Universitetet i Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Offshore Technology/Subsea and Marine technology	**Spring semester, 2018** Open / Restricted access
Writer: Egor Meshcheryakov	.... (Writer's signature)

Faculty supervisor: Ove Tobias Gudmestad

External supervisor: Anatoly Borisovich Zolotukhin

Thesis title: Concept of a FLNG vessel for the Russian Arctic shelf

Credits (ECTS): 30

Key words: FLNG, vessel motions, ice loads, wind loads, winterization, turret, Arctic shelf	**Pages:** 82 **Stavanger**

Abstract

The implementation of FLNG will introduce flexibility and mobility in the gas market. When we use pipeline transportation, the producer and the buyer are connected for decades by the created infrastructure, while in using the technology of LNG there is no such interdependence. There are also no dependences on transit countries.

Every day offshore production progresses into the deeper waters. Platforms, working in hundreds of kilometers from the coast, are created. To transport the extracted natural gas to a plant, which will turn it into LNG, it is necessary to build a corresponding length sea gas pipeline, that is a very expensive procedure. Moreover, transportation demands considerable energy too, so it also creates additional expenses. For this reason the idea to create the FLNG plants was proposed.

The main advantage of FLNG is mobility. After the depletion of deposits it is possible "to move" it to the new production site and continue to work. It significantly expands opportunities on payback of the project and will increase the profit: its price can be divided between several fields. Furthermore, application of FLNG plants will be important in minimizing the environmental impact of the coastal area.

There are several challenges on the way of realization of this idea in the Arctic. First, existing FNLG projects were created for working in the conditions of the warm seas. In the Arctic there are severe conditions. It is not only just cold there, but most of the territory is covered with ice. It provides essential technological complications. Secondly, in Russia there are no opportunities to build such technologically advanced vessels, because we don’t have enough experience, so we will have to collaborate with foreign partners. However, all these difficulties can be overcome. The main thing is that the necessary resource base is available here. It is enough to mention the huge Shtokman field, located 600 kilometers from the coast. In this work, I will emphasis on the design conditions for possible FLNG vessel on the Arctic shelf, winterization of the FLNG vessel and positioning of the vessel against drifting ice.

Acknowledgements

I am very grateful to my supervisor Professor Ove Tobias Gudmestad for supporting me during writing the thesis. I would also like to express my gratitude to Professors Anatoly Zolotukhin and Sveinung Løset for their important pieces of advice and general help. Also, I am thankful to all my professors and teachers from UIS, UNIS and Gubkin RSU of oil and gas, who gave me good knowledge and new experience.

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1. Introduction

The development of the Arctic shelf is one of the most important branches of the development of the oil and gas industry in the world. According to the forecast estimations, the shelf in the Russian sector of the Arctic contains about 90 trillion cubic meters of natural gas. Currently, large gas fields are being developed in the Northern and Barents Seas, near the coast of Sakhalin and other parts of the Russian Arctic shelf.

The construction of plants for liquefying gas from offshore fields will require huge funding for laying offshore pipelines, which is inefficient from an economic point of view. It is also unprofitable for the development of small offshore gas fields and all relevant infrastructure due to their remoteness from the coast. The development of the shelf requires the equipment, often comparable in complexity to spacecraft. At the same time, the demand for such unique equipment will grow. For such deposits, large companies-developers proposed new technologies for producing, preparing and transporting gas on the basis of floating LNG complexes.

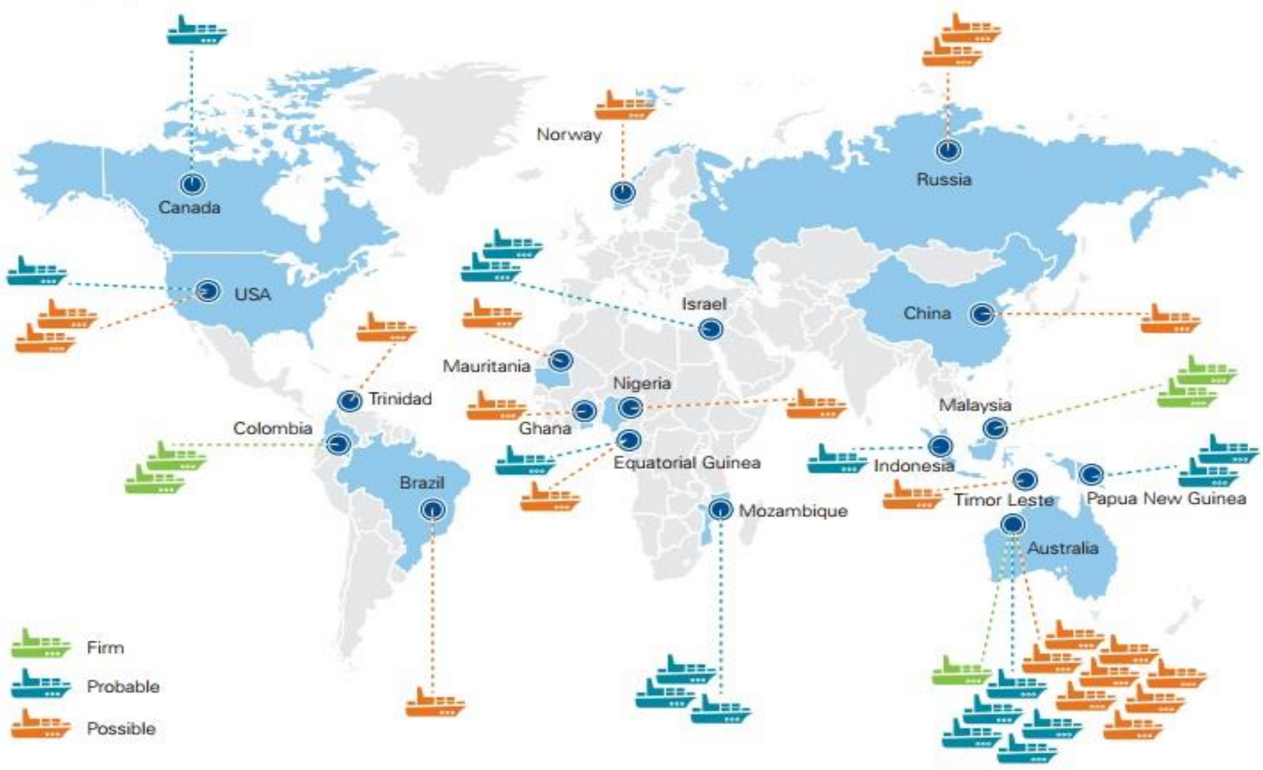

Figure1.1 The overview map of FLNG projects in the world (kpmg.com/energy)

As it can be seen from the figure 1.1 above, all firm floating LNG complexes are designed, taking into account the operating conditions in the non-freezing seas. For the conditions of the Arctic, production complexes with an ice-class hull will be required. In this work i will take into account the use of an ice-class hull (Arc7 class) (Look “Winterization” chapter) for a floating complex, as well as the manufacture of upper structures in winter version (with closed modules, electric heating, etc.).

In the well-known Shtokman project, a floating production complex with an ice-class hull was developed by Saipem, Technip, Hyundai, Samsung, Aker Kvaerner, and others (Figure 1.2). This concept was tested with expertise of leading expert communities and customer companies. An example of such a floating LNG complex is presented in the following figure.

Figure 1.2 The project of the floating LNG complex for the Arctic shelf (Khairov, 2016)

2. Distinctive features of FLNG

The LNG floating plant is a vessel or barge with the functions of a producing offshore platform, where installations for preparation, refining and dehydration of gas have been installed on the deck, together with technological lines for the separation and liquefaction of gas. In the hull of the vessel there are tanks for storage of LNG and liquefied hydrocarbon gases. The plant is equipped with an LNG offloading system for tankers. In addition, there are units, intended for the personnel of the floating complex on the deck.

The vessel should be located above the gas field and stay in place until the field is completely depleted, which will avoid the need to build long underwater pipelines. Therefore, it is very important, that the plant should be resistant to all unfavorable weather conditions.

Especially strict safety requirements have been introduced for the construction and operation of the floating LNG plants. The risk of emergency situations increases due to the close location of the plant area, storage areas and personnel areas. It should be noted, that the space available for placing the equipment is much less than the space allocated for such a plant on land. The optimum design solution will focus on reducing to the minimum size and weight of equipment.

Figure 2.1 Construction of FLNG Prelude (www.offshoreenergytoday.com)

The construction of a floating plant takes place on a modular basis with the minimum possible number of equipment. This will ensure cost savings and high quality of production. The construction of the ship itself and the complex of superstructures can be carried out in parallel, which will save the time for the establishment of the floating LNG plant (Figure 2.1).

The processes of production, storage and offloading of LNG and other products must comply with high safety standards. The operation of process units should be as safe as possible and carried out by a minimum number of maintenance personnel. The storage facilities for liquefied petroleum gases and the possibility of their offloading to ships should be provided.

There exist several different processes of gas liquefaction, for example the nitrogen-expander cycle. This is a cycle with two expanders, where the application of the second expander at a lower temperature level increases the thermodynamic efficiency of the process due to the decrease in the temperature difference during the supercooling of the LNG. Nitrogen refrigeration cycle has a number of advantages: quick start and stop, a small amount of equipment, simplicity of the scheme, ensuring safety in the absence of hydrocarbon refrigerants.

As for the environmental factor, the FLNG plants have less negative impact on the environment.

3. The very first FLNG in the world PRELUDE

The existing floating plant "Prelude FLNG" is the world's first liquefied natural gas plant (Figure 3.1). Nowadays, the "Prelude" is the largest floating object on Earth. The decision to build the Prelude factory was made by “Royal Dutch Shell” on May 20, 2011, and construction was completed in 2013. The scale of this project is impressive. The weight of the plant is 260 thousand tons. Displacement at full load is 600 000 tons, which is 6 times more than the displacement of the largest aircraft carrier. The total area of the deck is more than four football fields. This LNG floating plant will service the Prelude field, which was open in 2007, with reserves of up to 85 bcm. The planned volumes of fuel production in the Prelude project, as Shell officials said, will be at least 5.3 million tons of liquid hydrocarbons per year, of which 3.6 million tons of LNG, 1.3 million tons of condensate and 0.4 million tons of liquefied petroleum gas. The Prelude plant will operate at this field for 25 years. In the future, it is possible to use it in other deposits in Australia, in which Shell has a stake. To build such a unique object, many innovative engineering solutions were applied. The ability to rapidly build and deploy floating LNG plants, that can be used in various fields, is an important success factor for producing companies against the backdrop of a global increase in demand for energy. Taking into account this factor, Shell aims to create a Prelude plant, as a template for other future structures.

Figure 3.1 Prelude FLNG (www.offshoreenergytoday.com)

4. Perspective trends of the implementation of FLNG

The use of floating LNG complexes is an opportunity to develop resources from offshore fields with finished products at a point as close as possible to the field itself. As a result, we are able to avoid the construction of expensive pipeline infrastructure (for example, for the Shtokman project, the proposed construction of trunk pipelines with a length of about 600 km and, according to experts, with a cost of more than 4 billion US dollars).

The timing and budget of such projects is less subject to growth of the risks, because the main works, including start-up operations, are performed at shipyards and production sites in the factory with maximum efficiency and labor productivity, developed infrastructure and logistics of equipment delivery, regardless of weather conditions. Delivery of the LNG complex to the site of production and its connection to the infrastructure is realized in the shortest possible time, which practically minimizes the volume of costly offshore operations (compared, for example, with the installation of offshore fixed platforms or the laying of underwater pipelines).

Also, it is necessary to mention the change in the world gas supply market. The US withdrew as one of the major importers, but Japan and Germany increased natural gas imports. The European Union is also implementing a strategy for diversifying gas supplies to Europe or reducing dependence on the import of pipeline gas, which served as an impetus to the creation and a serious expansion of the infrastructure for receiving LNG.

In 2006 the company FLEX LNG was established in Norway, the only mission of which is the commercialization of floating liquefying plants for natural gas. The company's technical concept is based on the use of medium size power plants (1.5-2 million tons of LNG per year). As a process, a nitrogen cycle with an expander was chosen. FLEX LNG emphasize, that with the use of the concept, developed by them, for development of relatively small and remote deposits, development of which previously was economically unprofitable, is currently advisable. The competitors of

FLEX LNG are also the well-known Norwegian company Höegh LNG, which has successfully implemented the technology of creating regasification terminals for LNG import on the basis of tanker-gas carriers. After the construction of regasification terminals for import of LNG, Höegh LNG leases them to various customers around the world (Figure 4.1).

Figure 4.1 Regasification terminal "Independence", Klaipeda, Lithuania (www.hoeghlng.com)

It is also very important to note the advantages of supply logistics. The possibility of using the Northern Sea Route (Figure 4.2) as the shortest and most efficient route for the delivery of energy resources from the Arctic regions to the premium markets of Southeast Asia has been confirmed for several years already. In 2012, transit shipments through the NSR for summer-autumn navigation amounted to 1.26 million tons (46 vessels were conducted). In the same year, the first in the world transportation of liquefied natural gas in the NSR was held. The tanker "Ob River" transported 134,500 cubic meters of gas from Norway to Japan. The benefits of using NSR for transit transport are as follows:

• fuel economy;

• reducing the duration of one trip, which in turn reduces the cost of staff and the total cost of all expenditures;

• there is no payment for the transit of the vessel (in contrast to the Suez Canal);

• there are no time delays due to the limited capacity of some water bodies (as in the case of the Suez Canal);

• no risks of being attacked by sea pirates.

As the priority markets for the concept I see the market of Europe and the Asia-Pacific region. In view of the fact, that the cost of transporting products significantly depends on the distance, the Northern Sea Route becomes the only opportunity to gain access to the premium markets of the APR region and increase the economic efficiency of the project. The most promising are the markets of Japan, Korea and China, since the distance of delivery along the Northern Sea Route to these markets is minimal.

Figure 4.2 The Northern Sea Route (www.highnorthnews.com)

5. General information about the chosen field

5.1 Review of projects in the Barents Sea water area

The water area of the Barents Sea was chosen as a landfill for the implementation of the FLNG concept. This region is one of the most studied regions within the continental shelf of the Russian Federation. Nowadays, several gas and gas condensate fields have been discovered here: Murmanskoye, Severo-Kildinskoye, Ledovoye, Ludlovskoe and Shtokman. Futhermore, a number of promising structures and blocks have been also identified here, such as: Perseevsky, Central Barentsevsky, Fedynsky, and others (Figure 5.1.1).

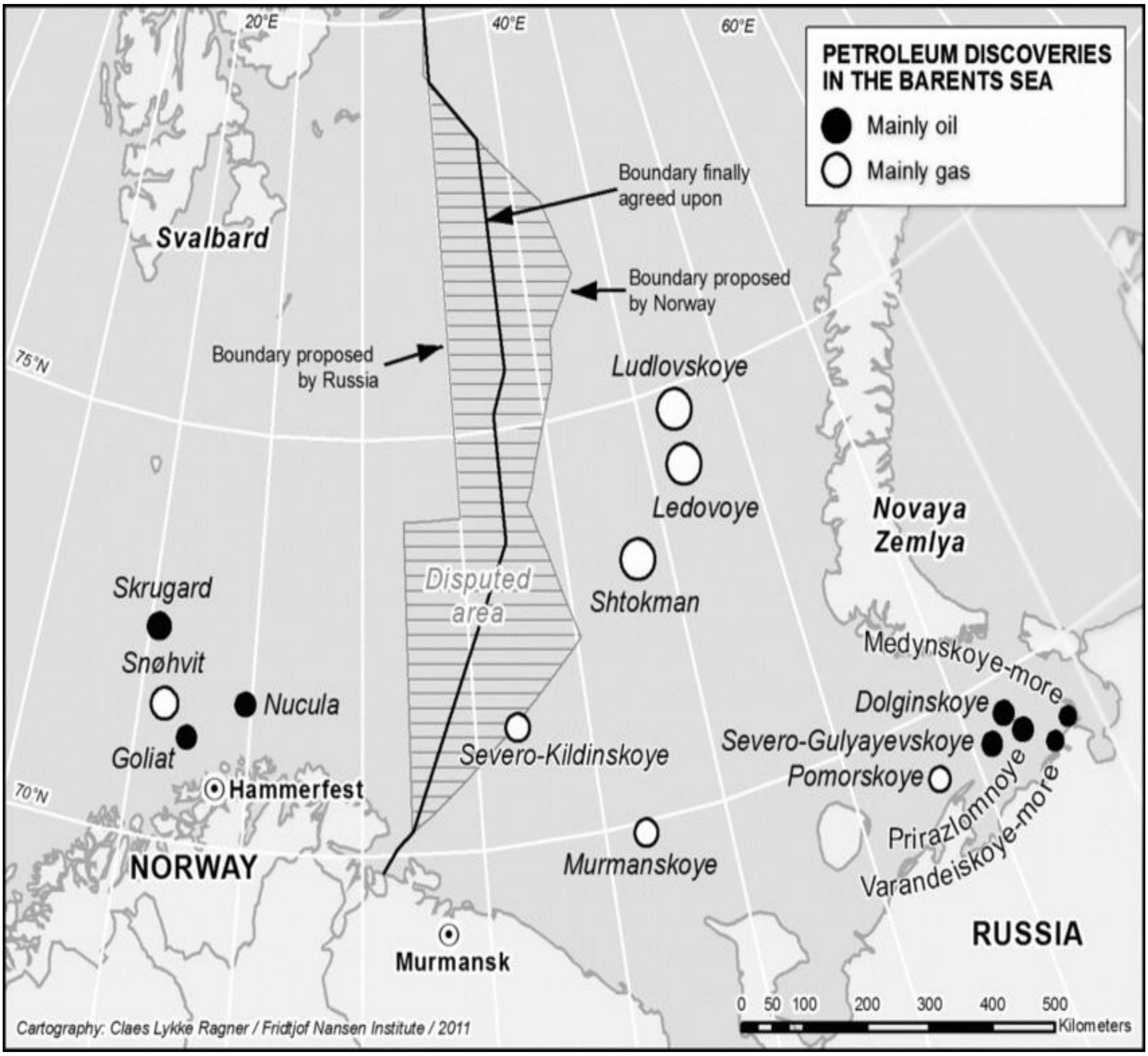

Figure 5.1.1 Fields in Barents Sea (www.researchgate.net)

The water area of the Barents Sea, unlike other seas of the Arctic shelf of the Russian Federation, is not completely covered with ice during most of the year, which simplifies solutions for the field development, associated logistics and maritime transport of manufactured products. Nevertheless, the Barents natural and climatic conditions have their own peculiarities, which create additional difficulties in the implementation of the project.

It is important to note, that in the Norwegian sector of the Barents Sea, consortia of international companies have been actively producing hydrocarbons for more than 10 years. For example, the Snohvit gas field, the Goliat oil field have been launched, and exploration is underway. In the Russian sector of the Barents Sea, the most studied is the unique Shtokman field, discovered in 1988.

5.2 Field selection

Taking into account the previously given criteria, the Ledovoye deposit, located in the northwestern part of the Barents Sea within the continental shelf of the Russian Federation, was selected.

This field is one of the most studied after the Shtokman in the Barents Sea, and at the same time, one of the most remote from any mainland infrastructure. According to the size of the reserves, the field is considered to be large. Nevertheless, the estimated reserves of the field are much smaller than the reserves of the Shtokman field. The main deposits of gas are concentrated mainly in the Middle Jurassic sediments. The condensate content is insignificant. The deposit is multi-site, reservoirs are arched, tectonically shielded.

The license for the field is owned by PJSC “Gazprom”. The Ledovoye field was discovered in 1992. The depth of the Barents Sea in the area of the field is 200-280 m.

Reserves:

- P1 - 91.722 bcm of gas, 0.999 mt - geological reserves of condensate
- P2 - 330.395 billion cubic meters of gas, 3.927 million tons - geological reserves of condensate

I also provided primary estimations of technological capacity of FLNG vessel for Ledovoye field, and they showed that it will produce approximately 7 billion cubic meters of gas per annum (with field lifecycle of 30 years), that will require nearly 8 production wells and 2 water injection wells for re-injection of formation water and carbon dioxide (CO_2) into the reservoir in order to fulfill the "zero discharge" requirements. It will produce 5 million tons of LNG per annum.

6. Architecture of FLNG

FLNG is a technological vessel, installed on the field and located by the anchors. The vessel consists of the following technological units: the lower ice-resistant hull with integrated storage tanks for LNG and condensate, and various technological tanks (for water, etc.). The upper structures should contain the main technological facilities for producing, preparing, liquefying and offloading of gas, as well as facilities for stabilization and offloading of condensate, auxiliary facilities and engineering support systems for the main process (coolant, compressed air, nitrogen, etc.), energy unit and living quarter (Figure 6.1).

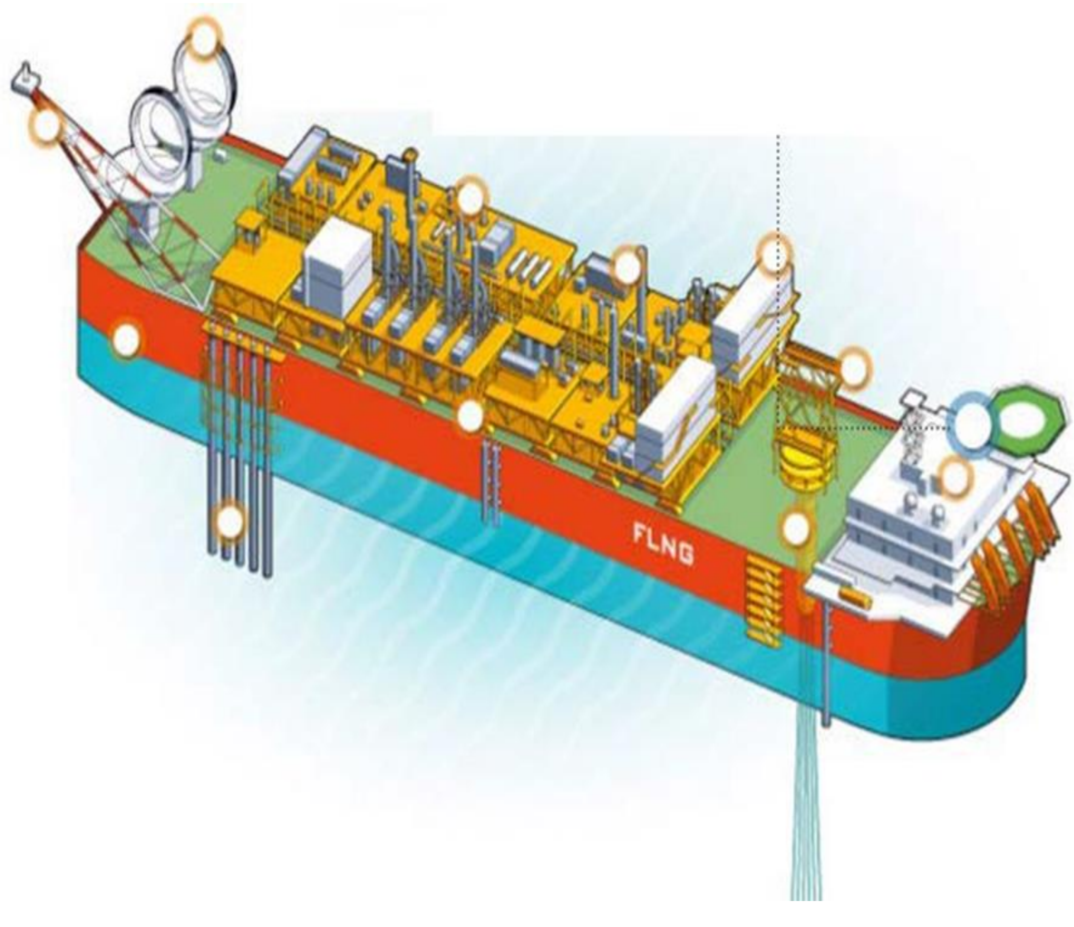

Figure 6.1 Structure and basic elements of FLNG (www.technip.com)

LNG carrier tankers, as well as tankers for the transportation of stable condensate, will receive products and deliver it to consumers. For offloading of LNG from the vessel to tankers I propose to use the system developed by the company "Bluewater". The tandem offloading system is based on existing practices as successfully used in crude-oil tandem offloading systems. Vessels are connected to each other with the help of special hawser system, which was already implemented in Bluewater's FPSOs. LNG is offloaded via special cryogenic flexible pipe. The tandem LNG transfer guarantees safety, reliability and operability. The separation distance between the two vessels during offloading is approximately 80 metres and allows connection at significant wave heights of up to 4.5 metres, while the loading operation can continue at significant wave heights of up to 5.5 metres. (http://www.bluewater.com/products-technology/lng-loading-offloading-systems/).

To prevent leakage during pumping, the loading line should be equipped with an emergency stop system, which allows to stop the supply of the product within 7 seconds. Before the start of offloading operations, tankers equipped with a bow loading system perform non-contact mooring. In spite of the wind and waves, the tanker can be held in place with the help of a dynamic positioning system. (Figure 6.2).

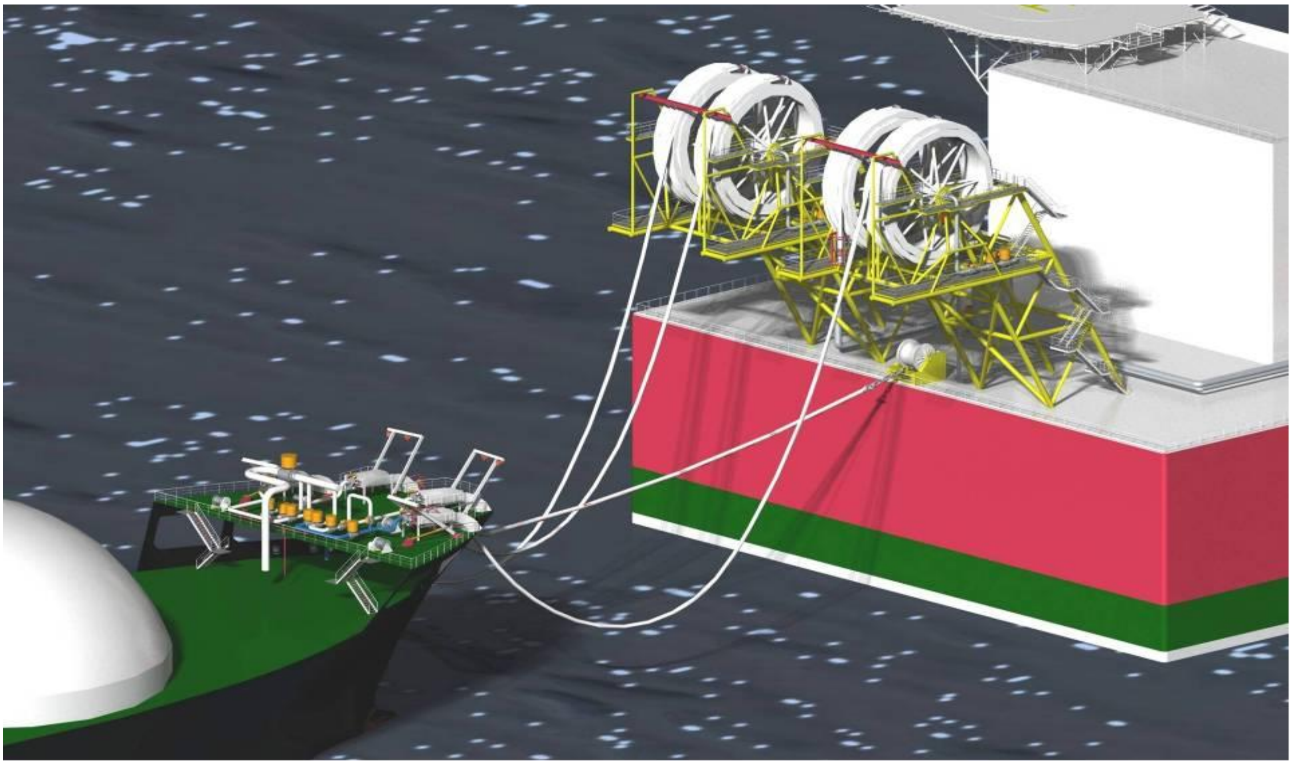

Figure 6.2 Schematic overview LNG offloading facility on board of a FLNG vessel (http://www.bluewater.com/products-technology/lng-loading-offloading-systems/)

The cryogenic pipeline through which LNG will be pumped to the tanker must be insulated to provide a relatively small heat input from the environment. The use of non-vacuum insulation with mats made of fiberglass and foam plastic coated outside with a polymer film protects the pipeline from moisture.

Yamalmax is a class of tankers for the transport of liquefied natural gas with membrane tanks in arctic conditions. The vessels correspond to the ice class Arc7 and have a capacity of 172,000 m^3 (figure 6.3).

Figure 6.3 Christophe de Margerie, a Yamalmax class LNG tanker (Marinetraffic.com)

With an approximate production of 13,000 tons of lng per day, tankers will need to come for loading once in 6 days.

Usually, the service life of such vessels is 25-30 years for the upper structures and 25-30 years for the steel hull of the technological vessel. After the expiration of this period, the LNG floating complex will need to be towed to the nearest appropriate seaport, then the production facility will need to be put into a dry dock for overhaul and modernization in order to extend the life of the facility to increase the economic performance of the project.

During operation, the floating LNG complex will be located directly above the field and connected to the underwater manifold and subsea well equipment by flexible risers and pipelines, going to the riser tower of the process vessel. The main functions of the riser tower are the connection of all field technological systems and pipelines to the production complex and anchoring of the hull (Figure 6.4). This mechanism also allows the ship to rotate around its axis.

Figure 6.4 Riser Tower (www.scanmatic.no)

It will also require a special mechanism to quickly disconnect the riser and anchors from technological systems in a case of approaching of large icebergs to the production complex and the inability to change the trajectory of their movement by the tugs or other technical means.

Through flexible pipelines and risers, gas and condensate, together with the formation fluid, flow from the reservoir to the floating production complex, and the carbon dioxide (CO_2) contained in the reservoir and the formation water are pumped back into the reservoir. Well clusters are integrated subsea production units. A powerful steel structure to protect against falling objects is installed above all underwater equipment.

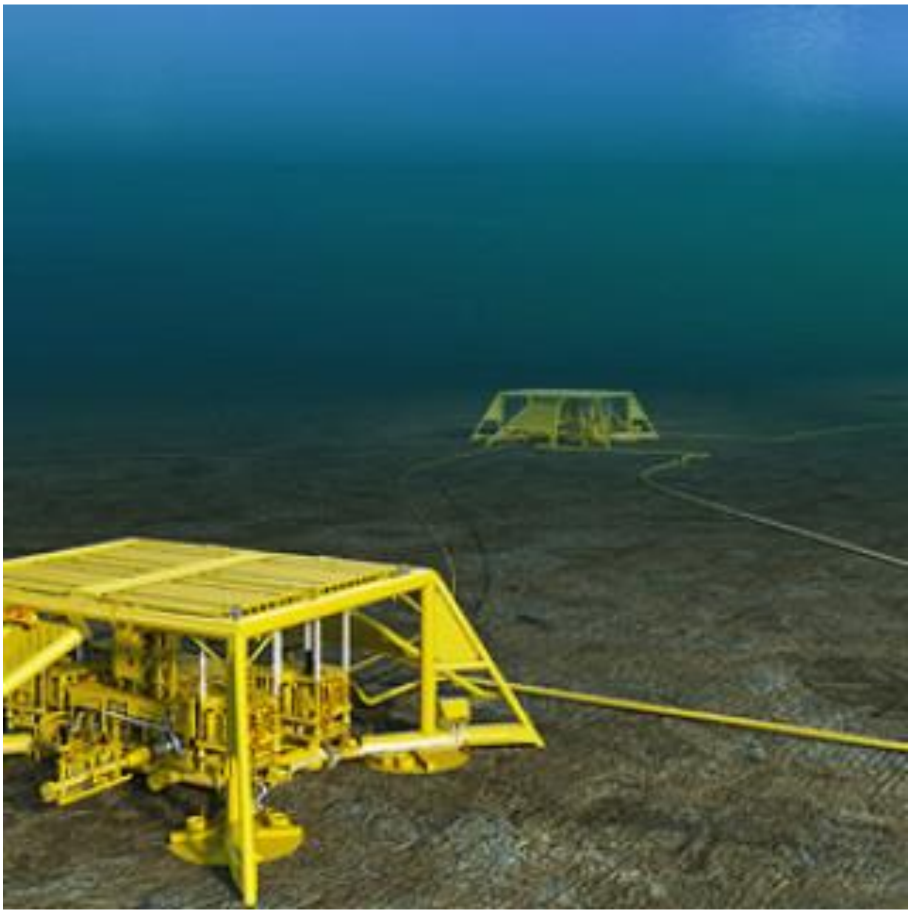

Figure 6.5 Integrated subsea production unit

(www.chesssubseaengineering.com)

In comparison with single subsea wells, the use of integrated subsea production units is seen to be more cost-effective (Figure 6.5). First, when drilling wells, there is no need to relocate drilling vessels or SSDPs (semi-submerged drilling platform) from one place to another, which saves a significant part of the drilling time and, as a consequence, its cost. Secondly, the reservoir fluid from all the wells of the integrated subsea production unit is collected as efficiently as possible through a manifold located in the immediate vicinity of the wellheads, which reduces the overall length of the underwater pipelines. Thirdly, wellhead control is also carried out through a single control unit. Finally, the time for installation and connection of integrated subsea production unit, as compared to individual subsea wells, is also reduced, which means significant savings for offshore fields. Management of all manifold monitoring systems, submarine systems, as well as gas preparation, storage and offloading of products will be carried out directly from the floating LNG complex via special umbilicals (Figure 6.6).

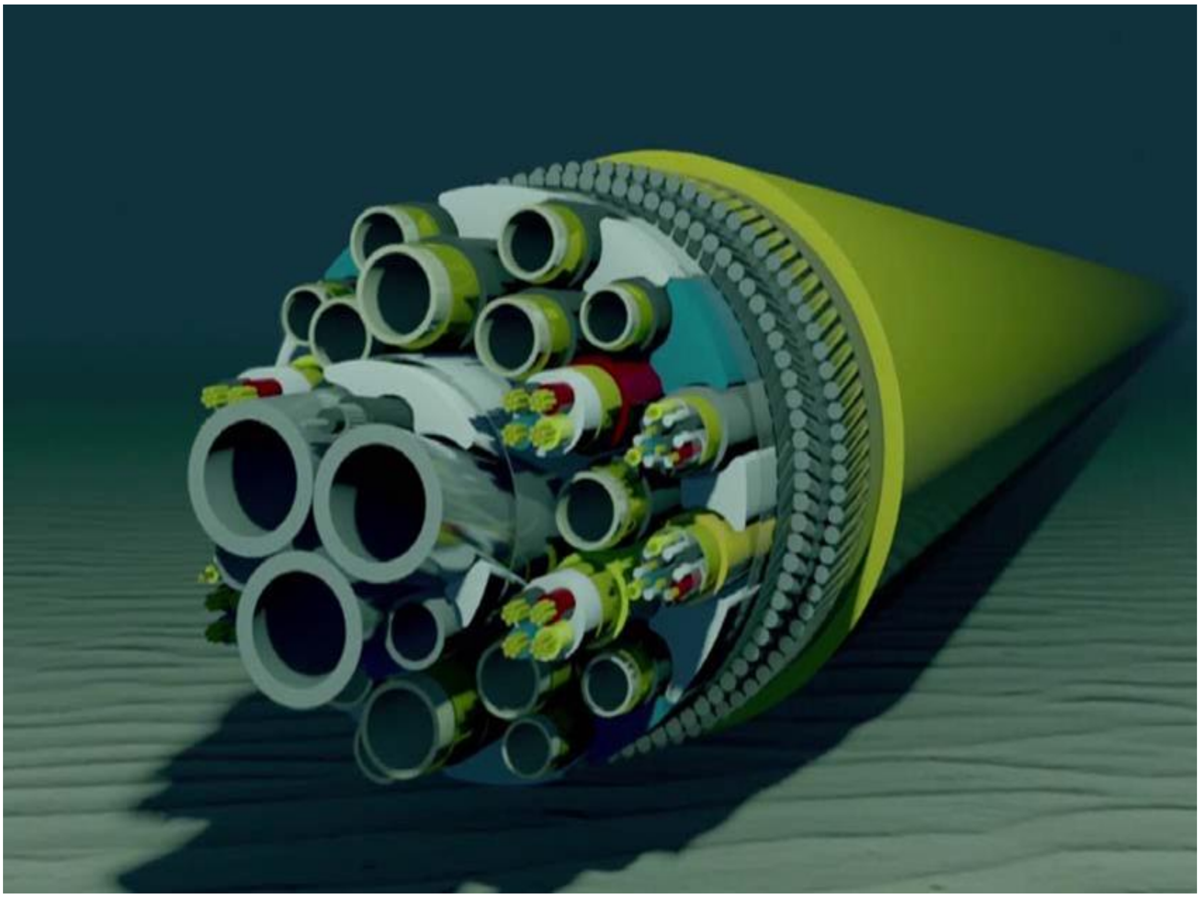

Figure 6.6 Underwater umbilical (www.subseaworldnews.com)

I analyzed in detail all ongoing FLNG projects and decide that my vessel would have approximately these parameters:

- Length – 400 m
- Beam – 70 m
- Height – 50 m
- Displacement tonnage – 500 000 tons
- Storage capacity for LNG – 250 000 m^3

7. Liquefaction technology

As a gas liquefaction technology, I propose to use a process using double mixed refrigerant (DMR) (figure 7.1).

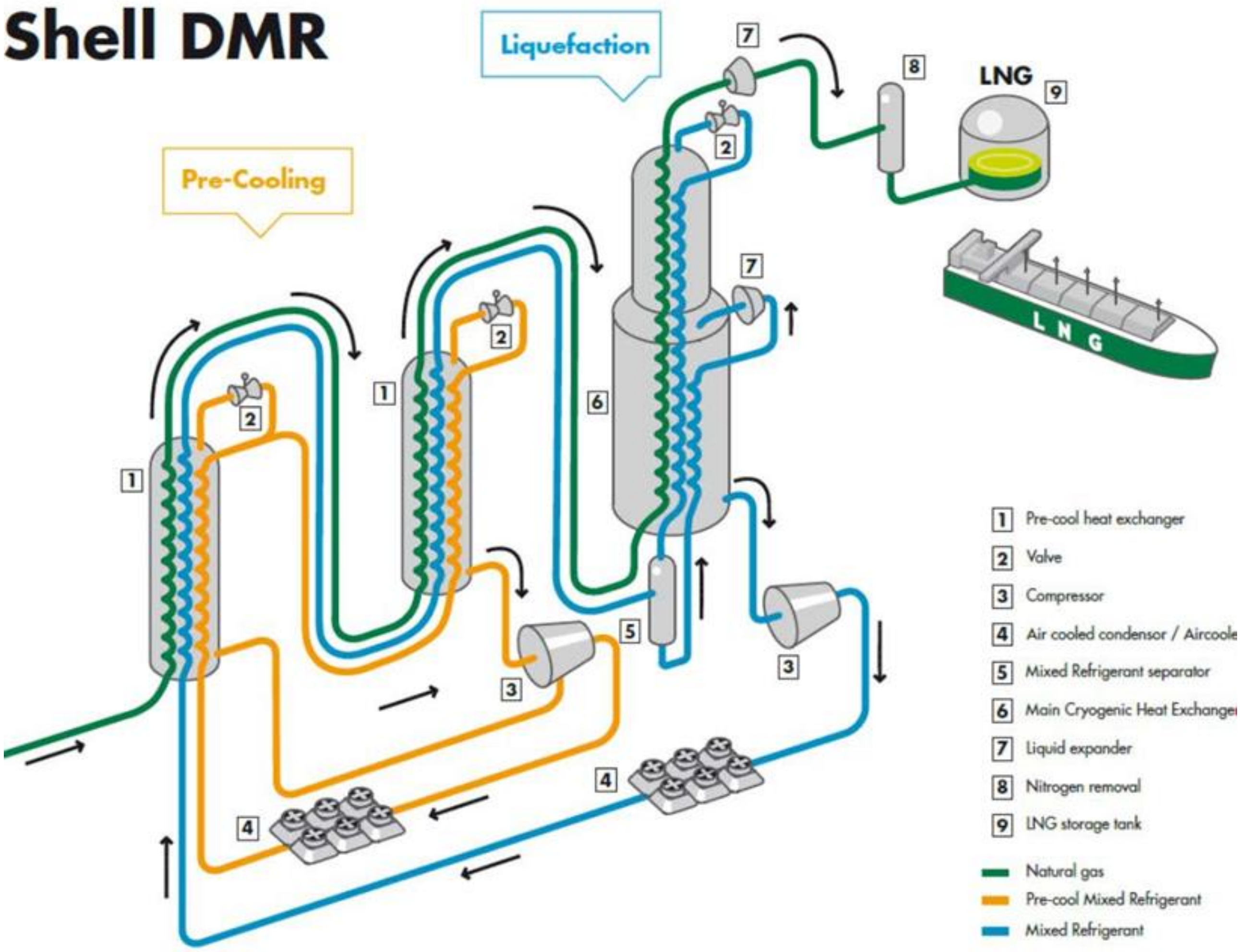

Figure 7.1 DMR technology (shell.com)

This technology is used on both the Prelude FLNG and the Sakhalin LNG shore plant, with the only difference being that air is used at the shore plant for auxiliary cooling of equipment and pipelines, and water is used on the floating complex. In both cases, the technology was developed and implemented by Shell. The DMR process is characterized as reliable and highly effective, especially at low temperatures of subarctic and arctic latitudes. In general, the use of dual mixed refrigerant can be used in a wide range of ambient temperatures, since it is always possible to adjust the composition of the mixed refrigerant of pre-cooling taking into account local conditions. This flexibility of the technology makes it possible to make the process of liquefying natural gas in floating LNG complexes independent of climatic conditions in the area of the complex's dislocation and, thereby, to increase its versatility.

Liquefaction of gas has two stages:

1. Pre-cooling: spiral-twisted heat exchangers, where gas is cooled up to about -50 degrees.
2. Condensation in liquid: cryogenic heat exchanger.

8. Vessel motions calculation

Ship motions are defined by the six degrees of freedom (Figure 8.1).

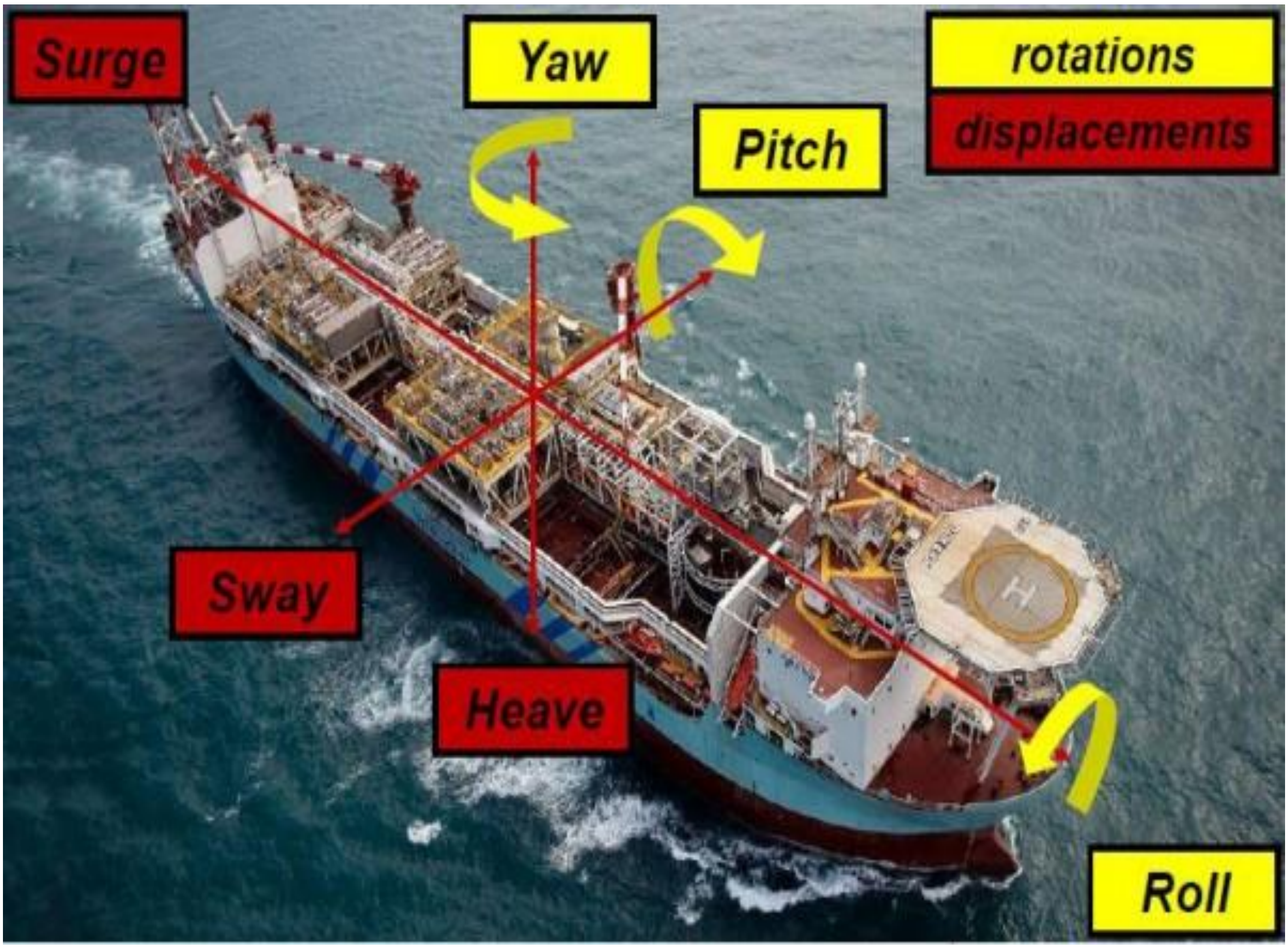

Figure 8.1 Vessel motions (www.ognition.com)

The importance of each of the 6 degrees of freedom in marine operations varies, depending on type of the operation, for example:

- Heave is vital for vertical operations
- Roll is very important for crane operations

Vessel motions can have a negative impact on the operation of systems and mechanisms on the vessel, due to the emergence of inertia forces. It is also important to know vessel motions periods to avoid resonance phenomenon.

I am going to consider heave, pitch and roll motions periods, because these parameters play key role in operating a vessel (Gudmestad, 2015).

Table 8.1

Initial data for vessel motions calculation

Mass of the vessel	500000	tons
Length	400	meters
Beam	70	meters
Height	50	meters
Density of sea water	1028	kg/m^3
Gravitational acceleration	9,81	m/sec^2

1. Force balance

$$M * g = \rho_{sw} * L * b * d * g \ ,$$

Where:

M - Mass of the vessel,

g - Gravitational acceleration,

ρ_{sw} - Density of sea water,

L - Length

From the equation of the force balance we can find draught (d).

$$d = \frac{M}{\rho_{sw} * L * b} = 17{,}37$$

2. Criteria for initial stability: $\overline{GM} > 0$. (Figure 8.2)

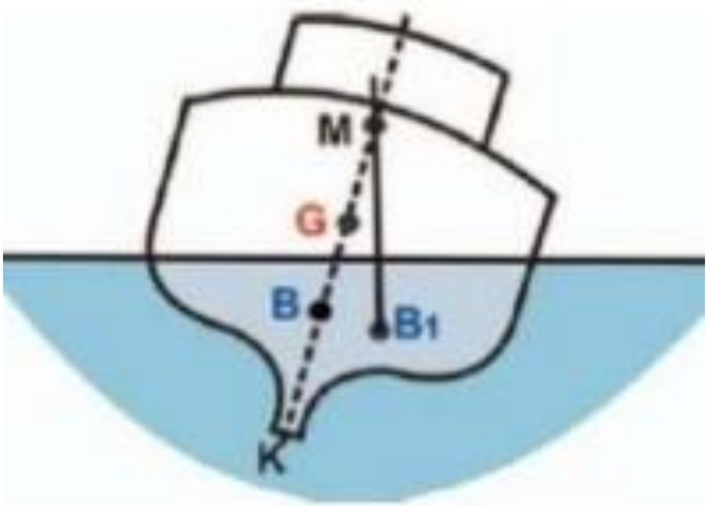

Figure 8.2 Metacentric height (www.slideshare.net)

$$\overline{GM} = \overline{KB} + \overline{BM} - \overline{KG} = \frac{d}{2} + \frac{b^2}{12 * d} - \frac{h}{2} = 7{,}2\ m.$$

3. Added real mass

$$M_{add\ real} = 1{,}36 * m_{add}$$

1) $m_{add} = \rho_{sw} * V_{add}$

2) $V_{add} = \frac{1}{2} * \pi * \left(\frac{b}{2}\right)^2 * L = 769300\ m^3$

3) Consequently, $m_{add} = 790840400\ kg$

Finally, $M_{add\ real} = 1075542944\ kg$

8.1 Heave period calculation

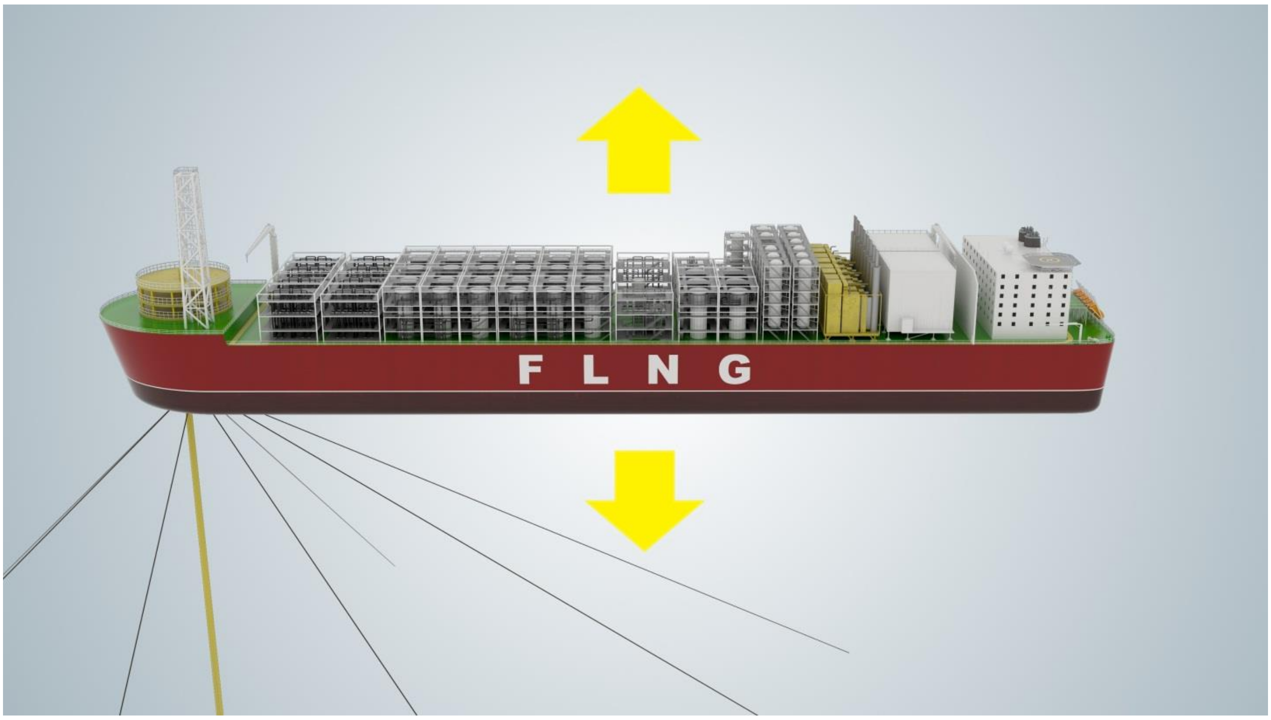

Figure 8.3 Heave motion of the vessel (www.seafasten.com)

Heaving involves upward and downward acceleration of ships along their vertical axis. Only in an absolute calm, upward and downward motions are equal and the vessel remains stable. Buoyancy varies as a vessel travels through wave crests and troughs. If the wave troughs predominate, buoyancy falls and the ship "sinks", while if the wave crests predominate, the ship "rises". Such constant oscillation has a marked effect on all the things, which are located on board. (www.rmrco.com/docs/m1207_ship_movements_at_sea.pdf)

$$T_{heave} = 2 * \pi * \sqrt{\frac{m_{heave}}{k_{heave}}} ,$$

Where:

$m_{heave} = M_{add\ real} + M$,

$k_{heave} = \rho_{sw} * g * L * b$.

After the realizing of all the calculations, we got the result: $T_{heave} = 14{,}8\ sec$

8.2 Roll period calculation

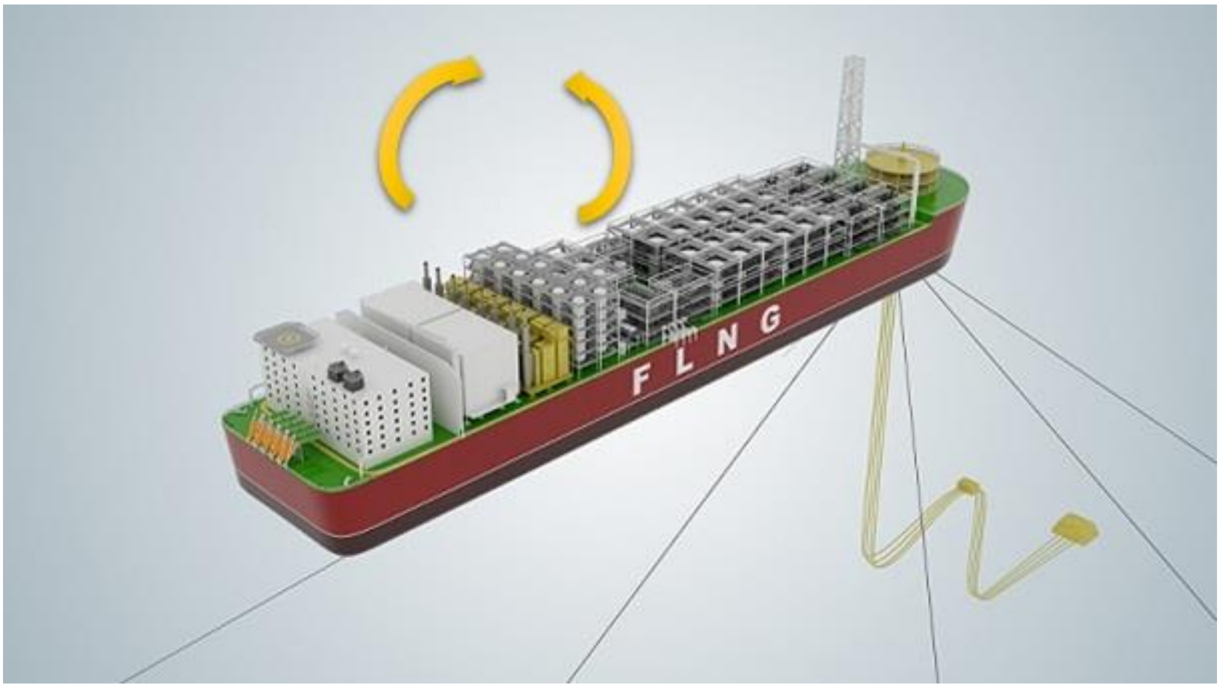

Figure 8.4 Roll motion of the vessel (www.seafasten.com)

Rolling is side-to-side movement of the vessel. It has a bad influence on the working conditions of mechanisms and devices. It also causes a decrease in the speed of the vessel. Negatively affects the human body, leading to deterioration of health and loss of efficiency. On ships, it leads to the inability to use established parts of equipment. At large amplitudes, it can lead to a loss of stability of the vessel and its flooding.

$$T_{roll} = \frac{2 * \pi * b}{\sqrt{12 * g * \overline{GM}}} = 15{,}2\ sec$$

8.3 Pitch period calculation

Figure 8.5 Pitch motion of the vessel (www.seafasten.com)

Pitch motion is a variable inclination of a floating vessel to the nose and stern under the influence of external forces. The location of the ship in relation to the movement of the waves exerts a significant influence. Pitching has a negative impact on operational quality of the vessel. Furthermore, it also influences on humans condition.

$$T_{pitch} = \frac{2 * \pi * L}{\sqrt{12 * g * \overline{GM_L}}},$$

Where:

$$\overline{GM}_L = \frac{d}{2} + \frac{L^2}{12 * d} - \frac{h}{2} = 750{,}7\ m$$

Accordingly, we obtain, that $T_{pitch} = 8{,}4\ sec.$

9. Type of positioning of FLNG vessel and its design features

9.1 Features of the Barents Sea

The Barents Sea is the only one of the Arctic seas that never completely freezes because of the inflow of warm Atlantic waters into its southwestern part. Due to the weak currents from the Kara Sea, there is practically no ice from there in the Barents Sea.

Thus, there is ice of local origin in the Barents Sea. Floating ice prevails in the sea, among which there exist icebergs (Figure 9.1). Usually, icebergs do not exceed 25 m in height and 600 m in length. Maximum size iceberg was spot in 1992 with 35 m above water height and 137 m draught and 8 million tons mass. (https://www.researchgate.net/publication/323007257_AJSBERGI_I_LEDNIKI_BARENCEVA_MORA_ISSLEDOVANIA_POSLEDNIH_LET_CAST_1_OSNOVNYE_PRODUCIRUUSIE_LEDNIKI_RASPROSTRANENIE_I_MORFOMETRICESKIE_OSOBENNOSTI_AJSBERGOV)

Figure 9.1.1 Iceberg in the Barents Sea (www.GREEN4SEA.com)

According to last investigations (Buzin et al.), an iceberg can appear in the area of the Ledovoye field once in 4 years. Most types of the icebergs, that can appear there are cuts and fragments of icebergs with height 5m above water, 300 m length and 11 000 tons mass. Such types of icebergs are not dangerous for our vessel, because they can be towed by means of special towing vessels, but we cannot exclude appearing of an iceberg with huge size, like it was in 1992. (https://www.researchgate.net/publication/323009189_AJSBERGI_I_LEDNIKI_BARENCEVA_MORA_ISSLEDOVANIA_POSLEDNIH_LET_CAST_2_DREJF_AJSBERGOV_PO_NATURNYM_DANNYM_I_REZULTATAM_MODELIROVANIA_I_VEROATNOSTNYE_OCENKI_RISKOV_STOLKNOVENIA_AJSBERGA_S_GIDROTEHNICESKIM)

The greatest ice cover is observed usually in the second decade of April, the smallest - in the end of August and the first half of September. In August-September, the sea is completely cleared of ice, and in the abnormally cold years the ice cover in these months is 40-50% of its area, located mainly in the northern regions. At the end of the harshest winters, over 90% of the sea surface is covered with thick, cohesive ice, and in particularly warm winters, even in April, the maximum ice cover does not exceed 55-60%.

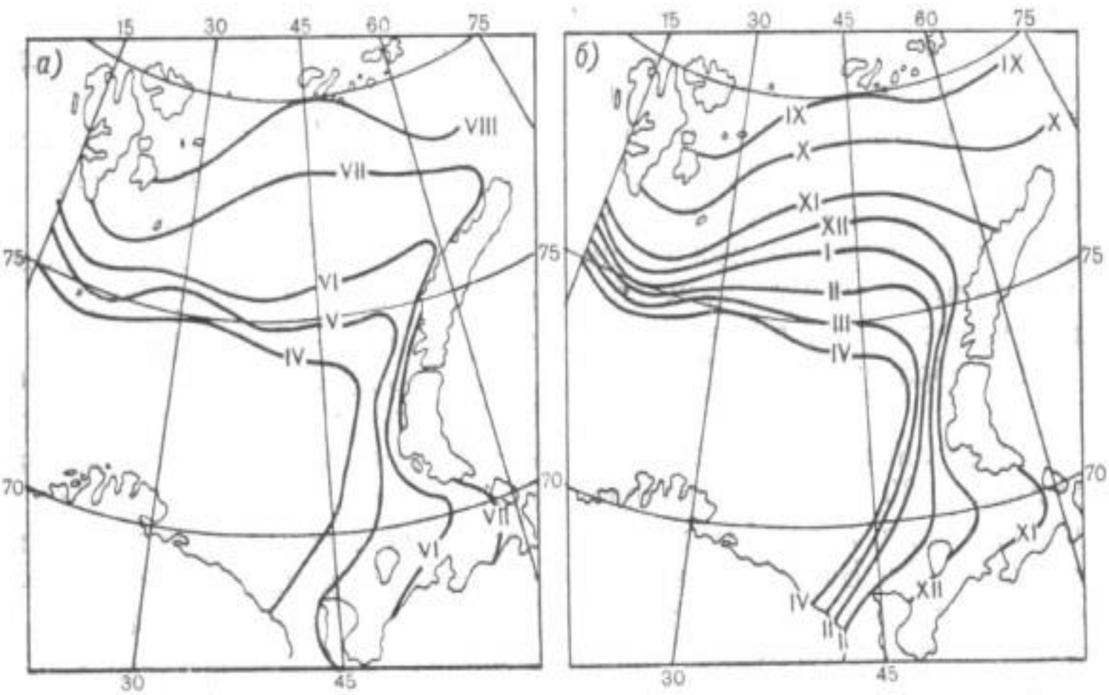

Figure 9.1.2 The average position of the edges of ice in the Barents Sea. Left) from April to August; Right) from September to April. (Bogolitsyn et al., 2012)

The ice thickness at the end of winter in the edge zone usually does not exceed 30 cm. As a rule, there are no ice fields here, and broken ice prevails. In the south-eastern part of the Barents Sea in winter, drift ice reaches 70 - 80 cm. The maximum thickness (about 130-150 cm) by the end of winter reaches ice in the northern part of the Barents Sea. The vast fields and debris of fields prevail here. As a result of frequent movements under the influence of wind, currents and tides, ice fields often break down, hummock and freeze again. In the northern regions, icebergs often come down from the glaciers of Franz Josef Land Archipelago and Spitsbergen. The ice drift in the Barents Sea is caused mainly by the prevailing winds and the system of permanent currents.

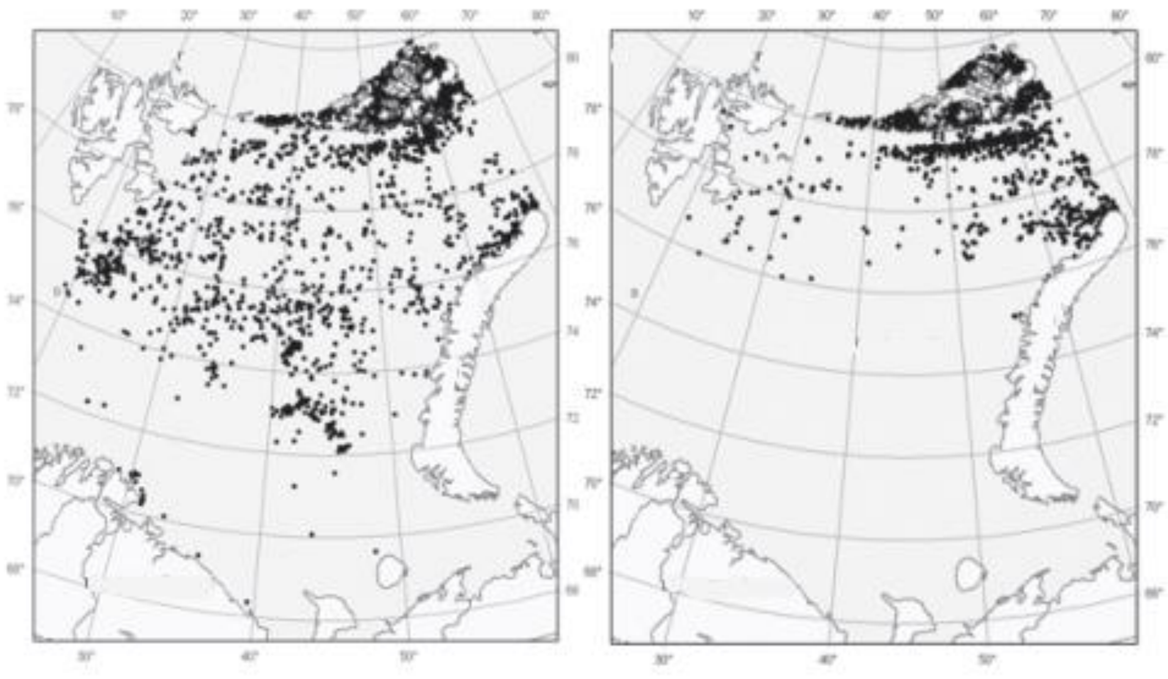

Figure 9.1.3 The location of icebergs, their debris and pieces found in the Barents Sea in April-May (left) and in September (right) spotted out from 1928 to 2007 (Icebergs and glaciers of the Barents Sea: data from the last years)

9.2 Type of positioning

During production, the main load from external influences affects on the anchor lines, however the dynamic positioning system gives the captain the opportunity to locate the vessel at the required heading angle and, if necessary, to compensate external loads. Double positioning system allows to increase the ice resistance of the vessel (Figure 9.2.1).

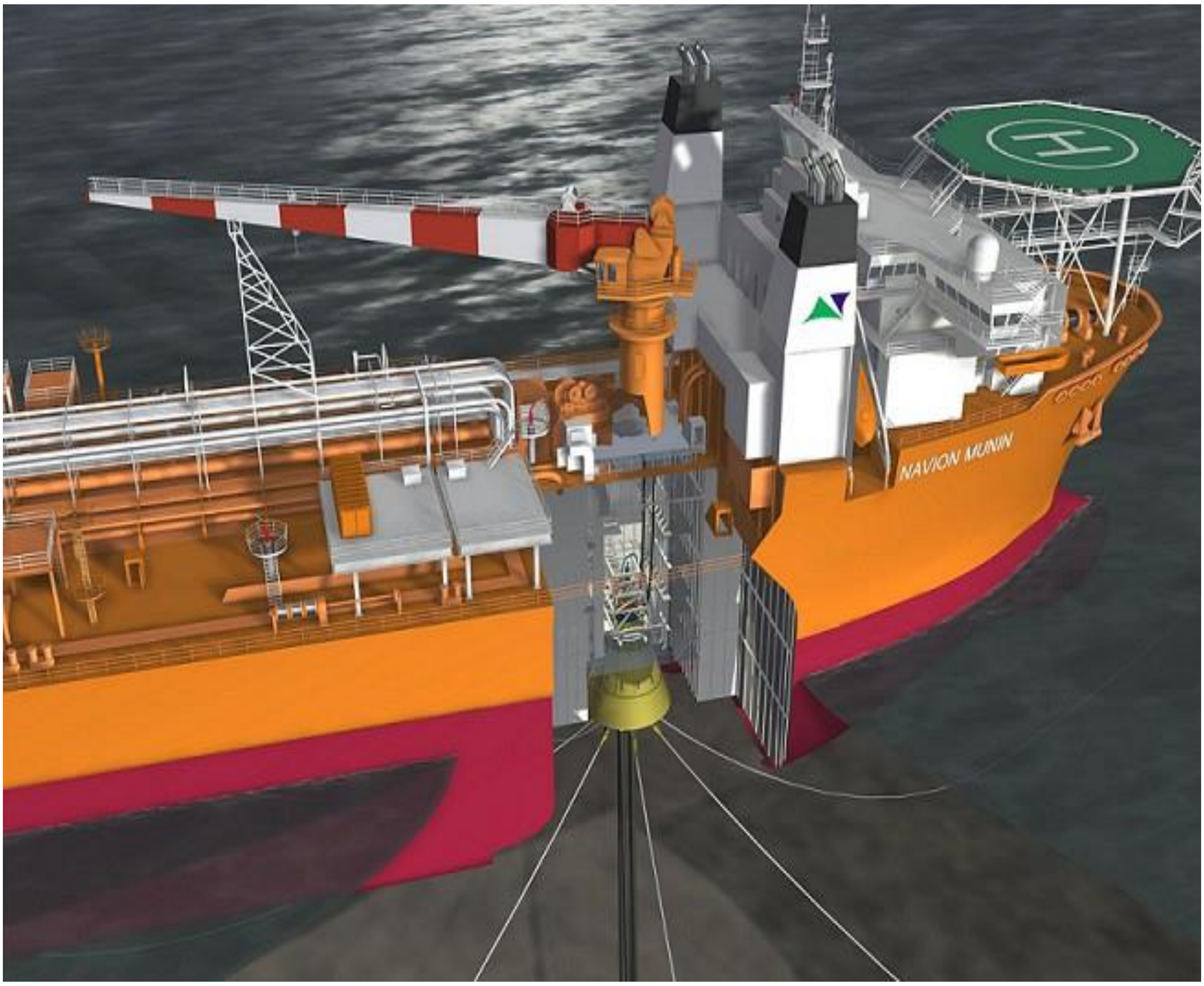

Figure 9.2.1 Double positioning system (Khairov, 2016)

As it is established in the project for the Shtokman field, which is located in close proximity to the Ledovoe field, all vessels should have a DP-2 positioning system.

The dynamic positioning system with class 2 is a system in which a single failure in the active DP system does not lead to a failure. The loss of position should not be due to the fault of one of the active components or systems, such as a generator, engine, commutator, remotely controlled valves, etc. But it can occur after the failure of static components, such as cables, pipes, valves, etc. ("MSC / Circ.645, Guidelines for ships with dynamic positioning systems").

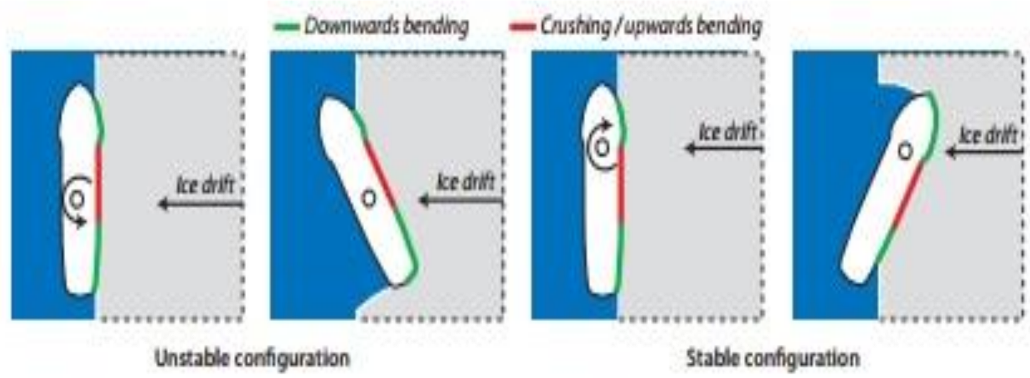

Figure 9.2.2 Positioning of the vessel due to ice drift with the help of DP (Vegard Ø. A., 2011)

According to the Norwegian Maritime Directorate: Class 2 of a ship with a DP system should be used during an operation when a loss of position can cause personal injury, pollution or damage with large economic consequences.

9.3 Turret

The turret provides the possibility of orientation of the vessel relatively to the well, since the vessel can be rotated around the central axis of the turret. Such a turn of the vessel is often necessary to reduce the external loads. To achieve this goal, the ship is oriented so that it is subjected to the minimum possible effect of the currents (Figures 9.3.1, 9.3.2). Turret system also should be disconnectable to avoid collision with icebergs.

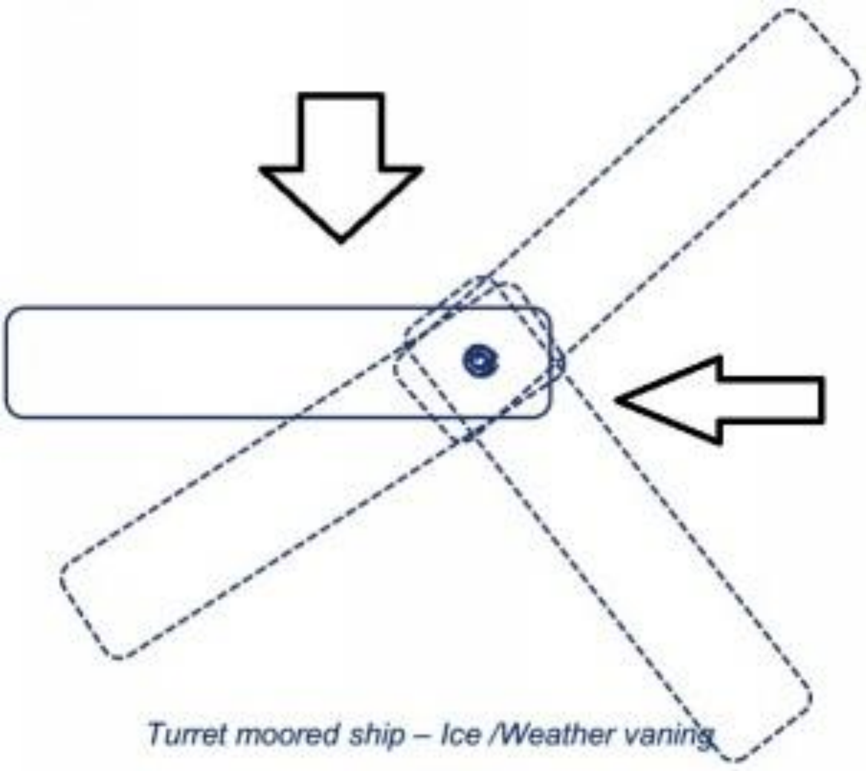

Figure 9.3.1 (Loset, 2017)

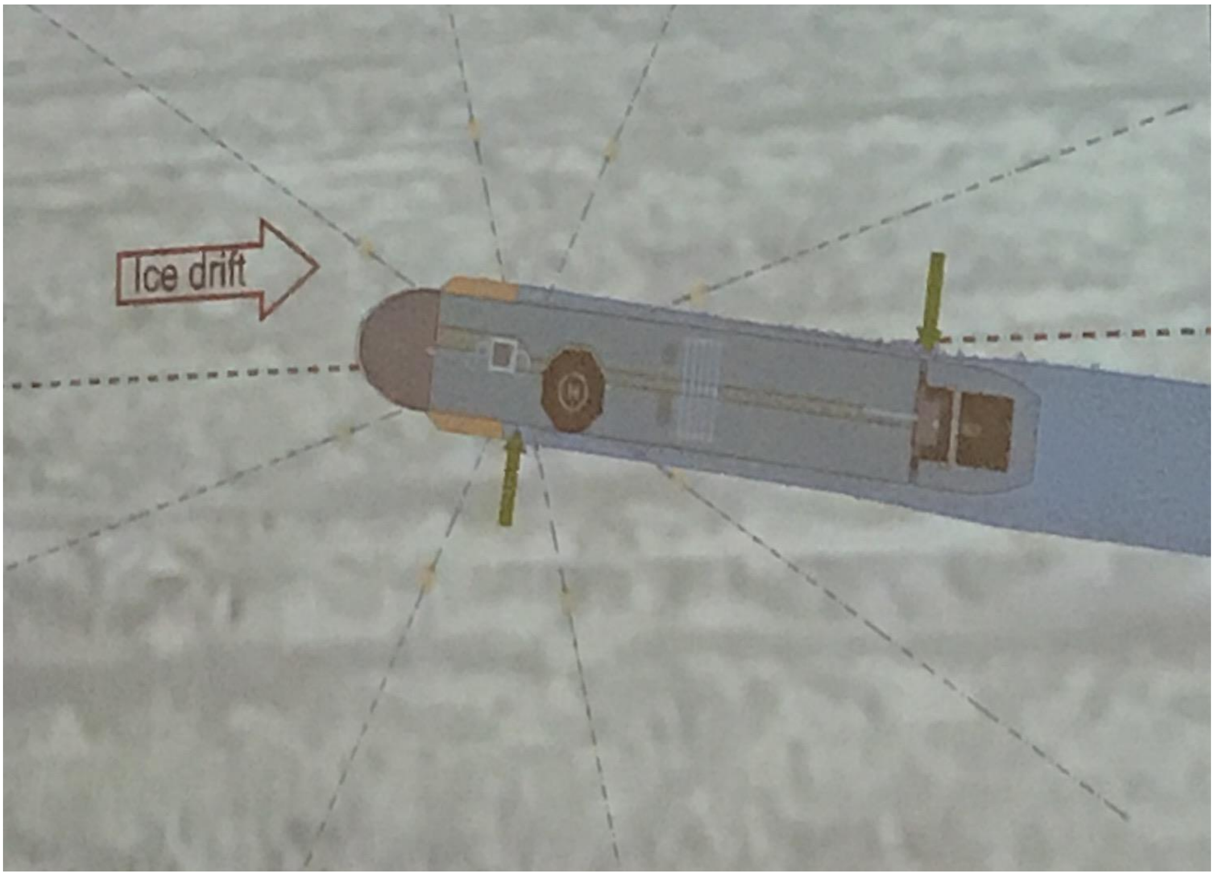

Figure 9.3.2 Turret moored ship in ice conditions (Loset, 2017)

In the Arctic regions, the difficulties associated with the presence of ice in the sea appear. They can be ice massifs (icebergs), which force the vessel to drift away from the well. Iceberg detection is usually realized by aerophotography. Also by means of sonar and radar sounding we can quite accurately describe the shape of the iceberg and estimate its mass.

Figure 9.3.3 Observation, management and critical zones (Kjerstad, 2016)

It is necessary to provide model testing in special pools to realize what size of the icebergs would be critical for our case. For example the FPSO Terra Nova can withstand icebergs impact with mass up to 100 000 tons. In other cases icebergs should be towed by means of special vessel. In 2005 iceberg with mass 160 000 tons was towed in Arctic waters. In case, when an iceberg cannot be towed by means of a special vessel, we must implement the process of disconnecting from the risers and retreating from the trajectory of a possible collision (Figure 9.3.4). Disconnection is realized during 4 hours and extreme disconnection can be realized in 15 minutes (https://www.offshore-mag.com/articles/print/volume-58/issue-4/news/exploration/terra-nova-system-designed-for-quick-release-iceberg-scouring.html).

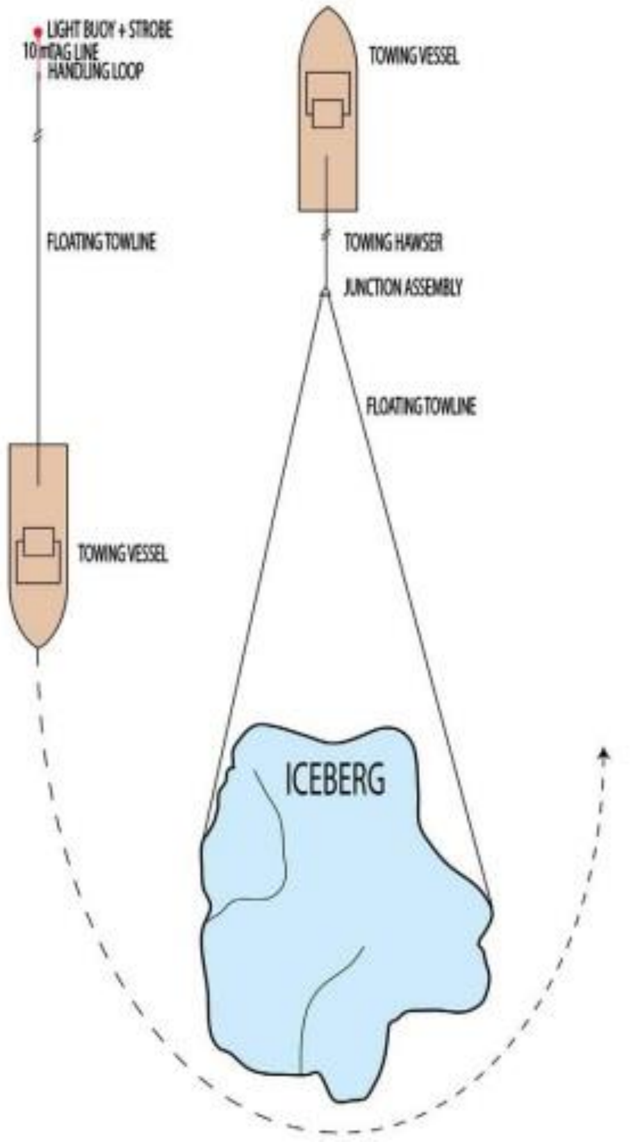

Figure 9.3.4 Towing of an iceberg (Kjerstad, 2017)

The Bluewater company offers their disconnectable internal turret mooring system. The turret has a lower part, which is arranged to be separated from the vessel, so that when it is separated, it sinks into the sea and assumes an equilibrium position. The lower part of the turret has such buoyancy that in the equilibrium position it partially lifts the parking brakes. The ship's design provides the ability to turn when it is exposed to ice drifting (Figure 9.3.5).

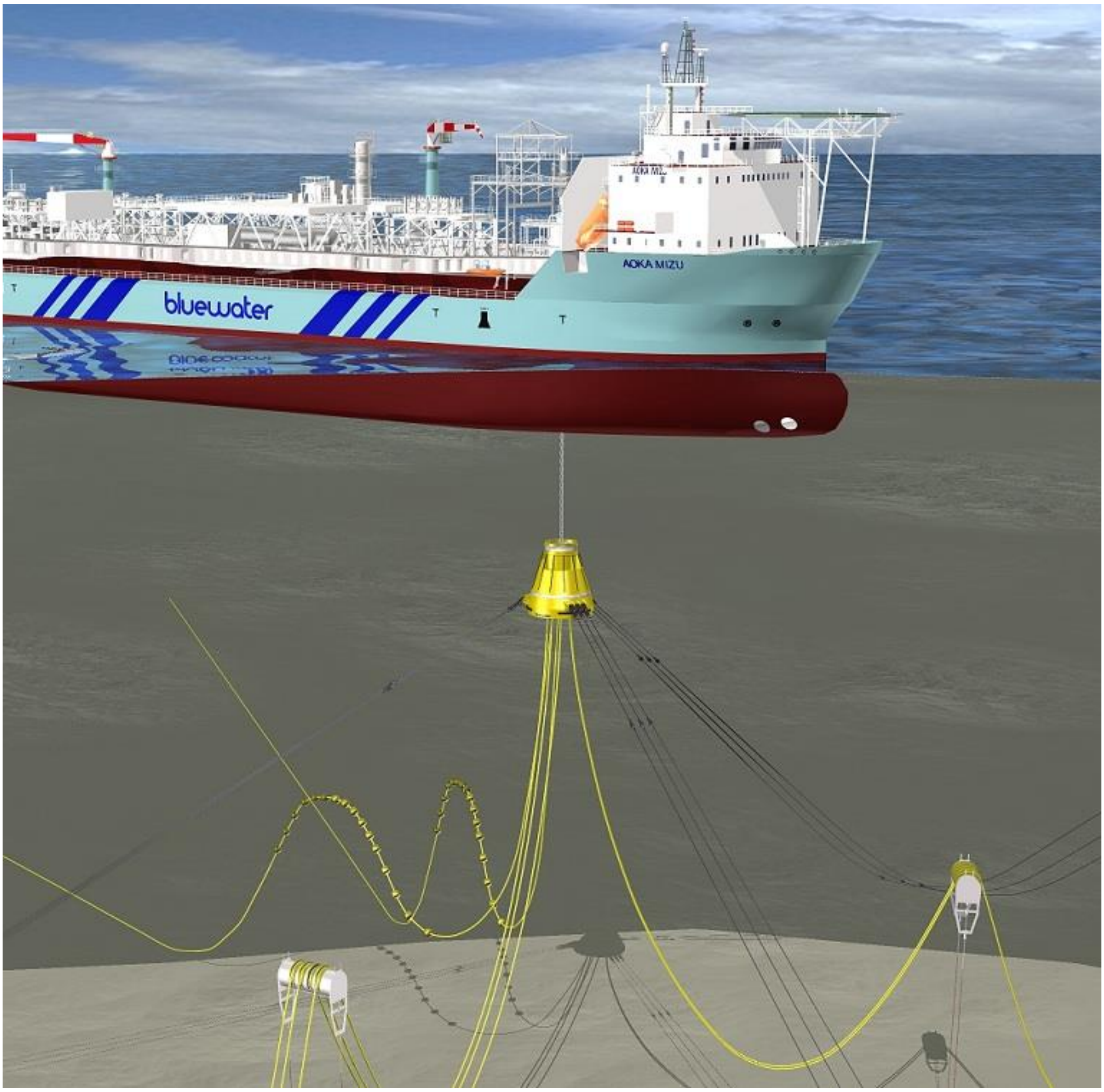

Figure 9.3.5 Disconnection of the turret from the vessel (http://www.bluewater.com)

The vessel is located above the gas well. A turret is arranged on the vessel, so that the vessel can freely rotate about its central axis during the work. When the spider buoy is disconnected, it will be immersed into the sea. The spider buoy is configured to assume an equilibrium position, at which it is so low, that it avoids collision with ice. Now the vessel is disconnected from the lower part of the turret and may depart from the well.

So, the turret should be constructed due to possibility of appearing a maximum size iceberg (137 m above the water, 600 m length). It means that after disconnection spider buoy with risers and anchors should be lowered down to approximately 150 meters under water.

The arrangement of an ice-removing device is also very important for vessels in ice waters. This device is described in patent No. 2499724 (Authors: Christensen Per Herbert (NO), Husem Ida (NO), Sand Hans Martin (NO), Jacobsen Carl Anton (NO); Patentee (s) : Moss Maritime As (NO)). The invention relates to a vessel for drilling oil or gas wells, as well as for production, in arctic waters. The vessel is designed to produce hydrocarbons through a riser that extends from a well on the seabed to a turret placed on a ship. The riser is designed to be disconnected from the vessel.

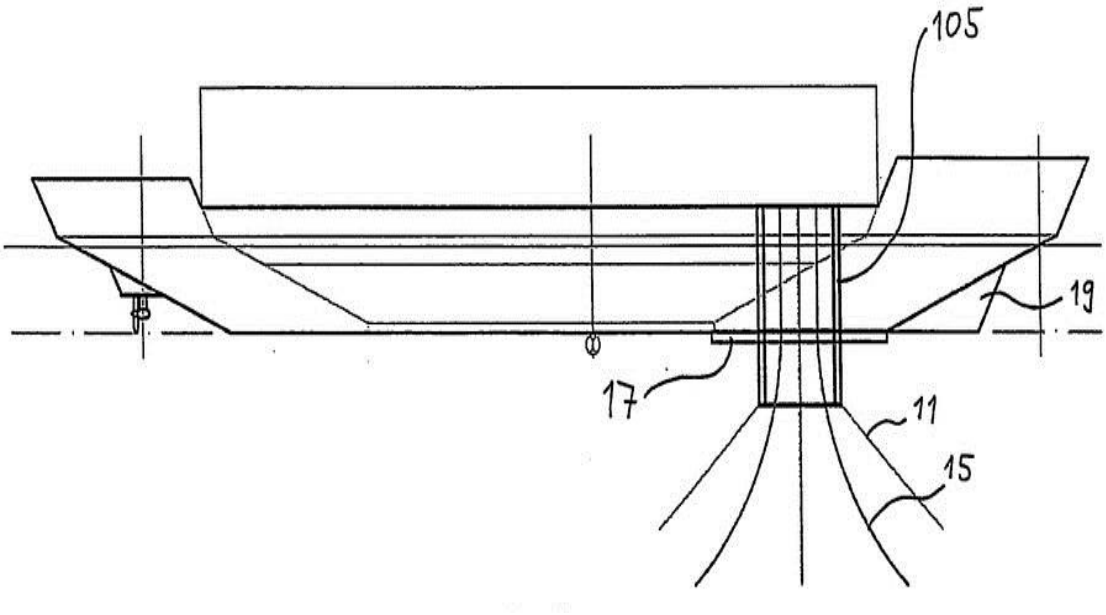

Figure 9.3.6 Ice-removing device (patent No. 2499724)

The ice-removing device (17) extending around the turret (105). If ice is at the depth of the ice-removing device (17), it will assist in carrying the ice past the turret (105) and splitting the ice masses. In this way, it will contribute to the protection of the flexible riser columns (15) and the parking braces (11). Moreover, the drawings show an ice cutter (19) placed on the bow of the vessel and configured to cut pieces of oncoming ice. Thus, the nose of the ship prevents the passage of ice under the keel of the vessel. The ice colliding with the vessel's nose will first be broken into pieces due to the angle of the bow over the waterline, then it will be retracted relative to the central longitudinal axis of the vessel (Figure 9.3.6).

10. Winterization

Figure 10.1 Icing on a vessel (www.arctic-operations-handbook.info)

Icing on the vessel is a growing layer of ice on the hull of the ship, ship devices, superstructures, deck cargo, boats and masts of the vessel. The most severe icing of ships is observed in the North Atlantic (Barents and Norwegian Sea, North-West Atlantic) and in the northern part of the Pacific (Bering, Okhotsk and Japan Sea). The main cause of icing is the spraying and flooding of the vessel in the negative temperatures during a storm. Significantly fewer cases of icing is caused by snowfall, subsidence on ship structures of drops of rain, fog, and steaming of the sea with a sharp temperature drop.

Spraying is characterized by the fact, that the sea surface after the mechanical action separates the mass of water, which, before reaching the ship's structures, spends some time in the air and gets cooled by it (Figure 10.2).

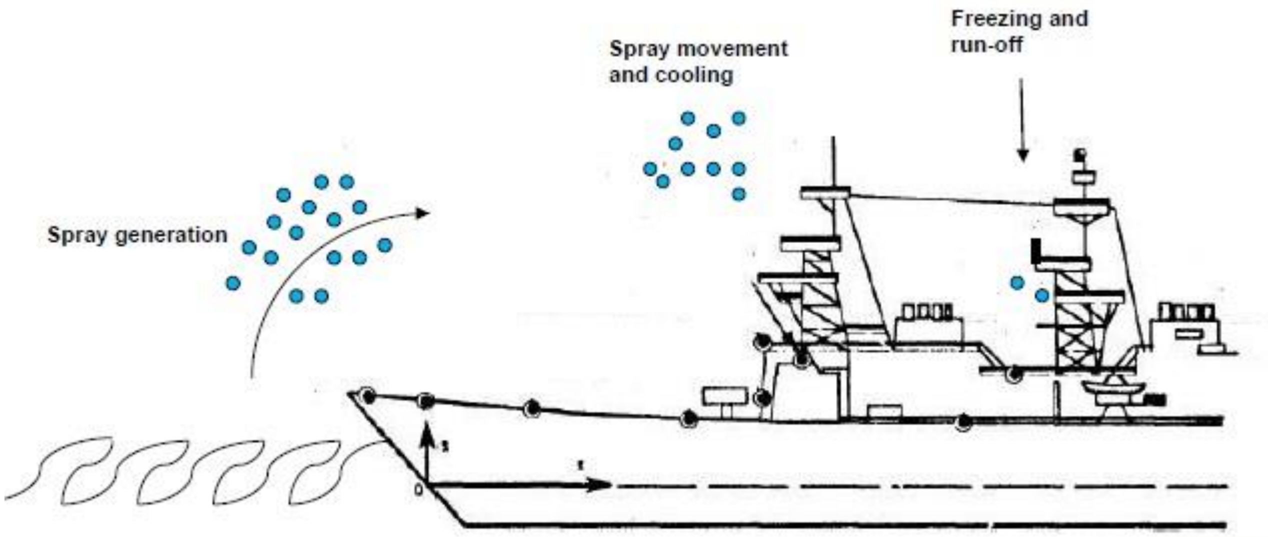

Figure 10.2 Spraying (Kulyahtin, 2017)

Sea spray icing is dependent mainly on the following parameters:

- Air temperature
- Wind speed
- Sea surface temperature
- Sea state
- Size and type of structure or vessel
- Course relative to the waves and speed

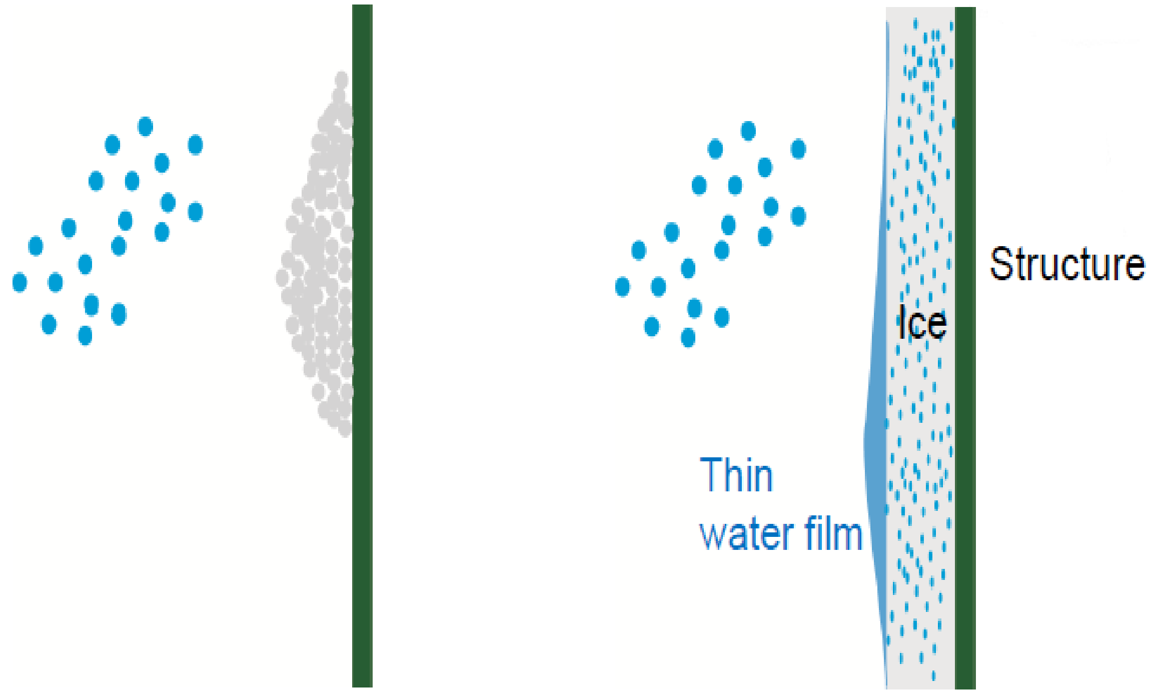

Figure 10.3 Left-mass limited, right- wet, thermally limited ice accretion (Kulyahtin, 2017)

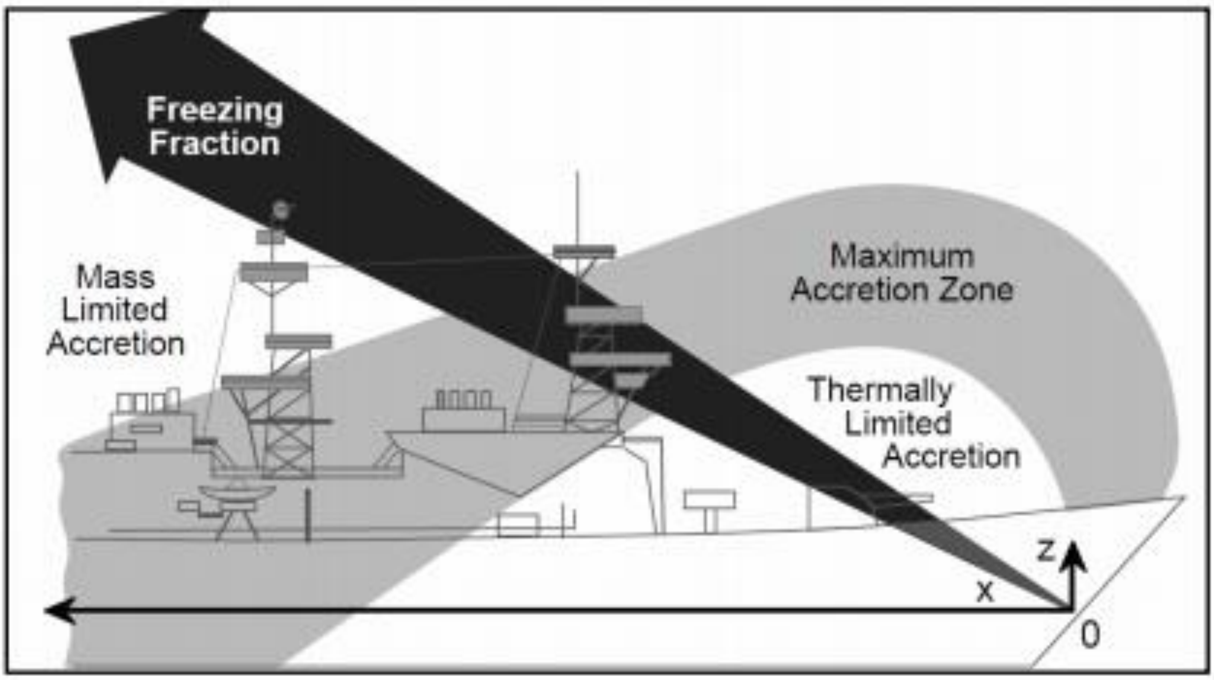

Figure 10.4 Ice accretion zones (Ryerson, 2009)

10.1 Climate conditions of the Barents Sea

The climate of the Barents Sea is influenced by the warm Atlantic Ocean and the cold Arctic Ocean. Frequent invasions of warm Atlantic cyclones and cold Arctic air determine the large variability of weather conditions. In winter, the south-west winds prevail over the sea, in the spring and summer - the northeasterly winds. Storms appear very often. The average air temperature in February varies from -25 ° C in the north to -4 ° C in the south-west. The average August temperature is 0 ... + 1 ° C in the north, +10 ° C in the south-west. Overcast weather prevails during the whole year. Annual precipitation is from 250 mm in the north to 500 mm in the south-west.

10.2 Calculation of the ice accretion predictor

A formula has been developed to predict the rate of ice accretion due to sea spray (Loset, 2006). The formula takes into account the wind speed (Ua), the freezing point of seawater (Tf), the sea surface temperature (Tw) and the air temperature (Ta). The ice accretion predictor (PR) has been developed by the National Oceanic and Atmospheric Administration (NOAA). The relationship between the predictor and the ice accretion rate is shown in the table 10.2.1.

$$PR = Ua(Tf-Ta)/(1+0,4(Tw-Tf))$$

Table 10.2.1

Relationship between icing predictor and rate of ice growth (Loset et al., 2006)

	Light	Moderate	Heavy	Extreme
Icing rate cm/hr	< 0.7	0.7 to 2.0	> 2.0	> 5.0
Predictor	< 20.6	20.6 to 45.2	> 45.2	> 70

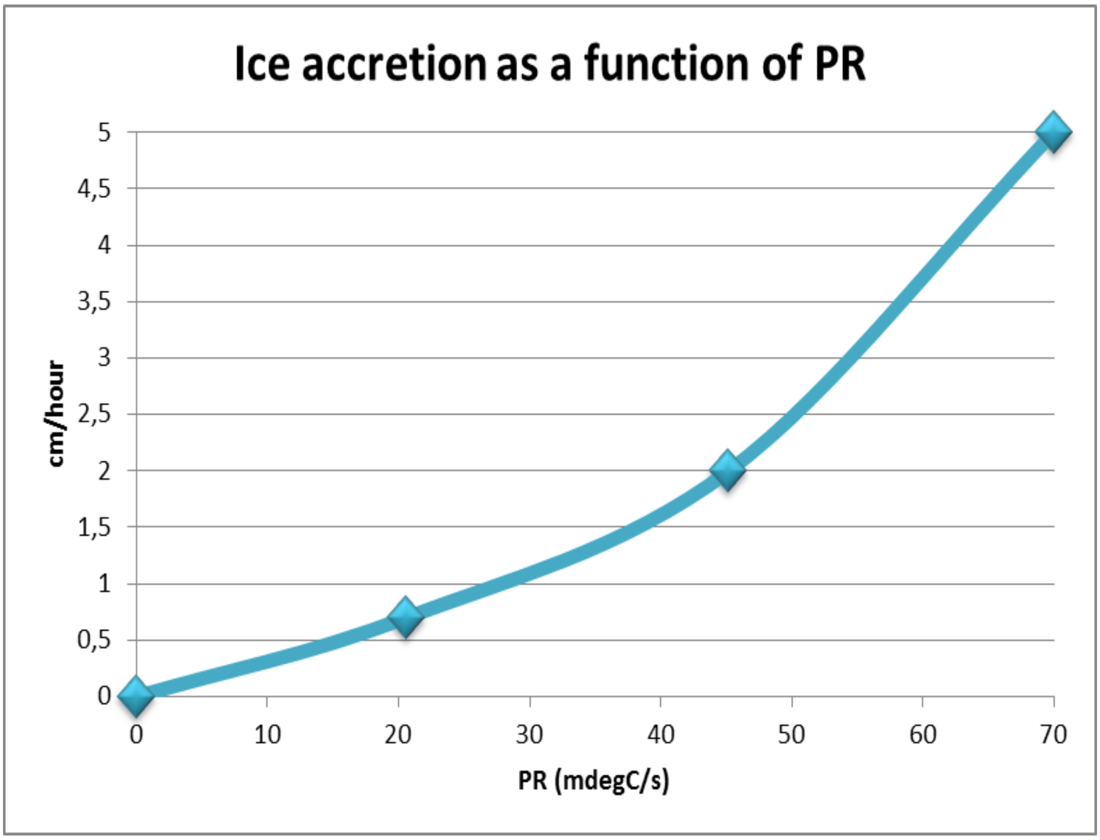

Figure 10.2.1 Ice accretion in cm/hour as a function of icing index, PR

The 2 figures below illustrate the relationship between two parameters, that are used in the ice accretion predictor. The wind speed in each chart corresponds to the lower limit for Beaufort force 6 to 12, ie fresh breeze to hurricane. Fixed air temperatures of -5 and -15 deg C are used to show the effect of decreasing air temperatures. It can clearly be seen that the predictor increases dramatically as the seawater temperature approaches the freezing point (Jacobsen, 2010). The freezing point of seawater (Tf) in the Barents Sea is equal to 1.9 deg C.

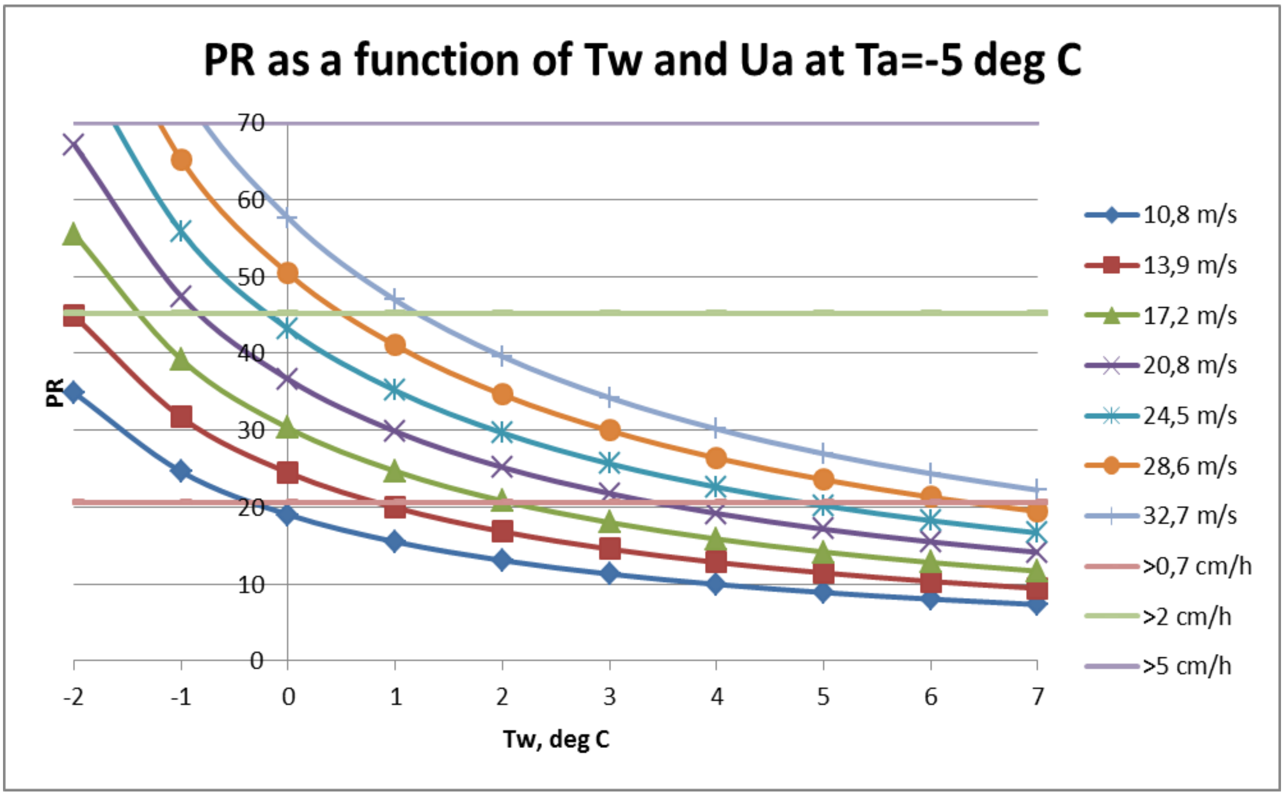

Figure 10.2.2 Icing index as a function of seawater temperature (Tw) and the wind speed (Ua) at air temperature of -5 deg C

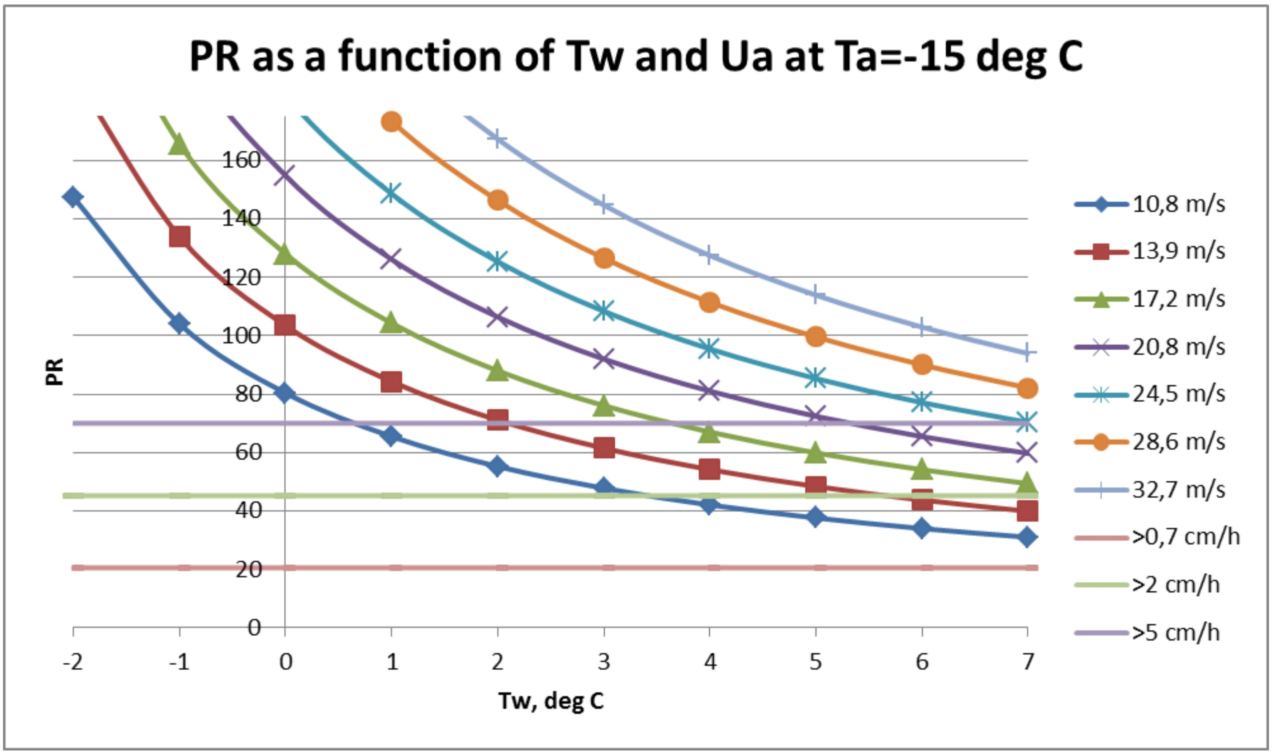

Figure 10.2.3 Icing index as a function of seawater temperature (Tw) and the wind speed (Ua) at air temperature of -15 deg C

10.3 International norms and standards

ISO 19906, 2010

Winterizing of equipment, instrumentation and piping is critical for topsides facilities design and operations in arctic conditions. Winterizing is also required to protect personnel working under arctic climatic conditions.

Winterizing can be achieved by a variety of techniques, including:

– elimination of pockets or dead ended pipes or legs in piping and design of piping to be self-draining;

– maintaining a flow in lines (such as fire water mains and cooling water branch lines) which are sometimes filled with static liquid;

– insulation;

– protective heating, generally combined with insulation; heating may be internal (e.g. when heating components are within a tank or vessel) or external (e.g. when heat tracing tapes are installed on instrumentation and piping);

– use of an enclosure, generally accompanied by heating from an internal heating element or by a heating/ventilation system;

– use of chemical or mechanical seals on instrumentation;

– use of windwalls to reduce rate of heat loss;

– addition of chemicals (methanol, for example) to reduce the freezing point of material.

Winterization characteristics that should also be considered include the build-up of atmospheric or spray ice, as well as protection for personnel and equipment from falling ice from higher equipment, flare towers and communication towers.(ISO 19906, 2010)

— Equipment and areas that require anti-icing measures should as far as possible be situated in protected locations, so that sea spray and weather cannot reach it. This may be accomplished by using fully enclosed spaces, semi-enclosures, recesses with removable "curtains" in front, or similar. A shielded location will normally be the simplest and most reliable solution for anti-icing wherever it is possible.

— Heating of spaces may be necessary depending on the type of equipment located therein.

— Hard removable covers may also be applicable for some types of equipment. Cover by canvas may be acceptable for some types of equipment, like fire monitors. Supply of heated air may be an alternative if the equipment in question is enclosed under a cover, hard cover or canvas.

— The use of electric heating blankets or heat tracing can be a solution for protection of equipment on open decks or unheated spaces.

— The use of anti-freeze additives or use of low temperature fluids in liquid systems alone or in combination with supplementary heating of either the piping or the circulating fluid. (DNV-OS-A201)

This standard has a very detailed description of the process of winterization for all parts of the vessel.

Figure 10.3.1 The Arctic water area, which is subject to the requirements of the Polar Code (www.imo.org)

According to the Code, in the construction of the vessels, authorized for operation in polar waters, only suitable for polar temperatures materials should be used. It is also said, that all ships should have structural arrangements adequate to resist the global and local ice loads characteristic of their Polar Class. According to the Shtokman field development project, which is located in close proximity to the Ledovoe field, all vessels should have an ice class Arc 7.

IMO(IACS) Polar class	Ice class to the Finnish-Swedish Rules	Category of ice strengthening of the RMRS 2007	Ice conditions WMO	Initial design Level ice Thickness, cm	Hummocking numbers	Coefficient of The growth of ice thickness	Equivalent ice Thickness in the channel, cm	Design icebreaking capability, m	Required minimal icebreaking capability, m
PC1			Multi-year	>550	1	1.3	>700	>3.0	3.0
PC2		Arc9	Multi-year	400-500	1-2	1.4	560-700	2.4-3.0	2.4
PC3		Arc8	Second-year	300-400	1-2	1.4	420-560	1.8-2.4	1.8
PC4		Arc7		200-300	2	1.5	300-450	1.3-1.8	1.3
PC5		Arc6		120-200	2-3	1.6	190-320	0.9-1.3	1.0
PC6	IA Super	Arc5(L2)		90-120	2-3	1.6	145-190	0.6-0.9	0.7
PC7	IA	Arc4(L1)		70-90	2-3	1.6	110-145	0.4-0.6	0.5
	IB	Ice3		50-70	2-3	1.6	80-110	0.3-0.4	0.35
	IC	Ice2		30-50	3	1.7	50-85	0.2-0.3	0.25
	Category II	Ice1		15-30	3	1.7	25-50	0.1-0.2	0.15

Figure 10.3.2 Ice classes table (www.maritimepress.co.kr)

10.4 First winterized vessels

The first "winterized" gas carriers were built in 2006: “Arctic Discoverer”, “Arctic Lady”, “Arctic Princess” and “Arctic”, designed to transport LNG from the Snohvit field in Northern Norway through the North Atlantic to the United States and Europe. These vessels are designed for 40 years of operation at low ambient temperatures of -18 ° C and the wave conditions of the North Atlantic. There are provided the steam heating of the sides on the upper deck, as well as of the side, by which the gas carrier is moored to the quay. Moreover, there are steam heating of cargo manifold, bridge, skipper's pantry, tiller compartment, landing site for the lifeboat. The bridge's wings are equipped with heated windows and thermal insulation. Electric heating of windows in living rooms and combined electric and steam heating of external doors are provided. In order to eliminate icing, hot water is supplied and watering of anchors, cargo manifolds, cargo tank domes is realized. Portable steam hoses and steam purging are provided in the required places. (Evdokimov, 2015)

10.5 The main strategy of winterization of the SEVAN FPU

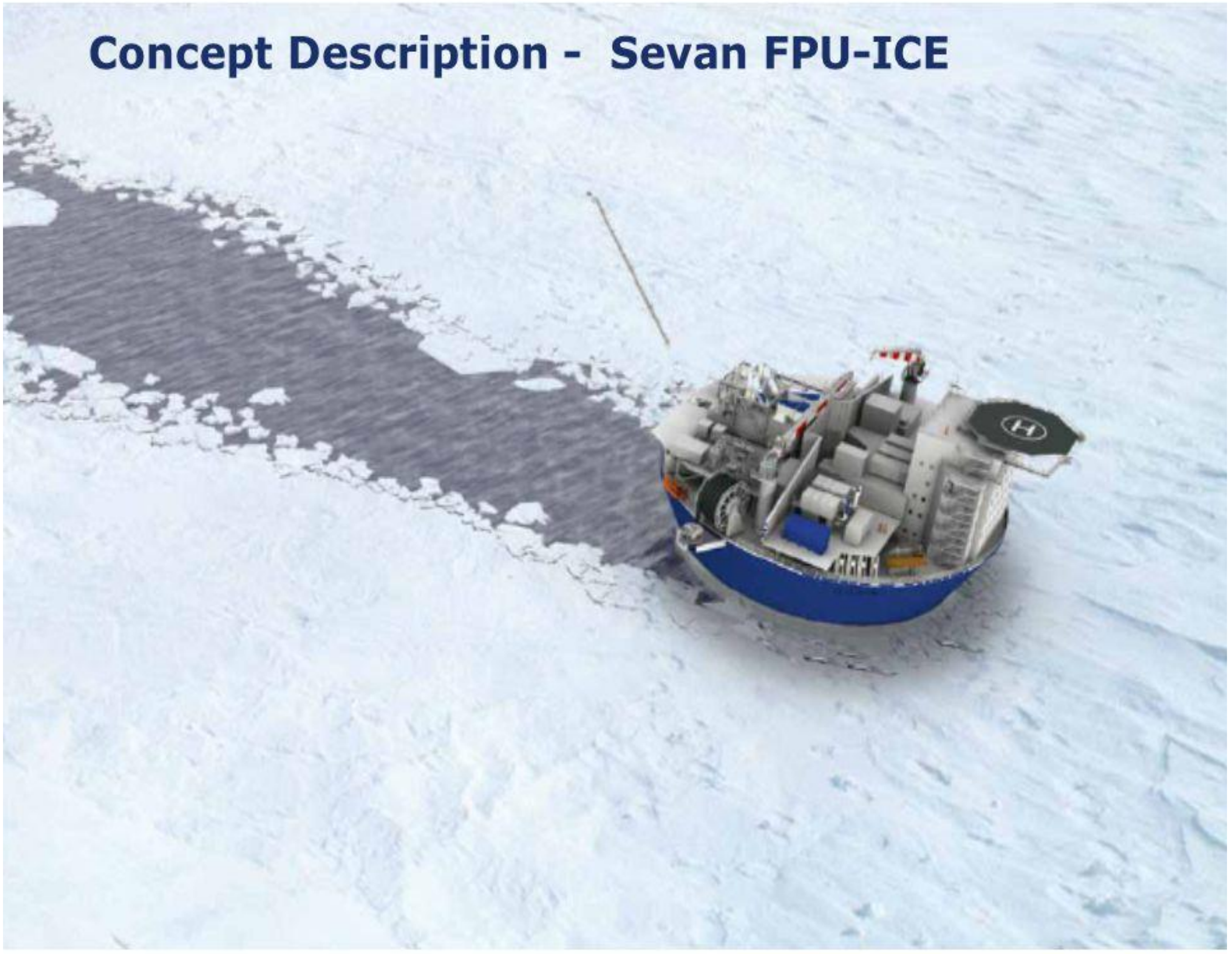

Figure 10.5.1 Sevan FPU (slideplayer.com/slide/2553070/)

- Protective shields around the open area
- Secure areas should be completely closed as far as possible
- Heating of the corresponding surfaces
- The technological area is closed by a protective wall with overlapping plates
- Fully closed roof of the technological zone (Fredrik M., 2015)

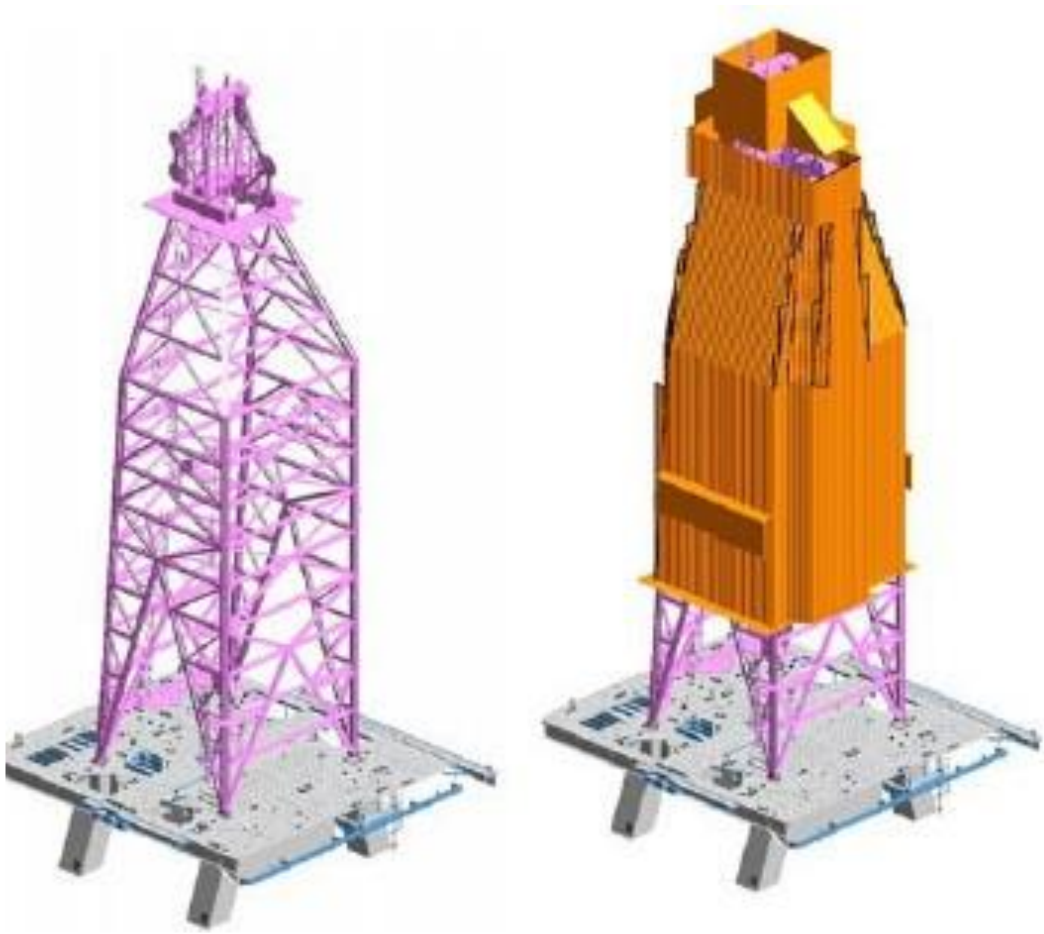

Figure 10.5.1 Example of winterization of the derrick (Aker H-6e Drilling Semi Submersible for Deep Water and Harsh Environment)

10.6 Existing systems of deicing of vessels

1) Vibration-resonance mechanical systems:

Vibration disturbs the adhesion strength of the ice to body. Special vibrators based on asynchronous motors are installed to the areas, which should be cleaned from the ice, both from the outside and from the inside of these areas. The fastening points should be provided with power supply and they should be possible to be installed/removed from vibrators by one or two crewmembers. Periodic switching on/off of vibrators will provide vibration in a wide range of frequencies, among which there will be also near-resonant, i.e., the most effective for chipping ice.

2) Induction-shock systems:

The idea was born on the basis of inductive-jet engines. They did not go further than experiments, but showed the possibility of creating thruster based on the interaction of the magnetic field and sea water. Ice from salt seawater, even at the lowest temperatures, retains electrical conductivity, which means, like any conductor, it will interact with an external magnetic field through the magnetic field of self-induction. Thus, under the influence of an alternating magnetic field, sea ice will undergo deformation, followed by destruction of the ice cover.

3) Ultrahigh-frequency heating:

It is a well-known fact that eddy currents (Foucault currents) appear in conductors under the influence of high-frequency magnetic fields. Eddy currents warm up the metal of the hull, which ensures thawing of ice and a reduction in the adhesion of ice with the hull. In turn, it makes it easier to manually destruct the ice, and in combination with vibration, it also makes it possible to mechanize the process of cutting off the ice.

4) Pre-treatment by anti-freezing structures:

This technical solution of combating with ice comes from aviation. The outer surfaces of the hull and superstructures of vessels can be treated with a special deicer from the sprayers. (https://shipdesign.ru/Sea/2011-02-15/3_280-287.pdf)

THERMON heating systems are designed to protect all pipelines, vessels, tools and equipment when operating in cold temperatures with cold seawater and strong wind.

The four basic design principles are:

- Anti-icing: preventing ice formation and freezing when the surface temperature is held above the freezing point at the design parameters of the "worst case scenario" of the ambient air temperature.

- Ice removal: removal of ingrown ice in the calculated period of time, if necessary.
- Frost protection: for pipelines, valves, tools and equipment containing liquids.
- Maintaining the required process temperature: maintaining the necessary temperatures in pipelines, valves, tools and equipment.

The company provides such procedures as:

- ✓ Door seals - Waterproof doors require a significant amount of heat to prevent icing of the seals
- ✓ Ladders - A heating line to prevent icing or de-icing on the ladders is installed from the bottom of each stage
- ✓ Handrails - To provide a secure support for the staff, a heating line is installed to prevent icing of the handrails or the removal of ice from them
- ✓ Heliports - Helipads may also require anti-icing or ice removal
- ✓ Management and control - The operation of the heating system is vital and therefore requires increased monitoring and supervision. Centralized management and control of heating systems are important for large electric heating systems where energy management is necessary
- ✓ And many other procedures

11. Ice Loads

As a rule, all marine structures designed to operate in the Arctic region should be able to withstand harsh environmental conditions and especially significant loads of ice. The figure 11.1 below shows all the ice actions, which must be taken into account during the development of the concept of the vessel.

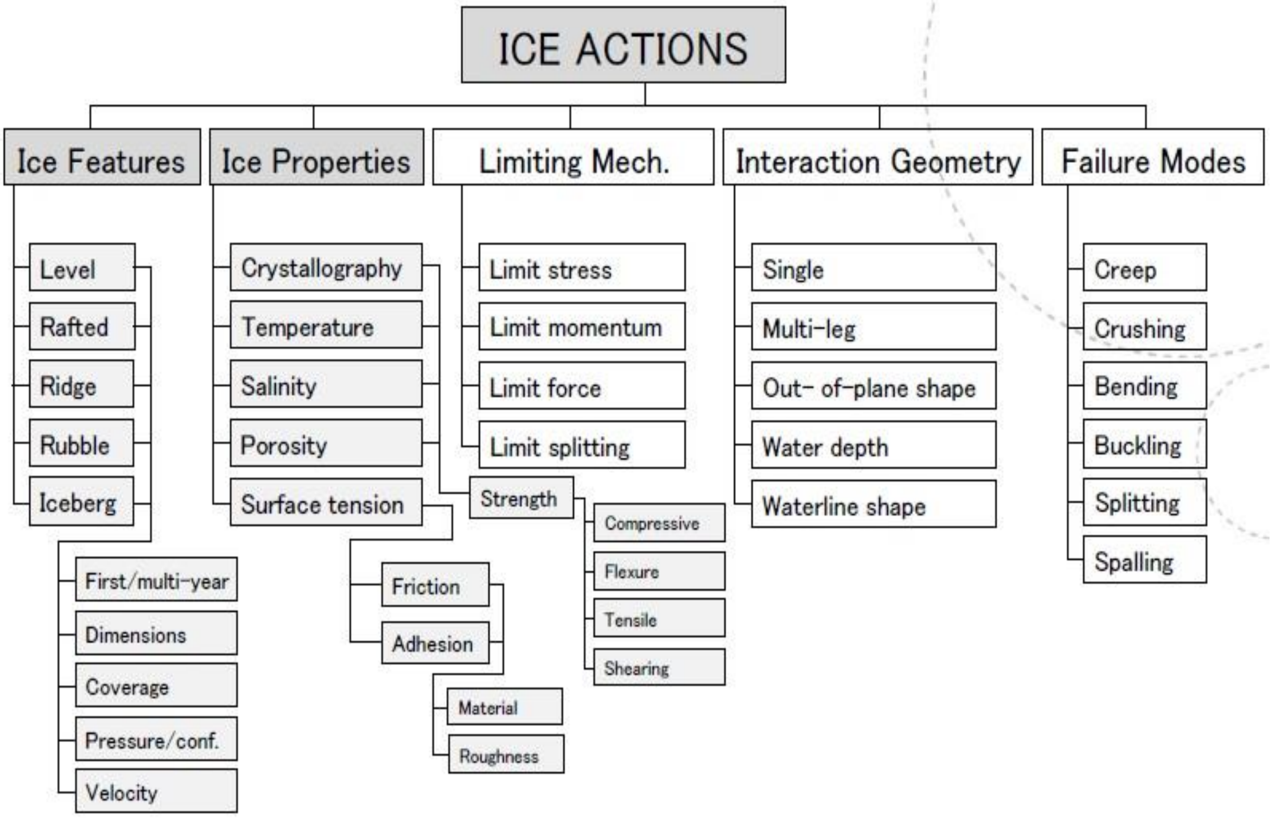

Figure 11.1 Ice actions (Loset, 2017)

As it was listed by Loset, the main resistance components are:

The forces include loads:

- Generated by crushing of the ice sheet,
- Ventilation above the broken floe,
- Buoyancy of the ice pieces,
- Viscous drag of the ice floes,
- Acceleration of the broken ice mass.

Summarized by:

- Crushing at the contact
- Breaking of ice floes
- Turning broken ice floes
- Submergence of broken ice floes

The ice breaking process and ice-structure contact are introduced on the pictures 11.2 and 11.3 Below

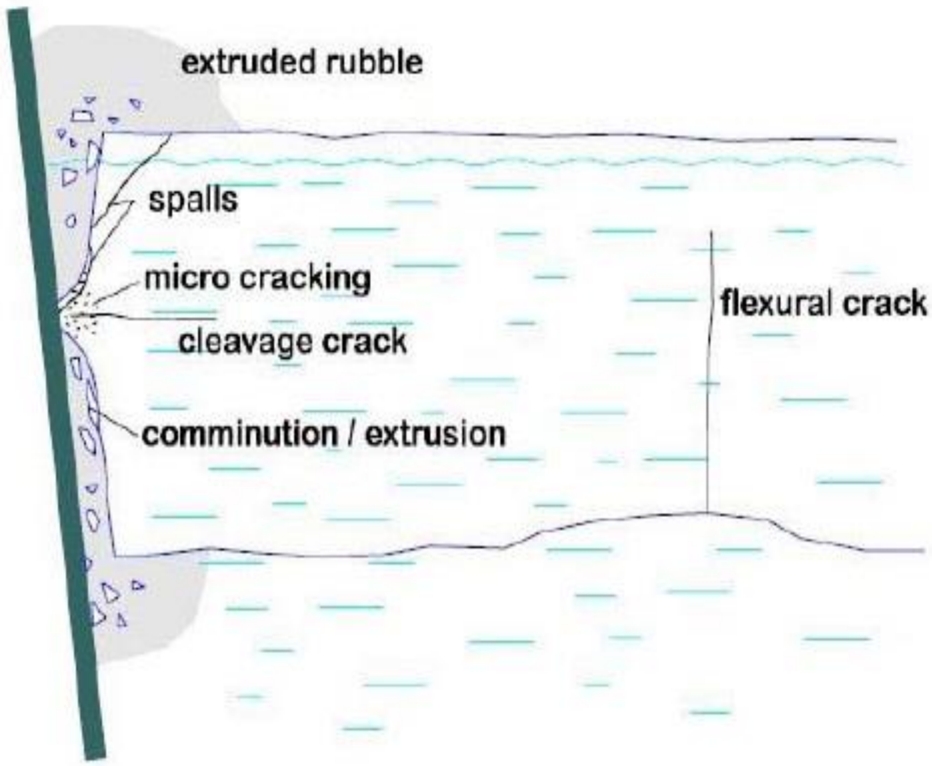

Figure 11.2 Crushing mechanisms during ice-structure contact (Loset, 2017)

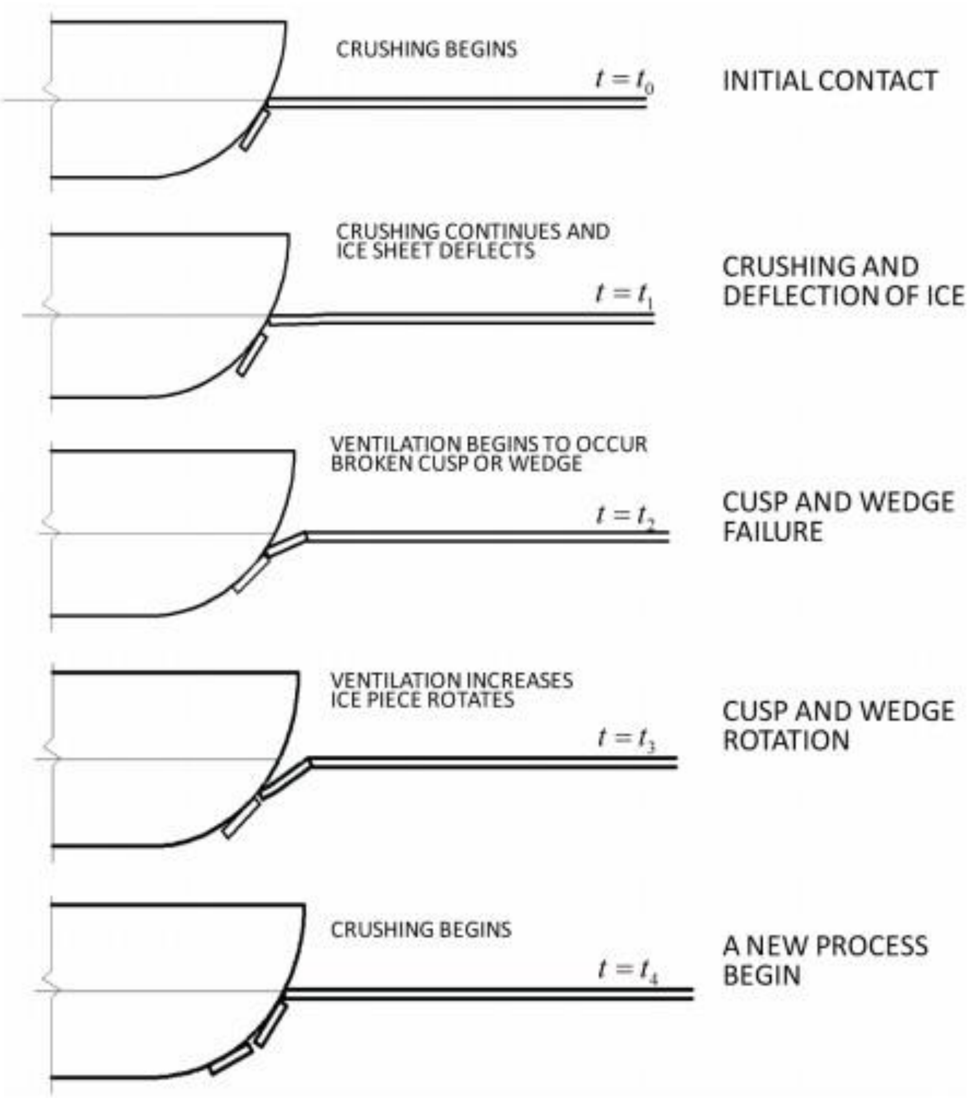

Figure 11.3 Ice breaking stages (Loset, 2017)

11.1 Calculation of the ice loads

The prediction equation for resistance (units MN) in unbroken level ice has the following form as reported by Loset (2017).

$$\begin{aligned} R_{ice} &= 0.015HC \cdot S \\ &\times B^{0.7} L^{0.2} D^{0.1} h^{1.5} && \leftarrow \textit{ship size term} \\ &\times (1 - 0.0083(T + 30)) && \leftarrow \textit{friction term} \\ &\times (0.63 + 0.00074\sigma_f) && \leftarrow \textit{ice strength term} \\ &\times (1 + 0.0018(90 - \gamma)^{1.6}(1 + 0.003(\beta - 5)^{1.5}) && \leftarrow \textit{bow form term} \end{aligned}$$

Where:

HC – hull condition factor

S – factor for salinity of water

B – ship beam (m)

L – ship waterline length (m)

D – draft (m)

h – equivalent ice thickness

T – ice surface temperature (°C)

σ_f - flexural strength of ice (kPa)

γ – average bow flare angle at waterline (°)

β – average buttock flare angle at waterline (°)

The open water resistance (MN) is given by:

$$R_{ow} = (Displ)^{1.1}(0.025F_n + 8.8F_n^5)/1000$$

Where:

$Displ = \rho_w LBDC_b$ (tons)

ρ_w - density of sea water (1.03 tons/m^3)

C_b – block coefficient

F_n - Froude number

The total resistance is a sum of ice resistance and open water resistance.

Calculation of ice resistance:

Table 11.1.1

Initial data for ice resistance calculation

Parameter	Average	Maximum
HC	1	1,5
S	0,034	0,034
B	70	70
L	400	400
D	17,37	17,37
h	0,8	1,7
T	-5	-30
σ	500000	500000
γ	30	30
β	25	25

Table 11.1.2

Obtained results

	Average values	Maximum values
Ship size term	61,74	191,26
Friction term	1	0,7925
Ice strength term	370,63	370,63
Bow form term	2,59	2,59

R_{ice} = 30,3 MN

$R_{ice\ max}$ = 111,6 MN

Calculation of open water resistance:

Table 11.1.3

Initial data for open water resistance calculation

Parameter	Average	Maximum
ρ water	1,03	1,03
L	400	400
B	70	70
D	17,37	17,37
Cb	0,81	1
F	0,008	0,008

R_{ow} = 0,29 MN

$R_{ow\ max}$ = 0,37 MN

Total resistance:

1) (Using average values) R = 30,61 MN

2) (Using maximum values) R_{max} = 112,02 MN

12. Wind loads

Wind loads can have a significant influence on operating FLNG vessel in Arctic conditions, especially on upper structures, so it is very important to take them in account while designing a vessel. To realize wind loads calculations I used Russian standard called “СНиП 2.06.04-82”.

Lateral load:

$$Q_w = 73{,}6 * 10^{-5} * \gamma_f * A_Q * V_Q^2 * \varepsilon$$

Where:

γ_f - wind load factor (1,4)

A_Q - lateral surface area of the sail (13200 m^2)

V_Q – wind speed (40 m/s)

ε - coefficient that depends on the horizontal dimension (0,5)

Longitudinal load:

$$Q_w = 49 * 10^{-5} * \gamma_f * A_n * V_n^2 * \varepsilon$$

Where:

γ_f - wind load factor (1,4)

A_n - longitudinal surface area of the sail (2284 m^2)

V_n – wind speed (40 m/s)

ε - coefficient that depends on the horizontal dimension (0,7)

Results:

40 m/s – maximum wind speed that can occur during the hugest storms. So, we got:

Lateral load: 10,85 MN

Longitudinal load: 1,75 MN

13. Risk analysis

Procedures for risk assessment in the design and operation of structures in areas where ice can be met must comply with and follow the risk assessment procedures for construction in areas where there is no ice cover.

We will assume that the term "risk assessment" covers all areas of design of floating and stationary structures in those areas where ice interaction is possible. It should be noted that the concept of "risk" includes the risk to personnel, the environment, reputation and material assets and that the risk associated with the design and operation of structures could in principle be the cause of human casualties, environmental pollution and loss of property.

In general, there are three categories that are at risk for a vessel accident:

- population;
- crew;
- ship.

The risk to the population includes a threat to the life of all members of society, the risk of damage or loss of public property and the risk of damage to the marine environment. The marine environment of the Arctic has long been considered extremely vulnerable and fragile.

The risk of the category "Crew" includes the risk of an accident that will result in injuries and death of the crew members of the vessel, and in the category "Vessel" - the risk of an accident resulting in damage to or loss of the vessel or its components.

Although it is necessary to avoid the danger of risk of all degrees, from the point of view of society there is a certain gradation in this matter. Damage to the vessel does not affect on a society in a huge manner, although this event is very important for the owners of the vessel and insurance companies. The injuries or death of crew members are taken more seriously. Pollution of the environment or accidents affecting on large sections of society, depending on the severity of the catastrophes are very painful, and owners in every way try to prevent them.

Moreover, the danger is to overcome ice, especially when combined with the effects of ice and strong currents. The dangers associated with damage to the structure of the vessel should be in the following situations:

• interaction of vessel and icebergs;

• Loss of controllability;

• failure of the power plant;

• the influence of large waves, etc.

During operation, hazards are also associated with:

• possible leaks in equipment and explosions / fires;

• possible complications in the drilling process;

• possible contamination of the environment during loading / offloading operations or transportation.

Table 13.1

Hazid analysis for the operating of the FLNG vessel

Accidental scenarios	Description	Mitigation measures
1) FLNG loss of positioning due to interactions from ice	Because of the sea ice mooring loads become bigger than the capacity of the mooring system. FLNG offset from the riser system becomes so big, that it can break.	Good ice management should be implemented to avoid such situations. In critical cases we can realize riser disconnection and moving from the site.
2) FLNG loss of positioning due to icebergs	Because of the icebergs mooring loads become bigger than the capacity of the mooring system. FLNG offset from the riser system becomes so big, that it can break.	Good iceberg management should be implemented to avoid such situations. In critical cases we can realize riser disconnection and moving from the site.
3) Riser damages due to ice fragments	Fragments of ice may be under the FLNG body and potentially damage the elements of the riser. The ice fragment can also drop out of the iceberg.	The FLNG is designed to minimize the possibility of getting under the body fragments of ice. Ice management will be used to reduce the likelihood of such situation. In critical cases we can realize riser disconnection.

4) Hull damage due to sea ice	Ice loads on the hull can exceed its structural capacity.	The FLNG can withstand ice loads of a certain level. Good ice management minimizes the likelihood of over-impact and destruction of the vessel's hull. In critical cases we can realize riser disconnection and moving from the site.
5) Top side damages	Icebergs with large sail heights can destroy or damage some parts of equipment on the deck of the FLNG.	Good iceberg management minimizes the likelihood of occurring such a situation. In critical cases we can realize riser disconnection and moving from the site.
6) Hull damage due to icebergs	Iceberg loads on the hull can exceed its structural capacity.	The FLNG can withstand iceberg loads of a certain level. Good iceberg management minimizes the likelihood of over-impact and destruction of the vessel's hull. In critical cases we can realize riser disconnection and moving from the site.

Based on the conducted qualitative analysis, a risk matrix is constructed. The matrix was constructed on the basis of the occurred cases of similar projects and consultations with specialists from Stavanger, Svalbard and Gubkin universities. Yellow means that the risk is acceptable, green - the risk does not pose a particular danger, and red - is not acceptable.

Table 13.2

Risk matrices for operation of FLNG vessel

Probability		1	2	3	4	5
		Very unlikely	Unlikely	Possibly	Likely	Very likely
Consequences	Very high	(yellow)	5 (yellow)	(red)	(red)	(red)
	High	(yellow)	6 (yellow)	1,2,3,4 (yellow)	(red)	(red)
	Medium	(green)	(yellow)	(yellow)	(yellow)	(red)
	Low	(green)	(green)	(yellow)	(yellow)	(yellow)
	Negligible	(green)	(green)	(green)	(yellow)	(yellow)

Based on the results of the risk matrix, it is clear that all risks are acceptable, but only when carrying out appropriate operations aimed at reducing the expected consequences. It is also necessary to always have the means to immediately eliminate the consequences of these risks.

Bow-tie analysis of risk of damages due to ice loads

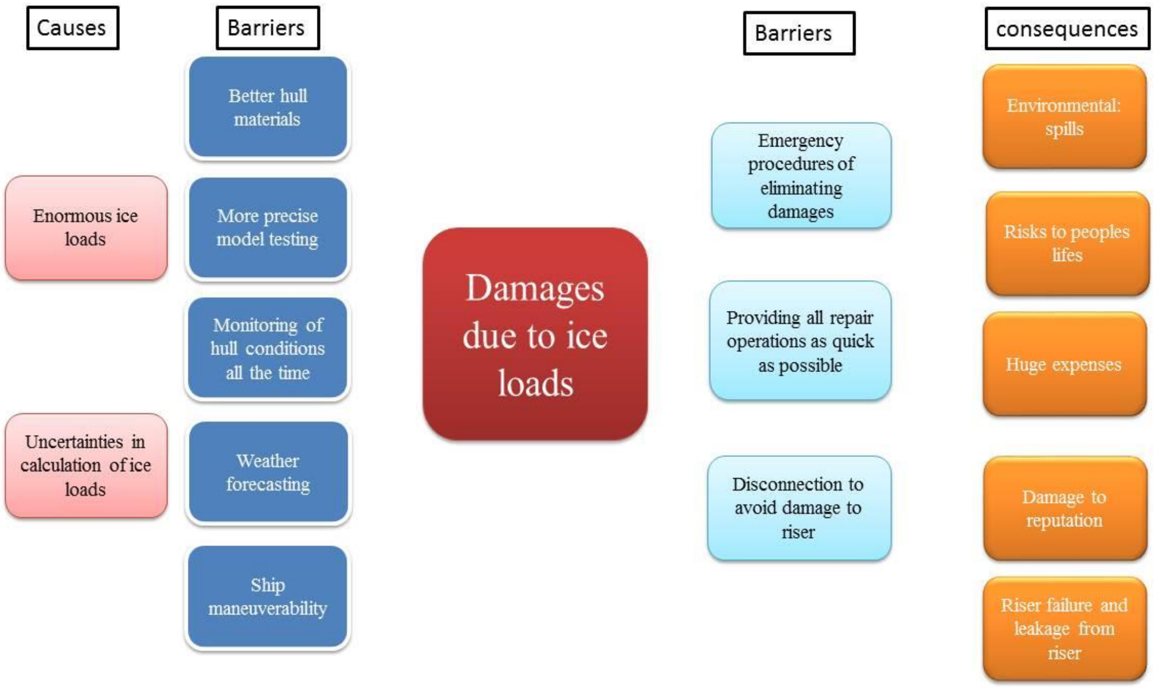

Figure 13.1 Bow-tie analysis

14. Economic analysis

Analyzing the financial component of the projects of the analogical fields and economic research data of D. Khairov, we can give an approximate estimate of the CAPEX project - from 10 to 12 billion US dollars.

Table 14.1

Prices for calculating CAPEX [13]

Element	Price
Production well	70 m$/well
Injection well	50 m$/well
Subsea production module	47 m$/well
Production riser	6 m$/km
Injection riser	4,3 m$/km
Infield pipeline	5,5 m$/km
Manifold	47 m$/unit
Umbilical	2,6 m$/km
Fiber-optic cable	1,4 m$/km
FLNG 5,5 mln.t /year	5 750 m$/unit
• Upper structures, equipment for offloading, power modules, technological lines, etc.	4 500 m$
• Living module	350 m$
• Ice class hull, including LNG and condensate storage tanks	800 m$
• Turret	100 m$
Project logistics and offshore operations for towing and installing a FLNG	700 m$
Commissioning and start-up operations	4 % from capex
Design and survey work	10 % from capex
Project management	10 % from capex
Insurance	3 % from all costs

It is difficult to say about the cost-effectiveness of implementing such a project, but I see a number of activities that can increase the profitability of the project:

- ✓ By improving the quality of project management, as well as partial replacement of imported equipment with domestic equipment, it is possible to reduce some of the capital costs. Unforeseen expenses can be reduced by 15-20 or more percent.
- ✓ Due to the strategic importance of the project and the significant impact on the Russian economy, it is possible to obtain additional tax benefits from the state. In particular, the full exemption of the project from the profit tax is supposed.
- ✓ An additional support mechanism may be the provision of concessional project financing from the state.

15. Conclusion

The use of technologies of FLNG will allow developing deposits that yesterday were considered as inefficient to develop. For the Russian Federation it will also mean the development of the Northern Sea Route, which will lead to the development of the infrastructure of the northern part of the country and will be an important step towards the development of Arctic resources.

The concept of implementing such a project in the harsh conditions of the Russian Arctic has been developed. The sizes of the floating LNG plant, the offloading system and the type of tankers for the transportation of the finished product are proposed. The LNG production technology has been determined, which has already proved itself on the analog projects. Based on the calculated parameters, it is possible to select materials for the construction of the vessel and its components. The selected positioning system and the winterization of the vessel will allow the operation of the FLNG in the Arctic conditions. The conducted risk analysis will help to avoid emergency situations and, in the event of their occurrence, develop systems for eliminating the consequences.

The Ledovoe field, for which the concept of development is considered, is taken as an example, since it combines the maximum number of negative factors for the implementation of the gas production project offshore. Development of deposits of such a type carries great risks and has the potential to be economically inefficient. At the same time, the developed concept has certain prospects for the development of such huge and remote hydrocarbon reserves away from the coastal infrastructure for which the construction of a pipeline system is not feasible.

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