norwegian Standard NORSOK N-003

The only Norwegian Standard that currently provides guidelines for ice accretion on offshore structures is NORSOK N-003 [11]. 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. 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.

The table of icing information provided is identical to the table provided in ISO19906 (see Table 23 above). It is important to note that the data is based on a 100-year return period, and represents NORSOK’s recommended ice accretion values for north of 68°N.

NORSOK states that these values may be used “in the absence of a more detailed assessment values for thickness of accumulated ice caused by sea spray or precipitation”.

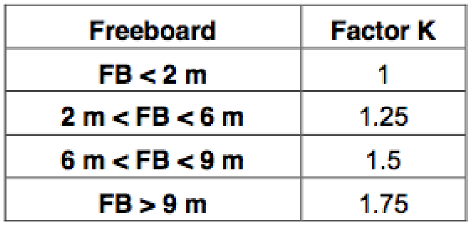
6.6 DNV Classification Rules for Ships

A a part of the DNV Classification Rules for Ships (Part 5, Chapter 1 – Ships for Navigation in Ice) [3], ships with class notation WINTERIZED COLD shall fulfill certain additional requirements. One part of these requirements relate to the Section C400 which gives the additional ice load to be included in the loading conditions and satisfying applicable stability requirements:

$$W = \left(\frac{300}{K}\right) * (1 - C),$$

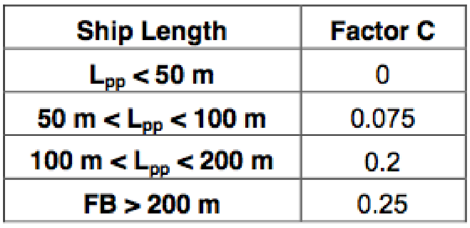
Where: W is the weight distribution over the horizontal projected area of the ship (in kg/m^2), and K and C are constants depending on freeboard and ship length (See Table 24 and Table 25):

Table 24 Table of K Factors [3]



Freeboard	Factor K
FB < 2 m	1
2 m < FB < 6 m	1.25
6 m < FB < 9 m	1.5
FB > 9 m	1.75

Table 25 Table of C Factors [3]



Ship Length	Factor C
L_{pp} < 50 m	0
50 m < L_{pp} < 100 m	0.075
100 m < L_{pp} < 200 m	0.2
FB > 200 m	0.25

For ships with lengths greater than 100 m the weight aft of L/2 can be set to 100 kg/m^2. According to the DNV Rules the weight on vertical surfaces has been taken into account in the above figures and need not be calculated separately. Taking these figures into account the unit weight of icing between the bow and midship is calculated to be:

$$W = \left(\frac{300}{1.75}\right) * (1 - 0.25) = 128 \text{ kg/m}^2.$$

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

7. Ice and snow accumulation at the Shtokman FPSO

This chapter presents calculations for ice accretion and snow loads for the Shtokman FPSO vessel according to the provisions of the Rules and Standards referred to earlier. This will be a combination of data and methods used in the available literature modified where appropriate to make it suitable for using it on the Shtokman FPSO. Icing loads and snow loads are treated separately as they are not expected to occur at the same time. Severe icing requires strong winds which prevents snow from building up on horizontal surfaces. First the icing loads will be treated followed by the snow loads. Of course here only final joint tables of the calculation results are presented because there are no detailed data on the FPSO Topside Modules dimensions available. Although a rough estimation based on height and width of most important topside blocks is carried out.

7.1 Approach to Icing and Snow Load Calculations

The overall FPSO dimensions are as follows:

Length: 320 m Width: 63 m Draft: 19 m Depth: 31.5 m

A major influence on the amount of icing that can accumulate on the vessel is the height of the topside modules. The RMRS Rules stipulate that no icing is expected to form at heights greater than 30 m above MSL, while ISO and NORSOK give an upper limit of 25 m.

Fig. 25 gives the height and plan areas of the modules needed for the calculations of icing and snow loads at the deck level and above. Snow can only occur on horizontal or slightly tilted surfaces whereas icing can also accumulate on the vertical surfaces exposed to spray generation from the bow.

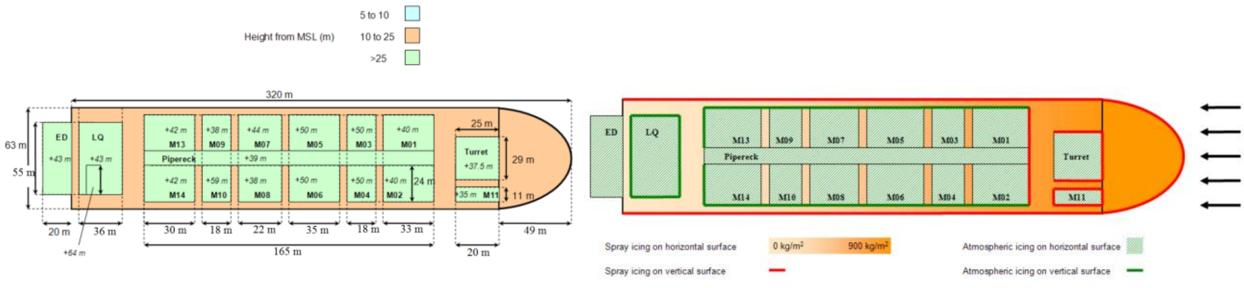


Fig. 25 Schematic plan of the Shtokman FPSO and ice accumulation areas

7.2 Ice accretion according to RMRS rules

Table 26 gives a general indication of the approach used for the ice accretion calculations, following the guidelines suggested in the RMRS Rules. The same approach is taken for the other standards referenced here. The table is broken down into three elements of the FPSO – horizontal projection of decks, vertical windage areas and ship sides. For each of the elements the areas are broken down into the height classes which control the magnitude of ice build-up. The RMRS Rules indicate, for instance, that no ice accumulation should be expected above +30 m.

Table 26 Icing Prediction According to RMRS Rules for MODUs and FOPs

(Reference: RMRS, 2008)

	Ice accumulation according RMRS Rules with assumption of uniform ice accretion from bow to stern				
Element	**Height from MSL, m**	**Exposed area, m^2**	**Unit ice mass, kg/m^2**	**Total ice mass, t**	**Notes**
Horizontal projection of decks and equipment	5 – 10	0	30	0	a)
	10 – 30	7500	15	112.5	
	> 30	13500	0	0	b)
Windage area of superstructure	5 – 10	0	30	0	
	10 – 30	1000	15	15	
	> 30	1500	0	0	
Ship sides	0 – 3	2100	0		c)
	3 – 12.5	6200	15	93	
Total icing mass (t)				220.5	

Notes: a) minimum deck level is 12.5 so no exposed decks are assumed below; b) RMRS states no icing above 30 m; c) waves wash away icing up to 3 m along the ship sides;

The total amount of icing accumulation predicted is 220.5 tones.

7.3 Ice Accretion According to ISO19906 and NORSOK N-003

The approach recommended by ISO19906 and NORSOK N-003 is similar to that specified in the RMRS Rules. The vertical height classes are slightly different in this instance. RMRS applies a constant icing build-up between 10 to 30 m of 15 kg/m^2 while ISO/NORSOK apply a maximum ice build-up of 128 kg/m^2 at a level of +10 m, reducing to 0 at 25 m height (See Table 27).

Table 27 Icing Prediction According to ISO19906 and NORSOK N-003 (References ISO, 2010 and NORSOK, 1999)

	Ice accumulation according ISO and NORSOK Rules with assumption of uniform ice accretion from bow to stern				
Element	**Height from MSL, m**	**Exposed area, m^2**	**Unit ice mass, kg/m^2**	**Total ice mass, t**	**Notes**
Horizontal projection of decks and equipment	5 – 10	0	128	0	a)
	10 – 30	7500	128	960	b)
	> 30	13500	0	0	
Windage area of superstructure	5 – 10	0	128	0	
	10 – 30	1000	64	64	c)
	> 30	1500	0	0	
Ship sides	0 – 3	2100	0		d)
	3 – 12.5	6200	64	396.8	
Total icing mass (t)				1420.8	

Notes: a) minimum deck level is 12.5 so no exposed decks are assumed below; b) ISO and NORSOK give different ice thickness and density in this height range but we will take an ice thickness of 150 mm and density of 850 kg/m^3 that is equal to 128 kg/m^2; c) waves wash away icing up to 3 m along the ship sides.

The total weight of icing according to the ISO/NORSOK recommendations is 1420.8 tones.

7.4 Ice Accretion According to DNV Guidelines for Ships Operating in Arctic Waters

The following prediction of icing weight (See Table 28) is based on the DNV guideline for ships operating in Arctic waters (as described in Section 6.6) [3].

Table 28 Icing Prediction Based on DNV Guidelines for Ships

	Ice accumulation according DNV				
Element	**Height from MSL, m**	**Exposed area, m^2**	**Unit ice mass, kg/m^2**	**Total ice mass, t**	**Notes**
Deck forward half	-	6500	128	832	
Deck aft half	-	6500	100	650	
All vertical areas	-	2500	0	0	
Ship sied	-	10000	0	0	
Total icing mass (t)				1482	

Main assumption: ice accumulation acts over entire deck not limited by height. Icing on vertical walls is included in figures for horizontal surfaces.

7.5 Atmospheric Icing

Atmospheric icing is not dependent on spray produced at the bow but can occur practically everywhere at the ship. For that reason atmospheric icing is assumed to occur at all surfaces of the ship according to the values in Section 4.4 except for the surfaces on which sea ice is present. No reduction is applied in these loads.

It is considered that the flare and cranes on deck can be kept free of icing by means of mitigation measures such as heat tracing, but at this stage it is unclear to which extent this can be achieved as the amount of power to produce the heat might be limited.

7.6 Ice Accretion with Mitigation

All of the above estimates assume that icing will build up in an extreme icing event with no attempts at passive or active mitigation measures. However it is desirable, and even necessary, to control icing as much as possible, not so much for stability considerations, but also for basic safety concerns.

The following basic mitigation measures are assumed:

The deck areas between modules are provided with canopies extending to the top of the modules (thus preventing icing to form due to their height). In addition, and as backup, the walkways would be provided with resistance heating elements at deck level. The combined measures will reduce ice accretion to zero.

The ship deck areas underneath and around the outside of the modules, up to the ship railings, would also be protected by canopies or heating elements, and it is assumed that the resulting icing levels would be also be reduced to zero.

The ice accretion for vertical surface exposed to wind-blown spray would be controlled by active measures such as mechanical removal, hot water, or steam. It is assumed that this would be only 25% effective, especially under extreme cold or wind (i.e. that icing build-up would be 75% of expected levels).

The ice accretion for ship sides could be also controlled by active measures such as mechanical removal, hot water, or steam. It is assumed that this would also be only 25% effective under extreme cold or wind.

Flare and cranes are assumed to be free of ice by means of mitigation methods such as heat tracing and mechanical removal.

The resulting mitigation measures have to reduce the icing build-up. These ice-protection technologies are discussed it details in Chapter 9.

7.7 Snow Loads

Snow loads will only be exerted on horizontal or nearly-horizontal surfaces. In this analysis it is conservatively assumed that besides the horizontal deck areas the modules will also accumulate snow and no snow removal or other methods are available to remove these. This means that a uniform load is assumed on all areas according to Fig. 26.

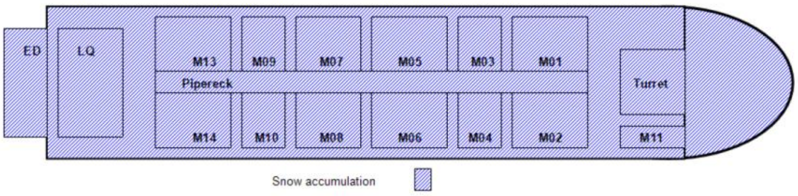


Fig. 26 Snow loads

As referred to earlier, RMRS states that 10 kg/m^2 should be used for snow load on manned structures. But snow accumulation can become 74 kg/m^2 (based on a thickness of 67 cm and a snow density of 110 kg/m^3). As it is unclear to what extent snow can be removed from deck and roof tops it is recommended to take 74 kg/m^2. With this assumption the total snow load would become 1500 t.

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[1] Borisenkov, E. P., and V. V. Panov. *Fundamental results and perspectives in research into the hydrometeorological aspects of snip icing*. Arkt. Antarkt. Nauchno-Issled Inst. T298, Leningrad, 1972;

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[13] Ryerson, C., and A. Ramsay. *Quantitative ice accretion information from the automated surface observing system (ASOS)*. Journal of Applied Meteorology and Climatology, 2007;

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[15] Stallabrass, J. R. *Trawler icing: A complication of work done at N.RC. Mech*. Eng. Rep. MD-56, N.R.C. No. 19372, National Research Council, Ottawa, 1980;

[16] Zakrzewski, W. P. *Icing of ships. Part I: Splashing a ship with spray*. NOAA Tech. Memo., ERL PMEL-66, Pacific Marine Environmental Laboratory, Seattle, 1986.

8. New Mathematical Model of vessel icing

8.1 Model assumptions:

- all water droplets are of the same size, but the gap between them in the spray or splash can be different;
- the droplet's movement is described as steady motion and there is no acceleration;
- there is no slipping between water droplets and air;
- the frame of water droplets is fixed, i.e. the relative speed of droplets is equal to relative speed of the wind and therefore to absolute speed of wind;
- the pack of droplets is cubic hexagonal;
- wind profile can be described with power equation;
- vessels are approximated with rectangles.

In reality water droplets are of different sizes (radius, see Fig. 27) and have random volume distribution. But in order to simplify the calculations in our model we will discuss the water droplets as uniform-sized droplets that form a cubic lattice. Let's assume that the cube's edge length (an element of the lattice, see Fig. 28) is equal to **a**, and that **a** varies with the height.

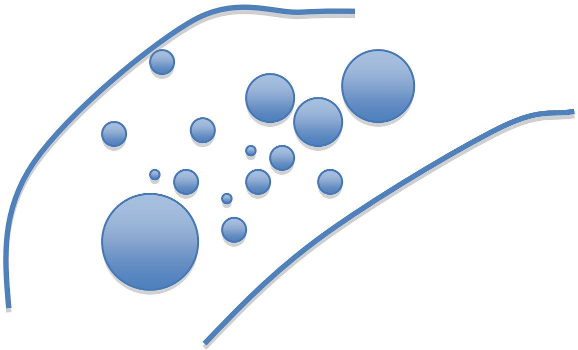

Fig. 27 Real droplet flow

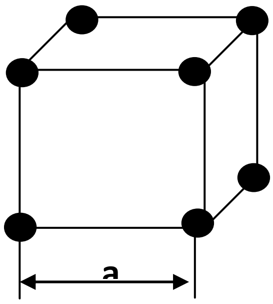

Fig. 28 Pattern element of cubic lattice

Let's introduce **m₁** and **r** as the mass and radius of one water droplet. Also we introduce the lattice parameter **Δx**, which is equal to the length of our cube's face (See Fig. 29).

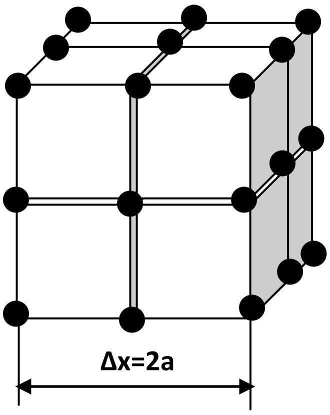

Fig. 29 3-D cubic lattice

Thus the mass of this cube without the mass of the air will be equal to:

$$\Delta m = \left(\frac{\Delta x}{a} + 1\right)^3 m_1$$

Let's move from microscopic description of the droplet structure to macroscopic introducing **dx**, **dy** and **dz**. We assume that **dx, dy, dz** >> **Δx**. Then the mass of an elementary volume contained in a 3D parallelepiped **dxdydz** is defined as:

$$dm = (\frac{\Delta x}{a} + 1)^3 m_1 \frac{dx}{\Delta x} \frac{dy}{\Delta x} \frac{dz}{\Delta x}$$

Introducing the wind speed **u** and assuming that water droplets move with the wind speed we have:

$$dx = udt$$

Let's introduce the mass gain for a unit area in the unit time **q**.

$$q = \frac{dm}{dt(dydz)} = (\frac{\Delta x}{a} + 1)^3 m_1 \frac{u}{(\Delta x)^3}$$

After simplification we get

$$q = (\frac{1}{a} + \frac{1}{\Delta x})^3 m_1 u$$

Using:

$$\frac{1}{a} \gg \frac{1}{\Delta x}$$

and introducing coefficient **n**

$$a = nr$$

we get

$$q = \frac{1}{a^3} u m_1$$

Presenting droplet mass through the radius and density we get:

$$q = \frac{1}{a^3} u \frac{4}{3} \pi r^3 \rho_w$$

Finally we have:

$$q = \frac{1}{n^3} u \frac{4}{3} \pi \rho_w = \frac{4}{3} \frac{\pi \rho_w u}{n^3}$$

Let's write down the expression for the force acting on the droplet:

$$F = \Delta p S$$

Where S – plane area of a water droplet, $S=Pi*R^2$.

Assuming the droplet frame fixed and using the Bernoulli (See Fig. 30) equation [1] we have:

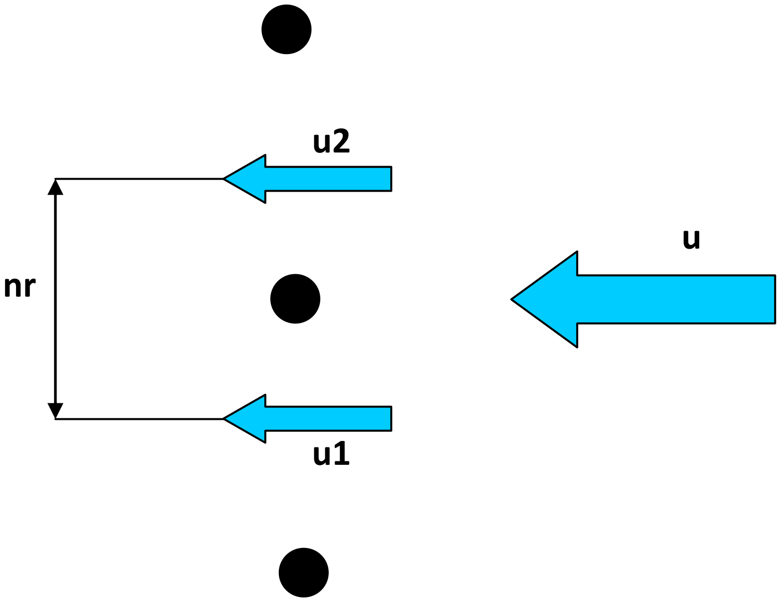

Fig. 30 Air flow through the cubic lattice

$$\Delta p = \frac{\rho_{air}}{2}(u_2^2 - u_1^2) = \frac{\rho_{air}}{2}\left(u_2 + u_1\right)\left(u_2 - u_1\right) = \frac{\rho_{air}}{2}2u\Delta u$$

Using square difference formula we have:

$$\Delta p = \rho_{air}u\Delta u \approx \rho_{air}udu = \rho_{air}uu'dz$$

Writing **dz** we get:

$$dz = a = nr$$

$$F = \rho_{air}uu'dz\pi r^2 = \rho_{air}uu'n\pi r^3$$

Setting the gravity force acting on the droplet and the pressure difference force equal:

$$\frac{4}{3}\pi r^3 \rho_w g = \rho_{air}uu'\pi n r^3$$

Evaluating **n** we get:

$$n = \frac{4}{3}\frac{\rho_w g}{\rho_{air} u u'(z)}$$

Combining the geometric equation and the forces equation we get the main equation for mass gain for a unit area in a unit time:

$$q = (\frac{3}{4})^2 (\frac{\rho_{air}}{\rho_w})^3 (\frac{uu'}{g})^3 (\pi u \rho_w)$$

$$q = \frac{9}{16} (\frac{\rho_{air}}{\rho_w})^3 \frac{u^4 (u')^3}{g^3} (\pi \rho_w)$$

It should be said that for the derivation of this equation a lot of assumptions with different extents of confidence were made. That’s why it is rational to introduce dimensionless deflection coefficient **k**.

$$q = k \frac{9}{16} (\frac{\rho_{air}}{\rho_w})^3 \frac{u^4 (u')^3}{g^3} (\pi \rho_w) \qquad (*)$$

Taking into account that wind speed changes with height we will follow the power function (from Marine Technology Course by Ove Tobias Gudmestad held at University of Stavanger in Spring 2011 [8])

$$u(z) = u_{hub} (\frac{z}{z_{hub}})^{0.11}$$

Coefficients are determined for the height of 10 m.

Taking the first derivative with respect to height we get:

$$u(z) = u_{10} (\frac{z}{10})^{0.11}$$

$$u'(z) = \frac{u_{10}}{10^{0.11}} 0.11 z^{-0.89}$$

Rewriting:

$$u_{10} = \bar{u}$$

and substituting in the equation (*) we have:

$$q = k0.11^3 (\frac{3}{4})^2 (\frac{\rho_{air}}{\rho_w})^3 \frac{\bar{u}^3}{10^{0.33}} z^{0.33} \frac{\bar{u}^3}{10^{0.33}} z^{-2.66} \frac{1}{g^3} \pi \rho_w \frac{\bar{u}}{10^{0.11}} z^{0.11}$$

After simplification we finally get (See Fig. 31 and Fig. 32):

$$q \approx k10^{-12} u^{-7} z^{-2.25}$$

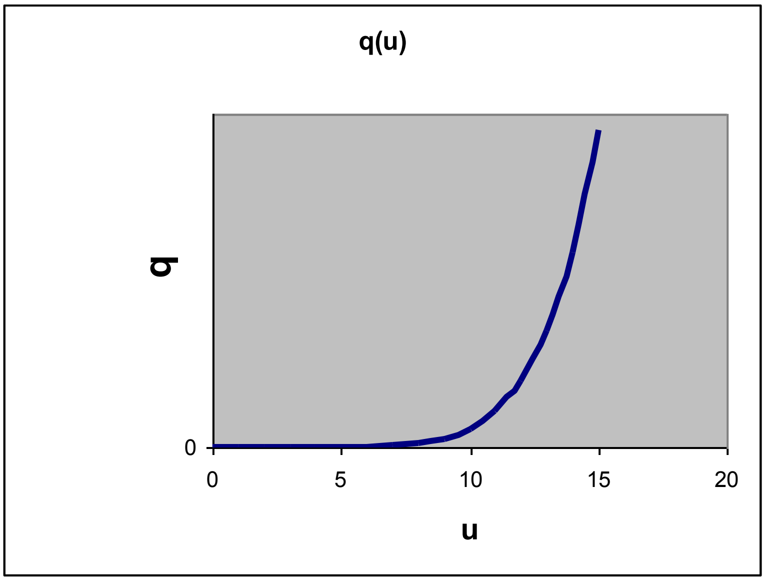

Fig. 31 Dependence of droplets mass flow* on wind speed u (m/s) at constant z

(*mass gain for a unit area in unit time)

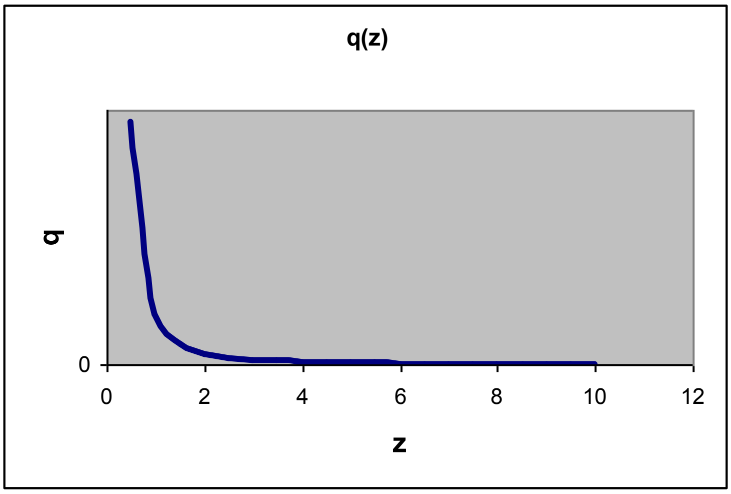

Fig. 32. Dependence of mass flow on height for a constant wind speed

8.2 Icing on fixed plate perpendicular to flow

For the geometry of the problem (See Fig. 33) the mass of water droplets hitting the plate can be determined as an integral:

$$m = \int_{0.5}^{h} k10^{-12}\, u^{7}\, z^{-2.25} btdz$$

$$m = k10^{-12}\, u^{7}\, bt\, \frac{z^{-1.25}}{1.25} \Big|_{h}^{0.5}$$

When t = time of accumulation of the mass.

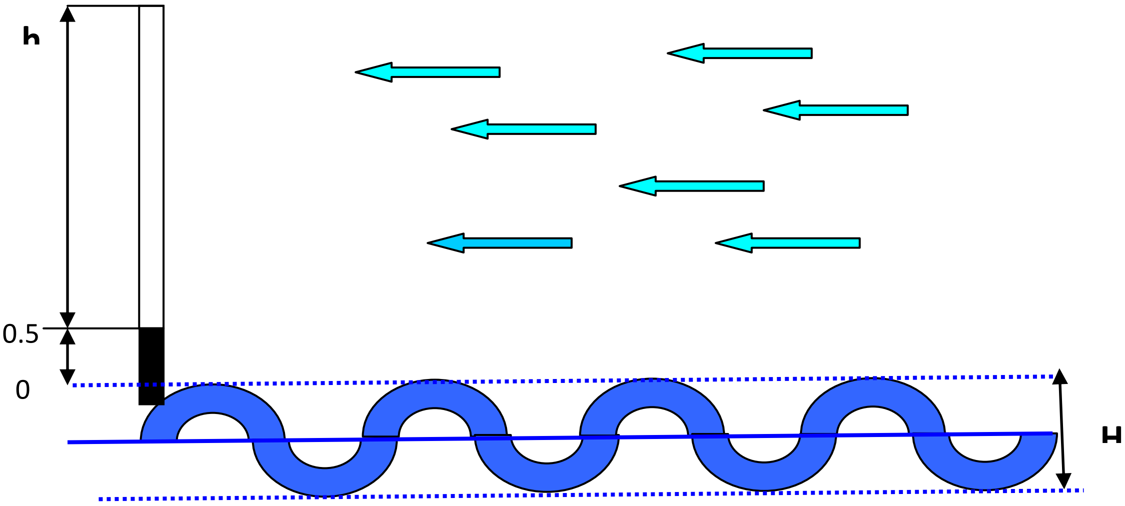

Fig. 33 Droplet flow perpendicular to a fixed plate

It's important to note here that the integration begins from 0.5 m – this gap above wave crest is selected to avoid influence of splashes and whitecaps in the proximity of the plate. **b** – width of the plate.

Using experimental data from [3,4] for icing we determine that our deflection coefficient **k** varies in the limits:

$$k: 2 - 5$$

8.3 Icing on a plate oscillating harmonically in the horizontal plane

This type of motion can represent the **heave** motion of a vessel in waves.

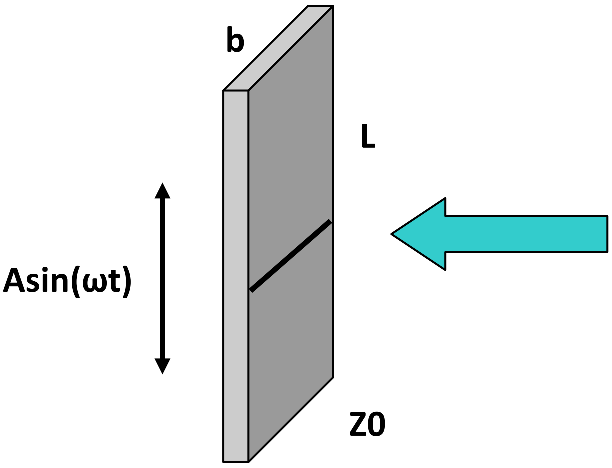

Fig. 34 Droplet flow perpendicular to the a oscillating in the vertical plane

For the geometry of this problem (See Fig. 34) the mass of water droplets hitting the plate can be determined as a double integral:

$$m = \int_0^T dt \int_{Z_0 + A\sin\omega t - L/2}^{Z_0 + A\sin\omega t + L/2} k 10^{-12} u^7 b z^{-2.25} dz$$

Evaluating the inner integral we get:

$$m = \int_0^T kb10^{-12} u^7 \frac{1}{1.25}((Z_0 + A\sin\omega t - \frac{L}{2})^{-1.25} - (Z_0 + A\sin\omega t + \frac{L}{2})^{-1.25})dt$$

Such type of integrals can be evaluated numerically. Using the Maple™ software we can get the following plot of the mass' dependence of the frequency.

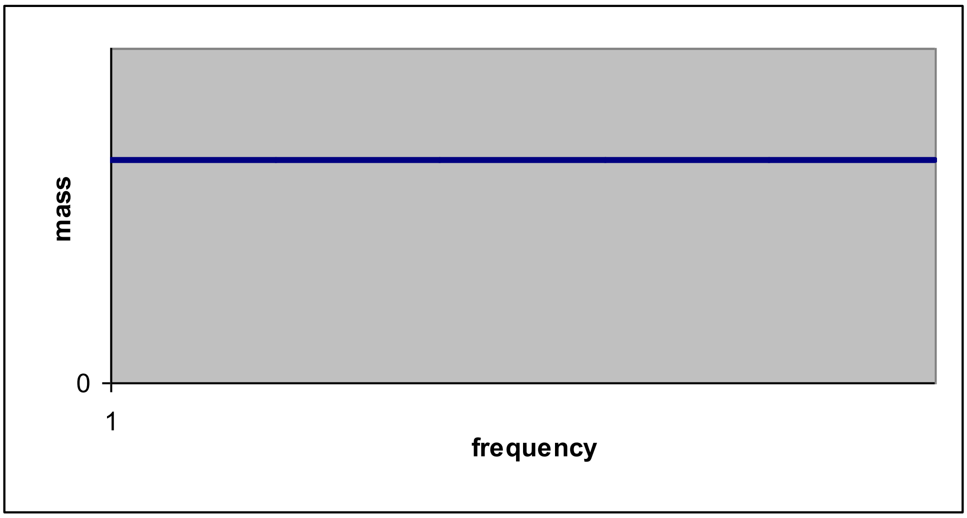

Fig 35. Releationship between wigling frequency and accumulated mass

This result gives the conclusion that the iced mass does not depend (See Fig. 35) on the frequency of the vertical motions of the plate.

8.4 Icing on the plate oscillating harmonically with changing angle between the vertical plane and the plate

This type of motion represents (See Fig. 36) the **roll** and **pitch** motion of the vessel in the waves.

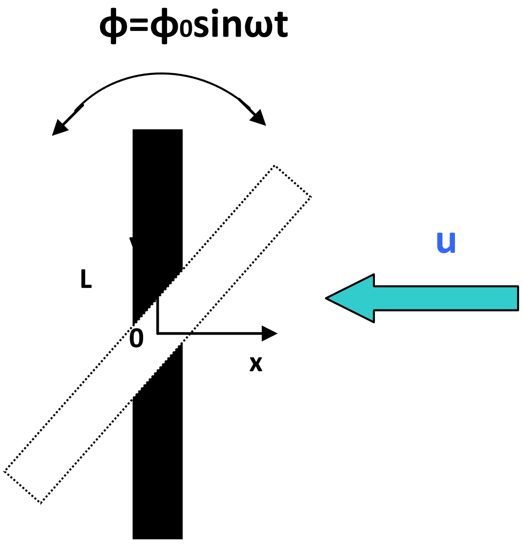

Fig. 36 Plate with harmonically changing angle

Introducing standard geometric nomenclature we get:

$$\phi = \phi_0 \sin \omega t$$
$$x = x_0 \sin \omega t$$
$$x_0 = y \sin \phi_0$$

Let's determine horizontal speed of the plate points as function **y**:

$$x = y\phi_0 \sin \omega t$$
$$V_x = y\phi_0 \omega \cos \omega t$$

We consider that whilst hitting the plate the total energy of the water droplet transfers in hit energy:

$$e = \frac{m_1 (u + y\phi_0 \omega \cos \omega t)^2}{2}$$

In the expression the drop's relative speed in the hit moment is taken into account.

Droplets hit energy plays a significant role in the icing process.

Introducing a dimensionless parameter **c** which determines the difference in density of water and water-air-ice mixture we evaluate the energy of hits on a unit area of the plate in a unit time as:

$dE = edxdydz$

$$\frac{dE}{dtdzdy} = \frac{c\rho_w}{2}(u + y\varphi_0 cos\omega t)^2$$

Thus the total hit energy in unit time for a plate with width **b** and length **L** can be determined as:

$$\frac{dE}{bdt} = \int_{-L/2}^{L/2} \frac{c\rho_w u}{2}(u + y\varphi_0 cos\omega t)^2 dy$$

After taking the integral we have:

$$\frac{dE}{bdt}=\frac{c\rho_w u}{6\phi_0\omega\cos\omega t}((u+\frac{L}{2}\phi_0\omega\cos\omega t)^3-(u-\frac{L}{2}\phi_0\omega\cos\omega t)^3)$$

Simplifying the obtained expression the get:

$$\frac{dE}{dt}=bc\rho_w u(u^2\frac{L}{2}+\frac{L^3}{4}(\phi_0\omega\cos\omega t)^2)$$

In the case of a fixed plate the total energy of hits in unit time can be determined as:

$$\frac{dE^*}{dt}=\frac{bc\rho_w u^3 L}{2}$$

Then during one wiggling period **T** the hit energy will be:

$$T=\frac{2\pi}{\omega}$$

$$E_T=bc\rho_w u\int_0^T\left(\frac{L^3}{4}(\phi_0\omega cos\omega t)^2+u^2\frac{L}{2}\right)dt$$

Taking the integral we get:

$$\frac{1}{4}\frac{bc\rho_w u\pi(4u^2+L^2\phi_0^2\omega^2)L}{\omega}$$

This expression has the minimum corresponding to the minimum hit energy.

$$\omega^*=\frac{2u}{L\phi_0}$$

Moving from the periods towards the total time **t** (for times significantly exceeding the plate wiggling period) we obtain:

$$E(t)=\frac{L}{8}bc\rho_w u(4u^2+L^2\phi^2\omega^2)t \qquad (**)$$

8.5 Motions of the FPSO and tankers

This chapter discusses the FPSO and tankers that might be used in the Shtokman Project from the point of possible icing issues.

<u>FPSO</u>

Dimensions:

- Length 340 m.
- Width 63 m.
- Draft 18 m.

Heave period – 9.5 sec

Roll period – 10.74 sec

Pitch period – 8.8 sec

The dependence of the heave period of the FPSO on the relative mass (See Fig. 37) of the condensate filling.

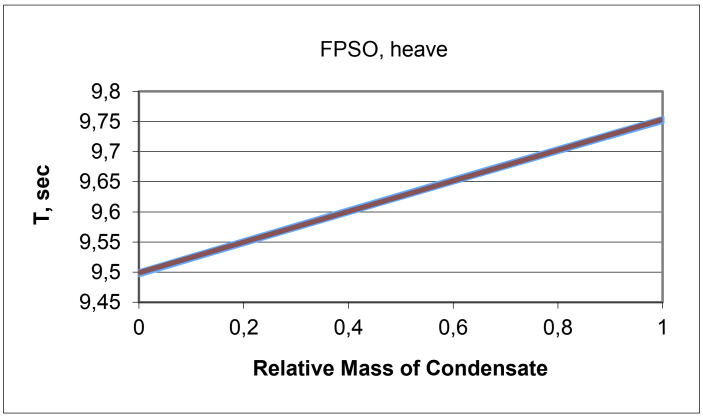

Fig. 37 Dependence of heave period on relative mass

Analyzing the graph we can say that filling up the FPSO with condensate affects the icing just in a small extent. In fact the only thing here that matters is the draft that leads to slight increase of icing.

Two tankers that might be used in the Shtokman project.

Tanker PERSEVERANCE

Dimensions

- Length: 228 m;
- Width: 32 m;
- Draft: 8.5 m;
- Board height: 18 m.

Heave period – 6.53 sec

Roll period – 8.35 sec

Pitch period – 6 sec

Tanker Vladimir Tikhonov

Dimensions

- Length: 281 m;
- Width: 50 m;
- Draft: 8.5 m;
- Board height: 18 m

Heave period – 6.53 sec

Roll period – 6.75 sec

Pitch period – 6.06 sec

Analyzing the data we can say that icing on the Vladimir Tikhonov tanker is much more than on the PERSEVERANCE tanker. This is due to the fact that 1) the roll frequency for Vladimir Tikhonov is bigger and 2) the board (front) area is also bigger.

8.6 Icing evaluation in case of stepped construction.

This case represents icing, for example, on topsides of the vessel when we have several blocks with different height above each other.

Let's assume that ice is accumulated only on horizontal pads and slips off from vertical walls (See Fig. 38).

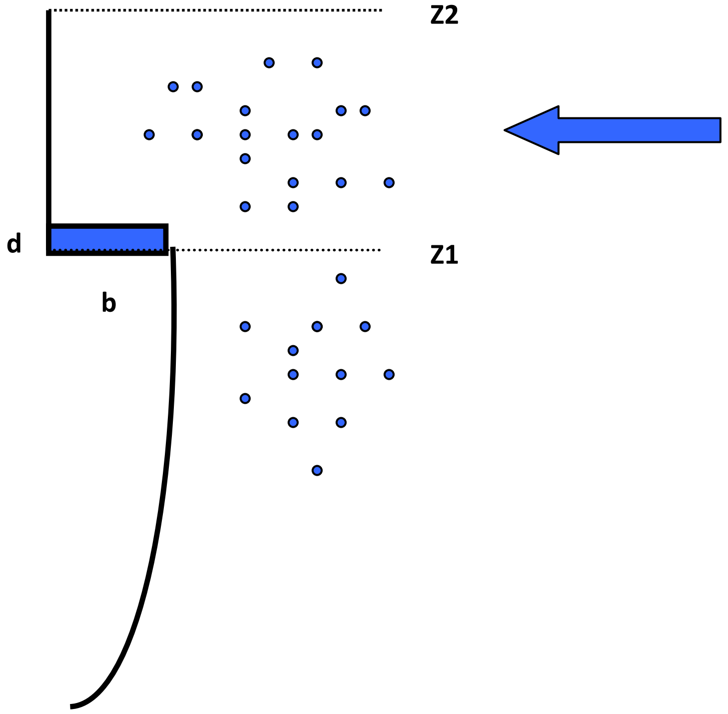

Fig. 38 Sketch of spray icing on the stepped construction (vessel type)

Let's determine the mass of ice accumulated on the horizontal pad in time **t**:

$$m = \frac{k10^{-12}u^7 lt}{1.25}\left(\frac{1}{z_1^{1.25}} - \frac{1}{z_2^{1.25}}\right)$$

The width of accumulated ice can be evaluated as:

$$d = \frac{m}{\rho_{ice} lb}$$

$$d = \frac{k10^{-12}u^7 t}{1.25\rho_{ice} b}\left(\frac{1}{z_1^{1.25}} - \frac{1}{z_2^{1.25}}\right)$$

8.7 Methodological instructions of stability estimation in case of severe icing on a vessel and the FPSO icing calculation

Main formulas [8] used for simplified stability estimation for a barge type vessel (See Fig. 39).

$$GM = \frac{d}{2} + \frac{b^2}{12d} - KG'$$

$$d = \frac{M_{vessel} + \sum_{i=1}^{n} M_{ice\ i}}{\rho_w L b}$$

$$KG' = \frac{M_{vessel} KG + \sum_{i=1}^{n} M_{ice\ i} z_i}{M_{vessel} + \sum_{i=1}^{n} M_{ice\ i}}$$

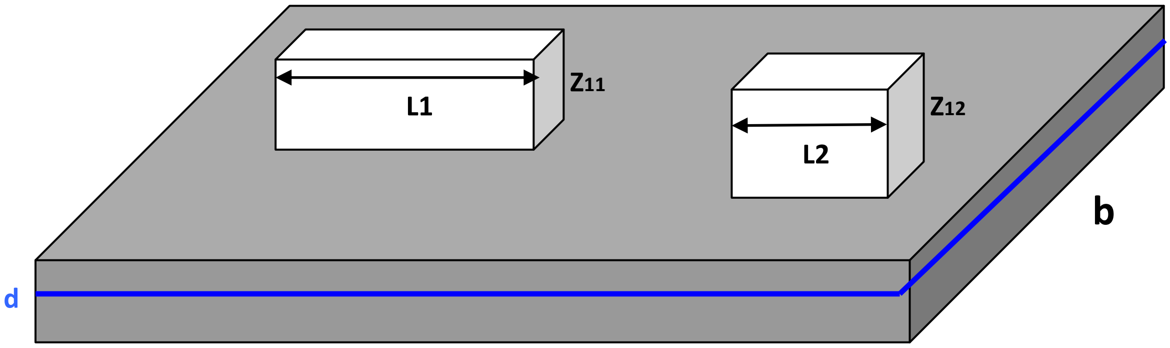

Fig. 39 Sketch of the vessel and deck constructions

Let’s re-arrange formulas taking into account that **d** – vessel’s draft and Z1i – vertical distance from the keel to the ice accumulation level. Then we have:

$$GM = \frac{d}{2} + \frac{b^2}{12d} - \frac{M_{vessel} KG}{M_{vessel} + \sum_{i=1}^{n} M_{ice\ i}} - \frac{\sum_{i=1}^{n} M_{ice\ i} z_i}{\sum_{i=1}^{n} M_{ice\ i}}$$

Let’s examine the numerator of the last term in the expression because it has the biggest influence on the stability.

$$\sum_{i=1}^{n} M_{ice\ i} z_i$$

Introducing coefficient **C**:

$$C = \frac{k10^{-12}u^7}{1.25}$$

We determine the mass of ice accumulated in time **t**

$$M_{ice\,i} = Cl_i\left(\frac{1}{(z_{1i}-d)^{1.25}} - \frac{1}{(z_{2i}-d)^{1.25}}\right)t$$

Taking into account and summarizing all the places of ice accumulation we get:

$$\sum_{i=1}^{n} M_{ice\ i} z_i = \sum_{i=1}^{n} Ctl_i\left(\frac{1}{(z_{1i}-d)^{1.25}} - \frac{1}{(z_{2i}-d)^{1.25}}\right)z_{1i}$$

By neglecting the term

$$\frac{z_{1i}}{(z_{2i}-d)^{1.25}}$$

we get that reduction of **GM** is proportional to:

$$Ct\sum_{i=1}^{n} \frac{l_i}{(z_{1i}-d)^{1.25}} z_{1i}$$

Analyzing the last expression we can distinguish three factors affecting **GM** reduction and thus the vessel stability:

1 – **time of icing**

$$t$$

2 – **meteorological factor**

$$\frac{k10^{-12}u^7}{1.25} = const * u^7$$

3 – **vessel construction factor**

$$\sum_{i=1}^{n} \frac{l_i}{(z_{1i}-d)^{1.25}} z_{1i}$$

More often than not, the blowing and thus the icing of the vessel happens to be from different sides. **The construction factor** can be presented as the perimeter of topsides and equipment: bridge, deck office, towers, etc.:

$$\sum_{i=1}^{n} \frac{P_i}{(z_{1i}-d)^{1.25}} z_{1i}$$

FPSO Icing calculations

Based on proposed model a rough estimation of ice build-up on the FPSO is carried out. So as we have found it out earlier in Chapter 8.6:

$$m = k10^{-12}u^7 bt \frac{z^{-1,25}}{1,25}\Big|_{+\infty}^{20}$$

Assuming mean wind speed as 25 m/s and effective FPSO’s length as 300 m, we have:

$$m = k10^{-12}25^7 300t \frac{1}{1,25}\left(\frac{1}{20^{1,25}} - 0\right)t$$

$$m = k0,035t$$

For mean period of possible icing at the site of 100 days we have:

$$m = k0,035 \cdot 3600 \cdot 24 \cdot 100 = k302\, t$$

Taking k – factor as 5 we have that total ice mass that can accumulate at the vessel is about 1500 tonnes.

References for Chapter 8:

[1] Bernoulli differential equation;

[2] Charles C. Ryerson. *Assessment of Superstructure Ice Protection as Applied to Offshore Oil Operations Safety*. Ice Protection Technologies, Safety Enhancements, and Development Needs, April 2009;

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9. Ice protection technologies and equipment

This chapter is devoted to ice protection technologies and equipment that can be used on an offshore platform. The main idea here is to provide information about applicability, readiness, and safety impacts of available ice protection technologies. Most of these are used principally in other applications and fields, and there is still a question how they may be transferred to specific applications in the offshore marine environment. Many of them have a long record history of use in other non-marine environment but some have been tested for sea conditions. The chapter is based on a report kindly provided by Dr. Charles Ryerson [17, 19 and 20].

There is additionally very good report by ERDC-CRREL [19] with all the engineering information about manufactures, vendors and patent-holders of ice protection technologies that can be used in our application. Ice protection technologies from other disciplines experiencing icing, especially from the highway, aviation, and electric power transmission industries, are summarized and matched to specific marine icing needs. Of course all the technologies have different level of applicability, advantages and disadvantages. Information is then provided if it is possible regarding the technology's actual or potential capability in the marine environment.

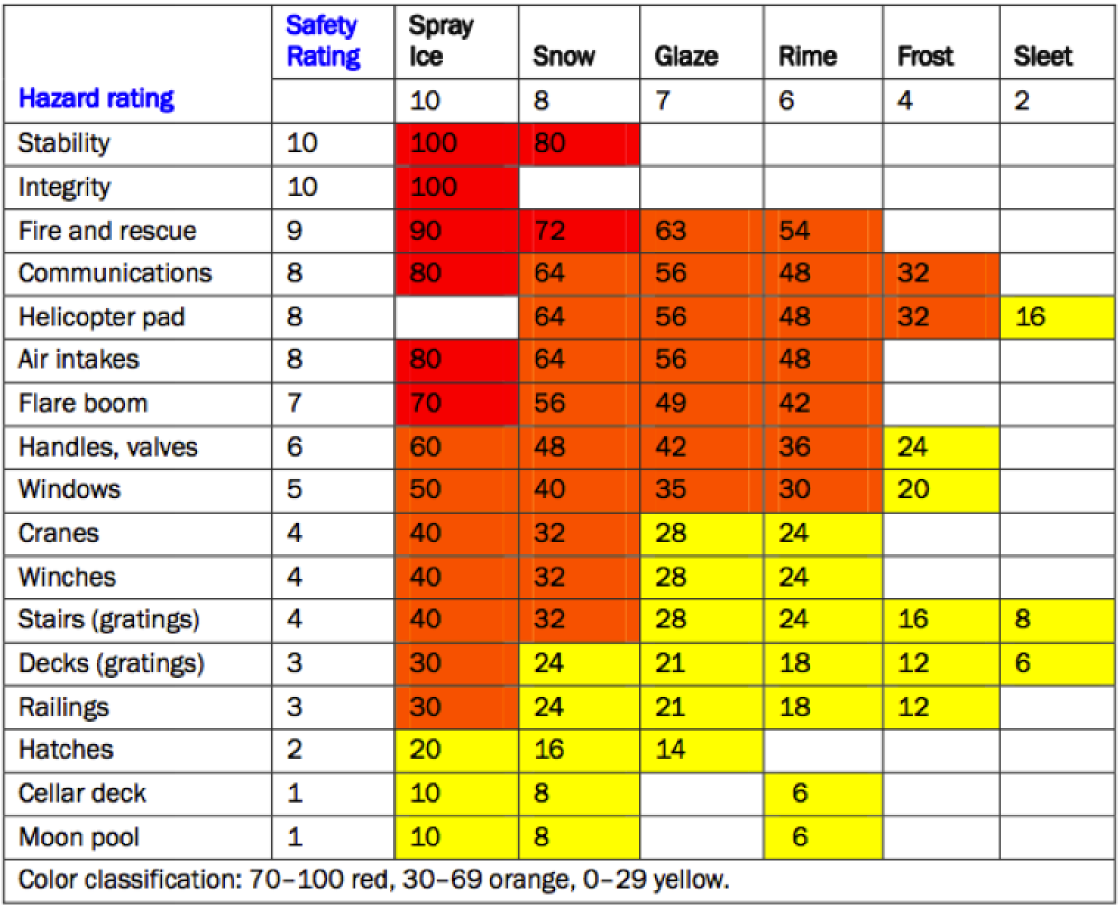
9.1 Safety of the platform philosophy

Implementation of promising deicing and anti-icing technologies for the platform will result in a relationship to icing conditions and the risk that specific ice type causes. Of course different parts of the platform have different safety importance and different ice types have different influences on the safety. We give a qualitative overview of the icing's impact on the platform parts in Table 29 [12]. For example, sea spray icing might have a significant impact on vessel stability. To the personnel and frost has a very little impact here but icing is a great hazard for crew due to the slippery stairs and paths.

Scores are provided in Table 29 for ice types and platform work areas or components with regard to their impact on safety. The scoring represents the experts' opinion and of course the actual risk matrix may look slightly different from this. But nevertheless it gives us an opportunity to understand the risk due to icing. Also evacuation is a great challenge in icing conditions

The importance of any technology as applied to a platform, therefore, is given in Table 29 as a function of the ice type versus specific platform locations or operations.

Table 29 Joint safety impact by ice type and platform component. The higher is the number the larger is the safety hazard [19]



	Safety Rating	Spray Ice	Snow	Glaze	Rime	Frost	Sleet
Hazard rating		10	8	7	6	4	2
Stability	10	100	80				
Integrity	10	100					
Fire and rescue	9	90	72	63	54		
Communications	8	80	64	56	48	32	
Helicopter pad	8		64	56	48	32	16
Air intakes	8	80	64	56	48		
Flare boom	7	70	56	49	42		
Handles, valves	6	60	48	42	36	24	
Windows	5	50	40	35	30	20	
Cranes	4	40	32	28	24		
Winches	4	40	32	28	24		
Stairs (gratings)	4	40	32	28	24	16	8
Decks (gratings)	3	30	24	21	18	12	6
Railings	3	30	24	21	18	12	
Hatches	2	20	16	14			
Cellar deck	1	10	8		6		
Moon pool	1	10	8		6		

Color classification: 70–100 red, 30–69 orange, 0–29 yellow.

This Table is based on qualitative assessment with a lot of subjective assumptions about the importance of different parts of the platform and safety hazards created. No doubt there is a potential error in assessing the technologies results on the platform but still it gives a good understanding of the problems and potential ways to solve them. This table represents the ALARP philosophy where top left red elements show that the combination of risk-consequences is the highest and these combinations must be avoided. This can be achieved with use of special mitigation measures. The middle orange area represents medium hazard situations where the risk level is acceptable but should be reduced if possible. Yellow right bottom area is a safe combination of risk probabilities and consequences.

9.2 Ice hazard ratings

Identifying safety problems caused by icing on offshore structures requires an understanding of the types of ice, where it forms, and how it affects operations [25, 20 and 19]. The sea spray and atmospheric icing threats are described and rated with regards to overall platform threat. Here grade 10 is the highest rating and therefore the highest threat for the platform and 1 the lowest.

1. *Sea spray ice (10):* Sea spray or superstructure ice [19] can reduce stability, potentially damage the structure and equipment due to changes in stresses on members, it causes slippery stairs, railings and decks, makes antennas and other navigation equipment unusable, destroys cargo, put obstacles to use firefighting and other equipment, freezes safety boats and creates problems with helicopter pads, winches and cranes that greatly reduces safety [11, 12 and 25].

According to [29] 22% of all crew injuries were caused by slipping and falling in Norwegian waters. Added weight during icing decreases stability and buoyancy, and additional sail area causes heeling [5]. Bridge windows become covered with ice; winches, boats, life rafts, firefighting equipment and valves become ice-covered and inoperable.

Vessels are designed to take stresses from the environment, such as waves and wind impacts. But due to all the changes of shape and form that result in different diameters, roughness coefficients might also change the wave response [21]. Løset [11] reported that the semisubmersible rig TREASURE SEEKER off the coast of Northern Norway accumulated 300 tons of spray ice in April 1981. The accumulated ice caused problems for handling anchors, caused an ice accumulation on the derrick, and caused problems with air systems, control systems, life rafts, external emergency ladders and firefighting systems [19,20 and 25].

2. *Snow (8):* Snow in most of the cases deposits only on horizontal surfaces such as decks or roofs. Of course this area might be significant and snow loads should be taken into account in the design. However, wet snow can also adhere on vertical surfaces of topsides walls, bulkheads, etc.. Multiple forms of icing, such as snow and sea spray, also often occur at the same time to cause multiple problems, especially in the lee of intense winter [29]. Besides snow must be removed after each event otherwise it will accumulate weight with time and finally will create a threat to vessel stability. Snow also creates a lot of problems for operations and technological processes. It causes a slipping hazard for personnel on ladders, decks, and helicopter landing pads, can damage or possibly contribute to the collapse of flare booms, prevent the operation of valves. I is indicated in [29] that atmospheric icing conditions were relatively infrequent on the

East Coast of Canada and account for only about 6% of icing reports [2,3,5,19]. However, it is reported [29] that more than 60% of trawler spray icing events off of Labrador and Nova Scotia were associated with snow.

3. *Glaze (7):* Glaze depositions from the freezing rain accumulate mostly on horizontal surfaces. Freezing rain is extremely dangerous to lattice structures such as boom flares because they present foundation for large glaze accretion due to huge area. Glaze itself creates personnel slipping hazards on decks, stairs, and helicopter pads, and can disable machinery such as winches and cranes by locking cables in continuous hard ice cover [14]. Glaze coats antennas and windows, hatches, rescue and firefighting equipment, and valves. It is a difficult ice to remove because of its high density and hardness [5 and 17].

4. *Rime (6):* Rime ice results from freezing of supercooled fog or cloud drops carried by the wind as described by Ryerson [21].

Brown [29] found rime icing to be most frequent in the Arctic in Canadian waters, and attribute it to high advection fog frequencies in the eastern Arctic. In the western Canadian Arctic, rime icing is most frequently caused by advection fog and sea smoke [14]. Objects facing the wind especially smaller-diameter objects such as railings, antennas, cables, and lattice structures will usually accumulate the largest rime ice thicknesses.

5. *Frost (4):* Frost deposits directly from water vapor onto surfaces. Frost forms in two circumstances. On windless nights with clear skies frost often forms on surfaces facing the sky. On days when warmer, moist air moves over surfaces that are cold soaked, frost will form on surfaces that are coldest and with no orientation preference [5]. Frost forms on decks, railings, stairs, handles, and cables and presents a slipping hazard for personnel.

Frost creates personnel safety hazards. Frost adds little to the weight of a rig, or to its sail area, thus it does not affect stability. Also, frost provides no material to fall from high structures.

6. *Sleet (5):* Sleet forms when raindrops freeze before hitting surfaces. Sleet is a transition form of precipitation between freezing rain and snow, generally in warm frontal conditions. Therefore, sleet usually does not freeze to surfaces; it accumulates on horizontal surfaces such as decks, stairs and helicopter landing pads. Sleet generally will not stick to objects because it hits surfaces as a solid form of precipitation. However, it may form a sufficient layer of round ice pellets on decks and stairs to cause slippery conditions [19].

9.3 Platform component and function safety ratings

Topsides design can have a large influence on ice accretion. Open structures exposing many small diameters, such as open lattice constructions with large surface areas, can accrete large amounts of atmospheric and sea spray ice.

Components and functions of offshore platforms are rated below with respect to the safety hazard. Components and functions are rated according to the importance of the function or component lost due to ice because of its effect on the survivability or operation of the entire platform and members of the crew. Threats to the safety of the entire vessel are more important than threats to the entire crew, which are more important than are threats to individuals, which are more important than are threats to operational tempo or production. From most severe to least severe are the threats to platform stability, fire and rescue equipment, communications, helicopter landing pad, air intakes, flare boom (problems with which might result in explosion or collapse), valves and handles, windows, cranes, winches, stairs, decks, railings, hatches and cellar deck [18,19,20,27].

Following are descriptions of platform, personnel, and production threats and ratings of each with regard to threat to platform safety and operations if disabled. A rating of 10 is the highest threat, and a rating of 1 is lowest, indicated in parentheses below and in Table 35.

1. *Stability (10):* Platforms can be theoretically destabilized and can capsize by large superstructure ice accumulations. Large masses of ice can cause larger roll moments and decrease freeboard for floating platforms. Differential ice accretion also may cause heeling because most ice typically accretes on the windward side. Although there are no proven records of vessels loses in oil and gas industry due to icing problem a lot of icing accidents that endangered ship and crew have been recorded (for example, Kolskaya rig as discussed in introduction). Loss of stability has a high hazard rating because destabilization of a platform can cause its loss, the loss of multiple lives, and large hydrocarbon spills [19,22 and 25].

2. *Integrity (10):* Integrity refers to structural integrity and the potential for a vessel to break up due to structural loads caused by ice on parts of the structure and production equipment. Crowley in [5] expressed concern that vessels are designed to take oscillatory stresses due to wave action, and changes in drag, inertia, diameter, roughness caused by ice accretion on these structures could change the structure’s design wave capability. These changes in stresses could cause fatigue and even loss. Breakup is a significant hazard because it would cause total loss of the structure, possibly loss of all lives aboard, and potentially massive hydrocarbons spills and chemicals [5,19 and 22].

3. *Fire and rescue (9):* Problems with firefighting equipment (fire extinguishers, fire hoses, etc.) might cause multiple life losses of crew in case of fire on a platform. Inability to release and use lifeboats also puts in danger crew members during rescue operations (See Fig. 40).

Fig. 40 Fire extinguisher and life rafts [19]

4. *Communications (8):* Despite of the fact that loss or inoperability of communication equipment will not necessarily cause loss of a platform, it might cause a lot of problems in operation and rescue activities. Inability to control the processes of treating hydrocarbons and chemicals can result in emergency situations.

5. *Helicopter landing pad (8):* Inability to use rescue helicopter due to icing of hangars and landing pad can result in serious problems in case of personnel evacuation. Helicopters must be ready to use in any moment to transport injured personnel from a platform to shore.

6. *Air intakes (8):* Ventilation is very important for all offshore constructions for any technological purposes (drilling rigs, production platforms, etc.). And it's even more important for constructions that are supposed to operate in cold climate regions of Arctic because these constructions must be winterized. Winterization involves full or partial closure of equipment in special covers. Without proper ventilation there is a possibility that toxic and even explosive gases will concentrate. Blockage of air intakes can increase the danger of poison and explosion in living areas or in locations with potential ignition sources. Besides, compressors and other pieces of equipment require combustion, exhaust and cooling ventilation. Loss of ventilation could cause failure of critical services and death to one or more crew members. Loss of power due to machinery shutdown could cause loss of the platform in extreme circumstances [2 and19].

7. *Flare boom (7):* Flare booms are exposed to icing more than many other structural elements because they extend over the water (Figure 41). Usually they are lattice structures presenting a large surface area for ice and snow accretion. Because they burn off potentially explosive gases, damage to the flare boom structure or blockage of the burner nozzles due to ice could cause an explosion (Fagan 2004). Ice effects on the boom can cause serious safety threats to personnel and possibly the entire vessel [19].

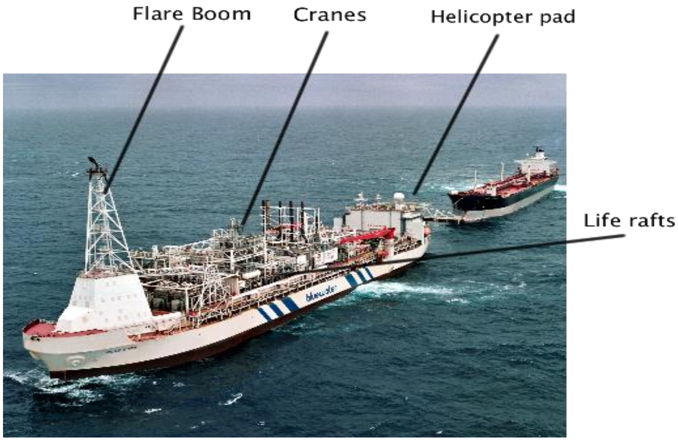


Fig. 41 FPSO and elements of high importance

8. *Handles, valves (6):* Iced handles and valves may not turn or may be difficult to operate (See Fig. 42). Frozen valve handles could prevent the operation of a critical component affecting the safety of the rig, or at least of personnel [19].

Fig. 42 Valves and deck of a Jack-up rig [19]

9. Windows (5): Visibility is also important offshore. Firstly, it is vital for officers on the bridge to monitor the situation around the vessel for possible icebergs or other threats. Secondly, crane and other machinery operators must have a wide visibility. Ice covered windows significantly reduce it. Although loss of visibility is a potential threat to life, it is most likely to cause accidents and injuries. However, a crane or similar accident could possibly threaten the platform and entire crew if an explosion or fire occurred [19].

10. *Cranes (4):* Iced crane components could jam the windlass and cause cables to jump pulleys or to jam in guides causing failure. Though not likely to be life threatening, loss of the crane due to ice could cause injuries or loss of operational tempo (See Fig. 43).

Fig 43. Unprotected cables ice readily and they may become inoperable [19]

11. *Winches (4):* Ice covered winches can prevent operations or cause breaks of cranes and other lifting equipment that can injure personnel or danger equipment (See Fig. 43).

12. *Stairs (gratings) (4):* Iced stairs are a fall hazard to individual personnel because they are slippery and can become irregular in shape, causing loss of footing.

14. *Railings (3):* Iced railings represent a personnel hazard because they become slippery and can increase in diameter, becoming irregular in shape and difficult to grasp. Even when iced, however, railings still prevent personnel from going overboard unless ice accretion on stairs or decks is thick enough to reduce the effective height of the railings [19 and 20].

15. *Hatches (2):* Removal of hatches can be difficult and even impossible when covered with ice because they become heavier, they become difficult to pick up and lift with bare hands or mechanical devices, and the ice can act as an adhesive holding hatch covers to the deck [13 and 19].

16. *Cellar deck (1):* Ice will accrete on many small-diameter objects and become a hazard for personnel movement and operation of equipment. Icing of the cellar deck principally reduces operational tempo [13].

17. *Turret (1):* Icing of the moon pool can affect the operation of valves and slip joints. Primarily it is a hindrance to operational temp [19].

9.4 Technologies of Ice Protection at the Vessel

Hydrocarbon production vessels operating in cold climate regions must be winterized to cope with severe weather conditions. Vessel icing as one of the most important parts of winterization must be also managed and controlled.

Ice protection technologies are common in most disciplines that deal with the effects of super cooled drops that strike and freeze upon surfaces, or the accumulation of frozen or freezing precipitation. The goal of ice protection is to provide an ice-free construction, and that can be achieved basically in two ways: anti-ice and de-ice. Anti-icing is a complex of measures to prevent ice accretion on the construction and de-icing is to remove already accreted. Information of icing processes and mass of accumulated ice is important in order to understand further operation actions. Therefore, ice detection technologies are also included in ice protection systems [11,19 and 20].

Ice protection is necessary in many disciplines, and this review of ice protection technologies is drawn from many areas. These include aviation, rail, road, and water transportation systems, electrical transmission systems, communication systems, and other disciplines and research environments where promising technologies may not yet have found application.

This chapter touches upon most current ice protection technologies. It indicates whether technologies are used for deicing, anti-icing, or ice detection, including a description of the physical principles used, application if any, and potential technological development [3 and 19].

The following technologies or applications are reviewed:

1. Chemicals
2. Coatings
3. Design
4. Electrical
5. Expulsive
6. Heat
7. Hydraulic and steam lance
8. Infrared

9. Mechanical
10. Millimeter wave
11. Piezometric
12. Pneumatic
13. Vibration
14. Ice detection

9.4.1 Chemicals and chemical distribution

Summary: Chemical methods of anti- and de- icing are most commonly used at the moment. They can be taken both in liquid and solid and this choice determines the application method. Application could be as simple as using sprayers for liquids, as is occasionally used for deicing small aircraft such as helicopters to hand broadcasting solid chemicals. The manual method of anti-ice chemicals distribution can be carried out in the areas with easy access for personnel: decks, stairs, rescue boats, etc. These should be horizontal planes because solid chemicals have very low adhesive force. Application of chemicals in superstructure icing areas, to the cellar deck and to lattice structures such as flare booms and derricks, may require dedicated spray systems where personnel cannot safely reach (See Fig 44) [13,15,19].

Applications to platforms: There is a huge variety of surfaces on a platform where chemicals might be used. And there are certain limitations due to potential wash-off and environment pollution. Most of the ice-protection chemicals are extremely unfriendly to the environment and therefore cannot be used in marine conditions. Another issue to chemical use is wash-off and corresponding concentration reduction. Nevertheless permanent spray application systems could be placed to protect support structures and piping, on cranes and the flare boom to deice the lattice structures, and possibly the helicopter landing pad, decks, and stairs [14 and 19].

Fig. 44 De-icing of an army air-craft (Source: Air Force photo/1st Lt. Kinder Blacke)

9.4.2 Coatings

Summary: Coatings are intended to reduce adhesion strength of ice to surfaces and are often considered a potential panacea with regard to solving the icing hazard. If adhesion strength between water and surface is low then water droplet doesn’t remain on the surface and rolls down before it freezes on the vertical or inclined wall. In case of horizontal surface, water droplet will freeze in a spherical form and will have less friction coefficient, so it can be easier removed (See Fig. 45). Although adhesion strengths of 40 kPa and lower have been measured on coatings, adhesion strengths have not been reached that are sufficiently low so as to prevent ice formation. Only the super-hydrophobic coatings have a possible near-term opportunity to prevent icing but that remains to be proven definitively [2 and 19].

Most coatings are somewhat hydrophobic (versus icephobic), with low surface energy holding the drop to the surface. The greater the sphericity of the drop, and thus the larger its contact angle with the surface, the more hydrophobic the surface is. Nanotechnology has made some progress in creating superhydrophobic surfaces. Some researchers suggest that development of an icephobic coating upon which ice cannot accumulate, or where ice could be sheared off by its own weight, may be achievable within 10 years [7,19,26].

In most cases, the following limitations apply to coatings. The properties of coatings and their performance vary widely with regard to their hydrophobic versus icephobic capability, their ability to tolerate heat or other active deicing technology characteristics, and their capability over various substrates (which can vary substantially). In addition, coating hydrophobicity or icephobicity generally decreases with time, coatings have a finite lifetime from months to several years, and contamination of the surface after application can decrease icephobic qualities [7 and 19]. There are two main issues in regards with coating usage: 1) there is still no ideal material that will prevent ice formation; 2) lifetime of coating is very short (up to several years only). This means that coatings must be renewed on platform. But this operation obviously is very hard or even impossible due to huge coverage areas, no accessibility to some elements (walls, flare boom, etc.) and environment conditions (air temperature, wind, presence of water).

Applications to platforms: There is a mass of opportunities to apply coatings to offshore platforms. Besides, application of special coatings will also help to remove ice. Coating can be used on sensitive elements and equipment that cannot be treated mechanically or with chemical agents. For lattice structures such as flare booms coatings can be a good solution to prevent ice accretion.

The application of coatings to most surfaces will assist the removal of ice. Fire and rescue equipment such as escape pods, if coated, may allow ice to be removed without damaging sensitive equipment, valves, and composite structures. Coatings on antennas would assist the removal of ice and may prevent antenna damage. Lattice structures such as cranes and the flare boom may benefit from icephobic coatings [7,18,19,24].

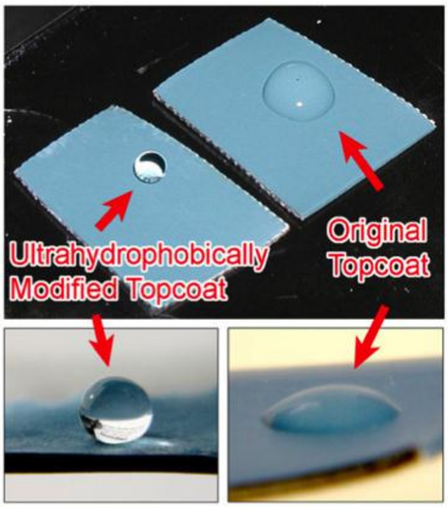


Fig. 45 Droplet contact angle on original substrate coating and after coating with Seashell ultrahydrophobic coating (courtesy Seashell Technology, LLC)

9.4.3 Design

Summary: Vessel design and design of topsides may be the best solution to prevent ice accumulation (See Fig. 46). But vessel icing problem isn’t the main problem that is taken into account by designers and shipbuilders. And icing is unlikely to dominate the design process but certain aspects are considered in the total winterization philosophy for platforms operating in the cold regions.

Generally icing can be most effectively reduced by decreasing the magnitude and height of spray generated by wave and swell impacts with the structure, by decreasing the surface area on which ice can form, and by reducing the number of small-diameter objects that increase ice collection efficiency. Greater distances between the main deck and the waterline should also reduce the liquid water content and median drop size of spray reaching the deck and work areas. Enclosing antennas and minimizing exposed cables and other small objects will also reduce icing [5,19,20]. The whole platform can be covered with special ice-protection hoods to minimize collection coefficient and area exposed to icing.

Applications to platforms: Enclosing decks, walkways, work areas, and stairs will reduce icing and increase crew safety and comfort. Also, enclosure of crane and flare boom lattice structures will significantly reduce ice accretion, and the difficulty of removing ice from those structures [19,20 and 22].

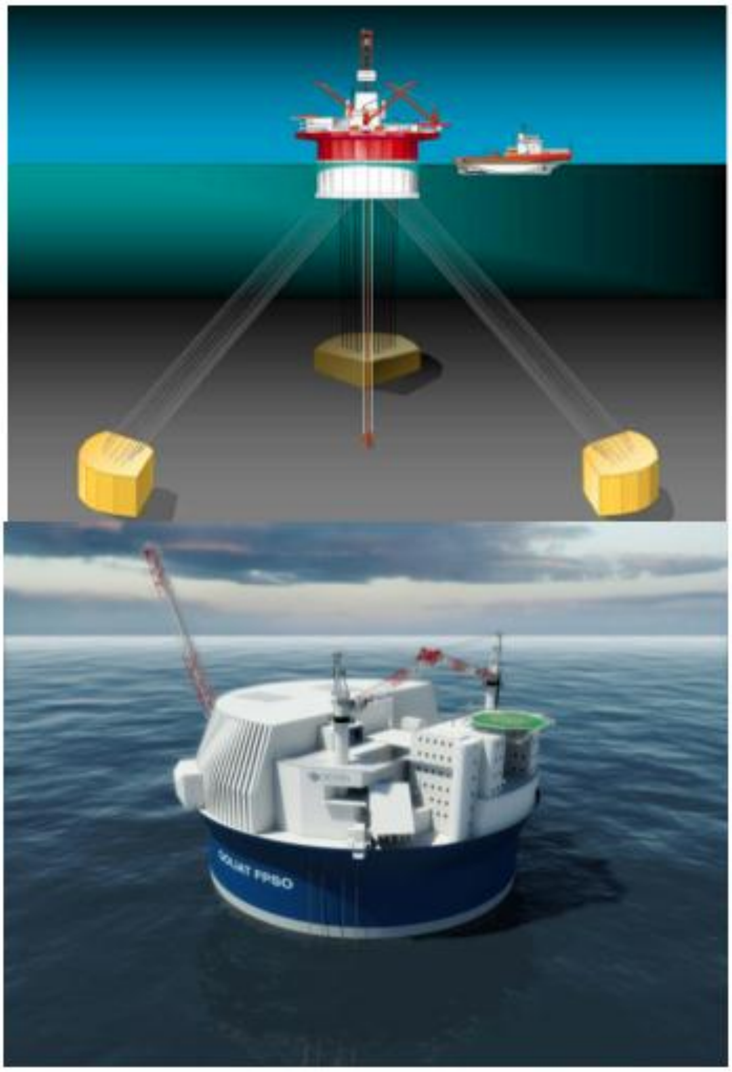


Fig. 46 Arctic semi-rigid floater for production in water depths of 80 to 500 m (top). The Sevan Marine FPSO (bottom) is a similar structure for the Goliat Field located north of Norway. The Sevan design focuses on minimizing superstructure icing and on creating an optimal working environment by locating all equipment in enclosed areas. The process modules are arranged with a top cover and transparent walls allowing gas releases to be ventilated (courtesy Sevan Marine)

9.4.5 Expulsive

Summary: Expulsive systems usually are used to deice but they can be also tuned to anti-ice. Anti-icing will request more energy consumption because these systems must always be on. Expulsive systems operate by deforming the surface, and therefore pealing ice from the surface, and by accelerating the surface sufficiently so that the moving ice overcomes its adhesion strength to the surface when the limit of motion is reached and rapidly decelerates (See Fig. 47). The systems vary from placing electromagnetic coils under a flexible metal skin, to gluing a thin flexible expulsive sandwich of conductors and dielectric material to a surface. Although the systems remove hard, brittle freshwater ice readily, their efficiency in removing soft saline superstructure ice is unknown. The systems are energy efficient when compared to traditional thermal systems, and have the capability of removing large masses of ice, such as from lock walls [1,8,19,20].

Applications to platforms: Expulsive systems may be applied with greatest advantage on platforms in areas inaccessible to personnel. For example, expulsive systems could effectively deice areas generally inaccessible to personnel in severe weather, in areas that need frequent deicing, and in areas where ice shards can fall without injuring personnel or material. Therefore, expulsive systems should not be used on bulkheads and locations where personnel could be struck by flying ice. Hatches and railings are also potential applications if access by personnel is limited when the systems are activated [19].

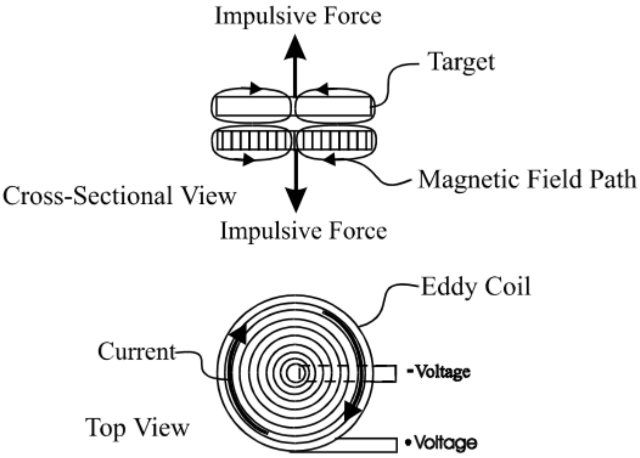


Fig. 47 Diagram of EIDI coil. Coil is positioned in close proximity to target surface and discharged with high current impulse source. Magnetic field lines induce currents in target surface to cause rapid shock to pulverize surface ice accumulation (courtesy Innovative Dynamics Inc.)

9.4.6 Heat

Summary: Heating technologies are the oldest studied for de-ice. Despite of the fact that there has been a lot of research in this field and even test prototypes have been presented, directional heating isn’t used at the moment. The main problem is huge energy demand for these systems to de-ice efficiently though heat can be delivered in many ways. These range from moist hot air that delivers much of its heat as latent energy, to dry hot air, to several electrothermal systems that promise to deliver heat with much greater efficiency than traditional electrothermal systems (See Fig. 48). Because methods of delivering heat vary widely, application on offshore platforms and supply boats will also differ considerably [19 and 20].

Two of the technologies deliver warm air to iced surfaces and melt the ice from the air-ice interface to the ice-surface interface. This requires that personnel maneuver a nozzle or head to deliver heat to the ice surface allowing the warm air to melt the ice [5 and 19].

The other thermal technologies offer a more efficient variation of electrothermal deicing technologies (See Fig. 48). Traditional electrothermal systems either operate as anti-icing systems (maintaining a surface temperature that is warmer than freezing) or they heat an area enough so that ice melts and eventually slides off from the air- foil. In addition, temperature is raised so rapidly that only a thin layer of ice at the ice-heater interface melts, and reduces the ice adhesion strength, and allows the ice to slide off from the surface. This allows the new heaters to be more efficient than traditional electrothermal systems. In addition, because they are not melting the entire volume of ice they expend less energy than systems that melt the entire volume of ice from the air-ice interface to the substrate-ice interface [7,10,19,20].

Applications to platforms: Hot air deicing systems can be applied to platforms, especially to areas where personnel can maneuver, to deice decks, equipment, bulkheads, windows, antennas and and railings. The temperature sensitivity of materials must be considered, as must the location of warm air sources versus hoses that must be maneuvered to deliver the warm air. However, other than placing systems onboard to deliver the warm air, little infrastructure change is necessary. However, considerable engineering may be necessary to accomplish this [10,14,19].

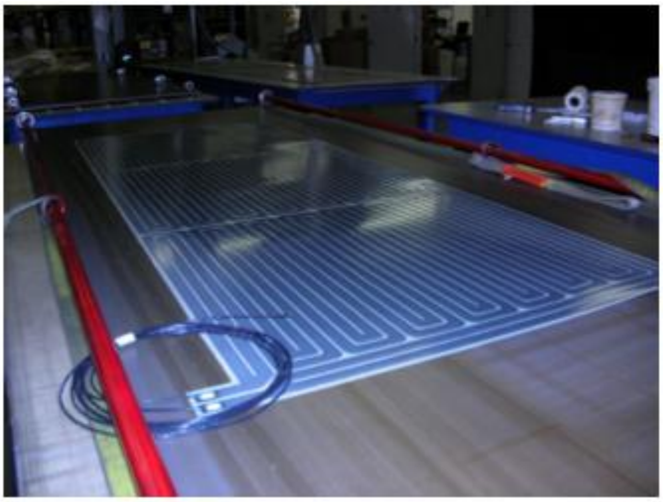


Fig. 48 Small QFilm heater areas (top) and 0.6- by 1.8-m section (bottom), both showing serpentine heater conductors and electrical connections (courtesy EGC Enterprises Inc.)

9.4.7 High-velocity air, water and steam

Summary: High-velocity air, water and steam have proven of value in removing snow and ice from structures. Steam lances have been used to remove ice from ships, and are often used to open frozen pipes and drains. Water and steam jets can cut significant thicknesses of ice from surfaces (See Fig. 49) [13,19,22].

Furthmore, injection of only small volumes of deicing fluid into the air stream, along with heat in the fluids, has been demonstrated to rapidly remove heavy wet snow and ice. These systems may be particularly effective for removing large masses of relatively soft, new superstructure ice from platforms and boats. However, some reengineering of existing systems would be necessary to provide the mobility needed to fully use the capability on a platform [19].

Applications to platforms: The utility of high-velocity systems on platforms is a balance between maneuverability and effectiveness. Removal of large volumes of snow or ice from platform components will require relatively powerful systems that are difficult for personnel to handle unassisted. In addition, maneuvering a system around on a platform, and especially lowering it to potentially heavily iced areas under the main deck, may require significant reengineering. High-velocity water, steam, or deicing fluid may provide viable solutions to these thick ice situations. Platform areas that could be deiced, or de-snowed, by high-velocity systems include support structures, decks, railings, stairs, the helicopter landing pad, and winches [19 and 20].

Fig. 49 AirPlus! sprays air and deicing fluid mist on helicopter blades (left). Large pieces of 10-cm-thick snow are removed from fuselage by air alone (right) [19]

9.4.8 Infrared

Summary: Infrared energy is an attractive tool for deicing and anti-icing. Infrared energy is a remote method of delivering heat to an object (See Fig. 50). Infrared emitters can deice or anti-ice where conventional, in situ deicing systems might be damaged. For example, emitters can deice walkways or work areas. They can be designed to emit the amount of energy needed, and some systems have lenses for focusing infrared energy making the heaters more effective at greater distances. The energy is absorbed at the ice surface, and the infrared energy is used to melt the ice. Most infrared energy does not penetrate the ice to the substrate and melt from the bottom, which would be more efficient if physics allowed it to be possible. Infrared energy intensity and wavelength can be controlled by emitter temperature, distance and time of use [19].

Applications to platforms: Infrared systems may be useful on platforms for anti-icing fire and rescue equipment, communication antennas, ventilation openings, valves and handles, irregular surfaces such as winches and windlasses, and stairs and deck walkway areas. Heaters could also be placed under the helicopter landing pad - heating it from below [20].

Fig. 50 Ice-Cat heater over helicopter (top) and complete Ice-Cat heater, boom, and truck system (bottom) [19]

9.4.9 Manual deicing

Summary: Manual methods, using baseball bats, mallets, and shovels are the traditional method of deicing marine structures (See Fig. 51). It is likely that many vessels have been saved using these methods. However, it is also possible that many have been lost when this is the only option. If decks are inaccessible due to heavy weather, for example, deicing is slow or cannot occur. It also requires a large number of personnel and exposure to potentially severe weather conditions, and has the risk for personnel. Objects on the platform or boat can be damaged or broken using manual methods. Manual deicing is cost-effective with regard to equipment, but costly with regard to personnel. However, it is likely that manual methods will always be required for those locations in the marine environment not fully protected by alternative deicing or anti-icing technologies. In addition, manual methods are an important backup if other methods fail [11 and 19].

Applications to platforms: Firstly, manual deicing methods can be effective on areas of platforms reachable by personnel (See Fig. 50). However, areas where personnel have no access cannot be deiced manually(derrick, the flare boom, cranes, etc.). Windows and antennas must be deiced with care, as should composite structures that may delaminate when impacted. Devices such as scrapers may be more appropriate for composite structures and windows [19 and 20].

Fig. 51 Manual de-icing during a research cruise in February 1997 to the Labrador Sea [30]

9.4.10 Piezoelectric actuators

Summary: The use of piezoelectric actuators to deice involves distorting and/or accelerating surfaces sufficiently so that the adhesion strength of ice is overcome. This is accomplished by placing piezoelectric actuators on the back of flexible surfaces. When turned on, the actuators elongate in one or more axes causing a reaction in the substrate material. The technology is currently in early development, and if prototypes become available, it may be applied in limited areas to protect specific items on a platform or a supply boat. Ultimately, with high-power actuators, large areas of structures may be protected if they are relatively uniform structurally. As with expulsive systems, falling particles of ice may require removal of sensitive equipment or personnel from decks and other surfaces located below the object being deiced [19 and 21].

Applications to platforms: Piezoelectric actuators may be able to protect stairs, decks and hatch covers. Ultimately, it may be possible to protect large structural support elements under the main deck, but that must wait for development of more powerful actuators.

9.4.11 Pneumatic boots

Summary: Pneumatic boots have been used successfully for deicing air-craft wing leading edges for more than 70 years. Boots remove ice in a manner similar to several other technologies — ice accumulates on the boot surface, and when sufficient ice accumulates the boot is inflated, distorting the boot surface, which causes peeling off and breaking the brittle ice.

Applications to platforms: Pneumatic boots may potentially, with testing, be placed in the support structure areas of platforms to protect it from large ice accumulations. They may be wrapped around the lattice structure of cranes and flare booms to reduce ice accretion area and to remove ice. Boots can protect communication antennas. It may also be possible to use small boots to protect solid pipe safety railings [19].

9.4.12 Vibration and covers

Summary: Experiments with low-frequency high-amplitude vibration of solid structures to remove ice have generally not been successful. Vibration has worked only when the structure is somewhat flexible; ice was removed when it flexed most violently at the resonant frequency of the structure, which damaged the structure. Success has been mixed with the use of flexible covers. Flexible covers have not been observed to deice themselves in the wind. However, during manually deicing, objects covered loosely with tarps are more easily deiced than objects that are tightly bound with tarps [19 and 26].

Applications to platforms: Covering of fire and rescue equipment, hatch covers, railings, and winches with tarps may allow them to be more easily deiced. Wrapping tarps around the lattice structure of crane and flare booms reduces the surface area that will ice and may make ice removal easier. However, tarps wrapped around lattice structures may increase wind load significantly [19,26].

9.5 Ice detection

Summary: Four fundamental types of detectors are available at the moment: wide-area, remote, in situ, and probe designs. Wide-area ice imaging technology shows the extent and, in some cases, the thickness of ice coverage. These are remote sensing technologies developed to determine whether there is ice on aircraft surfaces before or after deicing. Studies have demonstrated that wide-area sensing has the capability of substituting for tactile ice sensing, the standard method of determining whether aircraft surfaces were iced. Wide-area technologies may be applied to the marine environment, especially where incipient icing could cause slipping hazards on decks, stairs, work areas, and helicopter landing pads. Imaging ice coverage on the sea- facing surfaces of a platform may require a helicopter to obtain the proper view. The range of ice thicknesses that can be displayed, when they are provided by the technology, may be important for assessing walkway and helicopter pad safety where avoiding slipperiness is important. Wide-area detection may be most useful for monitoring areas where small ice accretions are a safety threat, such as walkways, work areas, stairs, landing pads, and perhaps the moon pool area [4 and 19].

Non-imaging remote detection, currently used for road weather information systems and for activating roadway FAST systems, indicates minimal ice thickness and the presence of water or ice and snow. This would be useful for monitoring the safety of walkways, stairs, work areas, and landing pads. Because remote systems require specific standoff distances and monitor relatively small areas, their signals should serve as an index for conditions in similar areas of a platform or a boat [19].

In situ ice detectors are embedded flush with the surface of a structure and are conformal with regard to shape. Although most important in the aviation environment, sensors embedded in a surface (if they are also thermally similar to their surroundings) can better represent the amount of ice forming on that surface because drop collection efficiency and wind flow over the sensor will more likely match that of its surroundings.

Probe ice detectors are the most common type of ice detector in aviation, weather, and electrical transmission line applications. In some cases, through many years of use, the characteristics of these sensors are well understood. As with most in situ sensors, probe sensors only provide an indication of the rate of icing and do not indicate how much ice actually resides on a surface. Ice thickness at any one location is highly dependent upon local factors. Therefore, correlations between probe sensors and surfaces of interest are necessary, correlations that are not necessarily accurate as conditions change from storm to storm [4,19].

Applications to platforms: Platforms could benefit from a variety of ice detection devices. Wide-area or remote detectors, and some in situ detectors, may be most useful for detecting the initial formation of ice on areas where ice can be a personnel hazard due to slipping. These detectors excel at determining the onset of icing and the beginning of hazardous conditions that can cause falls on decks, stairs, and in work areas. Helicopter landing pads cannot be imaged by permanently located wide-area or remote detectors because imagers must be mounted above the landing pad. However, in situ sensors that can tolerate traffic over their surfaces may be effective. Ice accretion on other platform surfaces such as large ice masses that may form from superstructure icing below the main deck, ice formation on lifelines and exterior bulkheads, and ice accretion on derricks, flare booms, and escape pods may be best detected with a combination of probe and in situ detectors. Detectors would need to be located in areas experiencing representative icing conditions, but also in areas not susceptible to damage. A significant hazard to most probe ice detectors (and to some in situ detectors) is the potential for damage during manual deicing activities. In all cases, any detector chosen must be integrated into a data acquisition and hazard annunciation system. In addition, they must be evaluated for effectiveness in saline ice conditions and for their ability to survive the marine environment [19].

9.6 Matrix of potential technology solutions

Impacts of icing on platform and supply boat locations and operations versus potential anti-icing or deicing technology solutions are paired. This Table 30 shows the technologies that may be most readily applied to reducing the impact of icing at the location, or for the operation, listed for platforms [5 and 19].

Table 30 Platform safety impact and technologies that can be used [19]

	1*	2	3	4	5	6	7	8	9	10	11
Stability	X	X	X	X	X	X		X	x	X	
Integrity	X	x	X	X	X	X		X	x	X	
Fire and rescue		x	X		X	x	X	X			x
Communications		X	X		X		X	x		X	x
Helicopter pad	X	x	x		X	X		X	x		X
Air intakes		X	X	x	X	x	X	X			
Flare boom	X	X	X			X	x		x	x	x
Handles, valves		x	x		x	x	X	X			X
Windows	X	X			X	X		X	x		
Cranes	X	X	X			X	x		x	x	x
Winches	X	X	x		x	X	X	X			x
Stairs	X		X		X	X	X	X	x		
Decks	X		X		x	X	X	X	x		
Railings		x	x	X	X	X		X	x	x	x
Hatches		X		X	X	X		X	x		x
Cellar deck		X	X	x	X	X	x	x			
Moon pool		X	X	x	X	X	X	x			

Bold uppercase **X** suggests a stronger match than does an unbolded lowercase x.

*Technology key
1. Chemicals and Chemical Distribution
2. Coatings
3. Design
4. Expulsive
5. Heat
6. High-Volume Water, Air, Steam
7. Infrared
8. Manual
9. Piezoelectric
10. Pneumatic Boots
11. Vibration and Covers

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Conclusions

This work deals with problems of vessel icing. It scrutinizes ice properties, the nature of icing and different mechanisms of its accumulation on the vessel. Geography and icing accident records are given. For the Shtokman site the precise meteorological conditions are presented. This gives a chance to predict possible icing on the Shtokman FPSO.

Several Rules and Regulations in regards of vessel icing are studied in details. All these standards and rules give more or less step-by-step guidelines to evaluate possible mass of ice that can be accumulated at the vessel. But all of them are based of different assumptions of vessel design and therefore can’t give precise data about possible icing. To solve this problem a new model to predict icing is proposed. This method uses an hydro-aero dynamics and basics of continuum mechanics. It’s believed that the proposed model might give better and more adequate results or at least become a part of a new standard.

Besides a possible FPSO icing is evaluated with regards to several international codes (ISO, RMRS, DNV and NORSOK) and the new mathematical model. No doubt these are approximate calculations of ice and snow loads because there no detailed info about the FPSO top-side modules lay-out is available. Furthermore, there is merely no data about its dimensions and positions on the deck. Thus all the calculations present results of simplified FPSO lay-out.

In the course of the proposed icing model the following results can be listed:

1. A theoretical model based on a geometric and force analysis of water droplets in the air is proposed;

2. The problem of icing on a fixed plate is solved;

3. The problem of icing on a plate wiggling harmonically in the vertical plane is solved.

The independence of thr ice mass on the frequency of the vertical motions is proved;

4. The problem of icing on a plate wiggling harmonically in the horizontal plane is solved. A quadratic dependency of water droplets' hit energy on the frequency of motions is found;

5. A correction coefficient for the model and the observed data is proposed. As it is in a range from 2 to 5 we can say that the model is adequate;

6. Motions of the floating production storage and offloading structures of the Shtokman field due to waves are discussed; their frequencies and effects on the icing processes are analyzed;

7. Evaluation of icing process on stepped constructions is carried out. Stepped constructions approximate real vessels with deck housings and structures, bridges and equipment;

8. Vessel stability evaluation in case of icing is carried out, changes of vessel's GM in case of icing is discussed;

9. The factors affecting on the vessel's stability in case of potential icing are proposed – time factor, meteorological and construction factors.

The proposed model showed very good results in comparison with other standards and rules. This gives a belief that further work in the direction of model development looks promising and might give even better results.

Nevertheless a bundle of technologies and techniques to fight and mitigate icing on platforms are presented. Most of this review was prepared by Dr. Charles Ryerson from the USA and CRREL. The author of a work would like thank Dr. Ryerson for his vital help, advice and materials. As a result a joint table of possible technologies that can be used at the platform in certain hazardous areas is given.