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Lars Løkling.

II. ABSTRACT

The world’s energy demands are increasing rapidly and the oil & gas industry is forced to search for new acreages for exploration and production. The Arctic is expected to contain a vast amount of the remaining undiscovered hydrocarbons on this planet, thus making it an attractive region that could be essential for securing energy supplies for the future. The Arctic is however regarded as the most challenging area on the Earth, due to its extremely harsh conditions. Remoteness, cold temperatures, ice, rapid change in weather and long periods of darkness are some of the main conditions that can be expected. In other words, the region will add numerous challenges to the drilling and production operations. Large distances, lack of infrastructure, severe ice conditions and communicational issues are only some of the challenges the industry will have to overcome.

This master thesis will be focusing on the challenges related to drilling and production in the Arctic, and the available technology and knowledge that exist to overcome them. With this in mind, the challenges that are relevant for the Norwegian Arctic when moving further north. will be reviewed and discussed. The usefulness of different rig types for exploration and field developments in the arctic will be presented, along with some modified versions, which are specifically made for application in the Arctic.

Ice management and overcoming the large distances seems the most challenging for the next step of exploratory drilling in ice-infested waters located in remote areas. The capacity and reliance on an adequate communicational system will also play a huge role of arctic operations. Cooperation might be the key to success, not only for overcoming the operational and technical challenges, but also to get the social acceptance, political support and to make operations economically feasible

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V. ABBREVIATIONS

AWSAR	All Weather Search And Rescue
BOP	Blowout Preventer
DP	Dynamic Positioning
FPSO	Floating Production, Storage and Offloading
GBS	Gravity Based Structure
MOB	Man Over Board
MODU	Mobile Offshore Drilling Unit
NCS	Norwegian Continental Shelf
SAMCoT	Sustainable Arctic Marine and Coastal Technology
SAR	Search And Rescue
TLP	Tension Leg Platform
TM	Turret Moored
UAV	Unmanned Aerical Vehicle
VDL	Variable Deck Load

1 INTRODUCTION

The expectancy of increasing global demand for energy in the future is pushing the oil and gas industry to search for new acreages for exploration and production. The U.S. Geological Survey (USGS), which in 2008 did a Circum-Arctic Resource Assessment, stated that the Arctic could hold up about 22 % of the world's remaining hydrocarbons yet to be discovered. As a response to these great projections, the oil industry has increased the activity in these areas significantly in recent years. Despite the Arctic being the most operationally challenging region in the world, the industry is eager to adapt and develop to be able to capitalize on the vast reserves. [1, 71]

Although there has been activity in the Arctic for several decades, there are still numerous unresolved issues. More capable solutions than currently available are required to ensure feasible exploration and field development in the Arctic.

1.1 Set-up

In this thesis, challenges that can be encountered in the Arctic will be presented and discussed. Ice management will be emphasized in particular and discussed in detail. Different rig types used for exploration and field developments will also be introduced, and their usefulness in arctic conditions discussed. The thesis comprise of the following chapters:

- Chapter 1: Introduction of the thesis
- Chapter 2: An overview of what the arctic is. This includes the definitions, boundaries and specific arctic conditions that can be expected in this region
- Chapter 3: Presentation of drilling and production related challenges
- Chapter 4: Presentation of different types of rigs and solutions made specifically for the Arctic
- Chapter 5: Description of the requirements of an ice management program
- Chapter 6: Presentation of the implications of an oil spill and a description of the preventive and mitigating measures available
- Chapter 7: Discussion of possible solutions for the described issues and challenges, and how to prepare for operating further north in the Norwegian Arctic
- Chapter 8: Conclusion and recommendations

1.2 Objective

The objective of the thesis is to present the experience gained so far from arctic operations, to highlight probable issues and challenges met in these conditions and to prepare companies moving further north in the Norwegian Arctic for what to expect and how to best meet the discussed challenges.

2 THE ARCTIC

The following chapter will introduce the Arctic by presenting a short description of the area, the different geographical boundaries and the specific conditions for this region.

2.1 What is the Arctic?

The Arctic is located in the northern part of the Earth. It covers as much as 6% of the Earth's surface, which comes to about 30 million km^2, about the same size as the whole of Africa. The Arctic consists of a large ocean, surrounded by several land areas. The ocean, named the Arctic Ocean, is the smallest and shallowest of the five major oceans. The arctic environment is often associated with low temperatures, harsh weather and icy conditions, as can be seen in Figure 1. The landscape is extremely diverse, consisting of areas of large mountains and forests, flat coastal plains and ice-infested waters. The arctic vegetation on the other hand is less diverse, although a wide range of plant life has adjusted to the harsh environment. Due to the tough living conditions in these areas, the Arctic is populated by a limited amount of indigenous people, typically reindeer herders, fishermen, nomads and hunters. Even today, some of these vast areas still contain relatively undisturbed eco-systems, both onshore and offshore. The Arctic is very fragile and recovery is often prolonged, which makes it extremely vulnerable. [12, 72]

Figure 1 - An example of an arctic environment [85]

2.2 Definition and Geographical Boundaries

The term “Arctic” is often considered a bit ambiguous. There are several different definitions and geographical boundaries for this region, some of whom include areas that do not represent the typical arctic environment one should expect. It is widely accepted that the Arctic is the region surrounding the North Pole, but each definition has its own description of which land- and sea area is included in the term. The most common definitions are as follows

- The Arctic Circle
- 10º C mean July temperature isotherm
- Northern Tree Line

2.2.1 The Arctic Circle

A well-known definition of the Arctic defines it as all land and sea-areas north of the Arctic Circle limited by an imaginary line located 66º 33 N of the Equator. This imaginary line, which is illustrated in Figure 2, is “drawn” at the southernmost border of the Arctic, parallel to the equator. It encloses the southernmost latitude at which one can expect a unique presence of sunlight for at least 24 continuous hours during summer solstice, and correspondingly a unique absence of sunlight for at least 24 continuous hours during winter solstice. However, the Arctic Circle is not fixed to this exact latitude though. There are fluctuations that vary within a margin of 2 % over a period of 40000 years due to the Moon’s orbit and the influence on the Earth’s tidal forces. [66, 7, 9, 10, 13, 15]

Within this vast circle, one can locate parts of northern Europe, North America and northern Asia, covering eight countries: Norway, Russia, Finland, Iceland, USA (Alaska), Canada, Denmark (Greenland) and Sweden. The issue with this definition is that there are areas within the Arctic Circle that strongly deviate from the normal arctic associations. For example, the northern half of Norway is located within the boundaries of the Arctic Circle, but the Gulf Stream provides enough warmth to make the coast ice-free throughout the year, thus making the arctic description somewhat excessive. [66, 7, 9, 10, 13, 15]

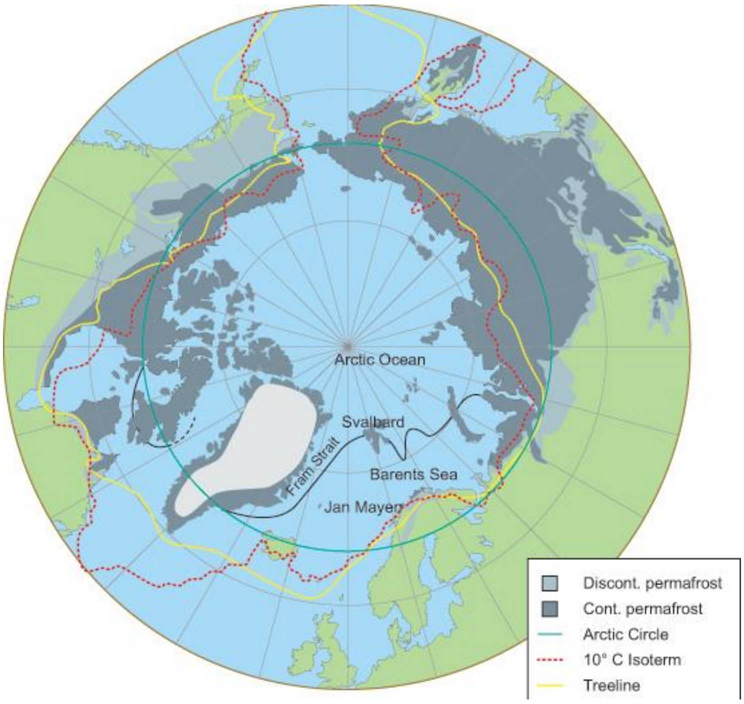

Figure 2 - Boundaries of the Arctic Circle, treeline and 10º C isotherm definitions [70]

2.2.2 Isotherm

An isotherm is a line that represents a constant temperature. Whilst trying to define the Arctic, the isotherm that represents a mean July temperature of 10º C is often used as the definitional boundary. This means that areas within the boundaries of the isotherm will not experience an average July temperature of more than 10º C. This definition is based on environmental and biological factors and thus its boundaries deviate from the Arctic Circle boundaries, which are based on latitude only. [15, 16]

2.2.3 Northern Tree Line

The boundaries of the Northern Tree Line are simply determined by the ability of tree growth. The temperature will decrease while moving north and at a certain point the environmental conditions no longer allow trees to grow. The typical conditions preventing growth are cold temperatures, insufficient air pressure and/or the lack of moisture. The tree line boundary basically defines the transition between forest and tundra, and is more similar to the temperature definition than to the Arctic Circle definition. This is due to both of these definitions being based on temperature. The tree line has a significant variation in latitude. In Russia trees grow as far north as 72º N, whilst in some places in Canada trees struggle to grow as far south as 56º N. Despite this, the tree line seems well defined from a great distance, and is in fact a gradual transition. [15, 18]

2.3 The Arctic Conditions

The following conditions define the arctic region:

- Climate
- Ice
- Visibility

2.3.1 Climate

The climate is an integral part of describing the arctic conditions. Temperature, precipitation, wind and polar lows will be described in the following sections.

2.3.1.1 Temperature

The temperature in the Arctic region can become extremely low. Especially in the winter season where the solar energy is at its lowest. The average temperature in January is in between -20ºC and -40ºC. During the summer, the average temperature is higher, although it only rises to -8ºC in August. Some parts of the Arctic can experience several months without any direct sunlight, making it difficult to get a warm climate. The cold temperature can be significantly enhanced due to the wind chill effect. [2]

2.3.1.2 Precipitation

Precipitation is defined as any form of water that falls down on the surface of the Earth from the atmosphere. Rain and snow are the most common examples of precipitation, but it can also appear in the form of dew, hail and hoar frost. For the most part of the Arctic precipitation levels are very low. In fact, some areas have been named polar deserts as the amount of precipitation is similar to the levels in the Sahara desert. The highest precipitation levels are found between Scandinavia and Greenland, due to moisture being brought up from storms in the Atlantic Ocean during winter. In the winter months, snow is the dominant form of precipitation in the Arctic, especially in the central Arctic. Exceptions occur, as transportation of warm air into the central Arctic Ocean can lead to rain. Precipitation in the form of snow is also possible during the summer months, but in the Atlantic region of the Arctic snow is rather unusual this time of year. [26]

2.3.1.3 Wind

Wind is created by differences in pressure when air moves from a zone of high pressure to a zone of low pressure. The wind speed is mostly depended on the pressure differential. The higher the difference in pressure between two regions, the higher wind speed. Other influential factors on both speed and direction are surface friction and Coriolis force. The rotation of the Earth can adjust the wind direction. This effect is called the Coriolis force. The adjustment in the northern hemisphere is possible because the Coriolis force deflect the wind to the right, which consequently causes the wind to make a clockwise circular motion near high-pressure regions and a counter-clockwise motion near low-pressure regions. In the southern hemisphere, the Coriolis force also applies, occurring in opposite directions. The surface friction from wind flowing over surfaces at both land and sea will affect both the velocity and direction. [26, 30]

Wind speeds in the Arctic are normally relatively low due to weak pressure gradients and temperature inversions. Temperature inversion is when the air at surface level has a lower temperature than the flowing air above it. Areas around the coast and around mountains tend to have stronger pressure gradients, and are therefore more prone for windy conditions. Gales are not uncommon in the Arctic, and these conditions can last for several days. Wind gusts with hurricane strength has been reported in Alaska during winter, reaching a velocity of 210 km/h. [26, 30]

2.3.1.4 Polar Lows

Polar lows are defined as small, low-pressure systems, called cyclones. This intense atmospheric phenomenon seen in Figure 3 creates a counterclockwise spiraling weather pattern, almost like a hurricane. These “Arctic Hurricanes”, as they are sometimes called, can have a diameter of 100-500 km and form when cold air travels with wind over warm open water. The cold air comes in contact with the surface of the warm water, is heated up and rises with an increase in moisture. A new volume of cold air flows in and creates a small, but very intense low-pressure system. The instability in the air can cause rapid changes in both wind speed and wave height. A small breeze can develop into a storm in only a matter of minutes and an increase in wave heights of up to 5 meters have been observed within only an hour. These quick changes are usually followed by heavy precipitation (rain, hail or snow) and can lead to strong ice accumulation. [28, 29, 76]

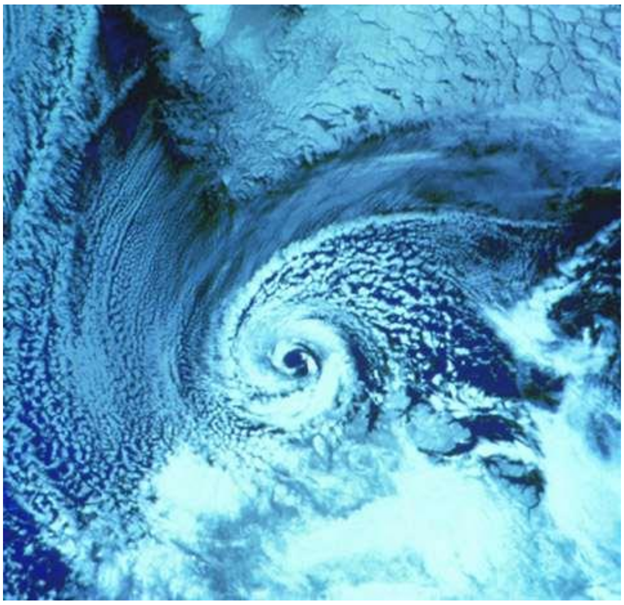

Figure 3 - Polar low seen from above [86]

The wind speeds vary within the low-pressure system and inside the eye of the spiral it is relatively calm. The average maximum wind speed is more than 85 km/h, reaching a strength equivalent to a severe gale. Wind speeds reach storm strength (over 90 km/h) in 35-50% of the polar lows and the highest recorded polar low wind speed in the 21st century was 130 km/h (hurricane strength). The upside to its sudden occurrence is its correspondingly quick disappearance. Polar lows usually last no less than 12 hours and no more than 36 hours, and the average duration is about 18 hours. The season for polar lows stretches from October to May, but with the majority of occurrences between December and March. The Norwegian and Barents Seas are the main areas where this phenomenon occurs, especially between 65 ° N and 75 ° N, reaching from the zero meridian to Novaya Zemlya. Other areas within the Arctic that are prone to polar lows are listed below:

- South of Iceland
- Southwest of Spitsbergen
- Hudson Bay
- Northern Japan Sea

[28, 29, 76]

2.3.2 Ice

The presence of ice is very common in arctic environments. Ice occurs in four different forms, three of which are found in the marine environment.

Ice phenomena:

- Permafrost
- Icebergs
- Pack-ice
- Ice accretion

2.3.2.1 Permafrost

Low temperatures over long periods of time can cause the soil to freeze. If it stays frozen for two or more consecutive years, it is called permafrost. This phenomenon can occur both onshore and offshore. Figure 4 shows an example of onshore permafrost, which is most common. The thickness of the permafrost has been estimated in the range of up to 1000 m in East Siberia in Russia. Offshore permafrost is an expression explaining when permafrost occurs beneath the seabed. Sub-seabed permafrost can form either by submerged onshore permafrost or by the temperature at sea-bottom falling below the freezing point whilst the seawater is more saline than the pore water underneath. The occurrence of offshore permafrost has not been discovered in water depths greater than about 100 m. The top of the permafrost is normally about 20-40 m below the seabed and the thickness rarely exceeds 100 m. [74, 75]

Figure 4 - Permafrost in the Arctic [87]

2.3.2.2 Icebergs

Most of the icebergs existing in the Arctic are pieces from fresh-water glaciers and ice shelves that have detached and fallen into the sea. The areas listed below are especially known for providing icebergs:

- Greenland coast (10000-30000 annually)
- Ellesmere Island

Icebergs are also regularly found in:

- Svalbard
- Franz Joseph Land
- Severnya Zemlya
- Novaya Zemlya

Figure 5 - Floating iceberg [98]

When they break off, these pieces can be millions of tones, hundreds of meters long and consist of large keels. Like illustrated in Figure 5, their massive size is usually hidden from the naked eye as 9/10 of the ice is normally under water. Because they originate from freshwater, their ice is extremely hard due to the lack of salt. As the icebergs travel along the currents they tend to melt gradually and break into smaller parts, although icebergs can spend many years drifting around before eventually ending up in the Atlantic Ocean, where they melt relatively fast. [72, 76]

2.3.2.3 Pack-Ice

In the winter, the temperature in the seawater in the Arctic region can get below the freezing point of around -1.8 ºC. When this occurs, and there is little movement in the sea, it can cause the seawater to freeze. As can be seen in Figure 6, the floes can form in various shapes and sizes. Freezing seawater, which contains salt, is a slower process than that of freezing freshwater. This is not only due to the lower freezing point, but also due to the change in density. Salt makes the seawater denser when it is close to the freezing point, resulting in the salt water sinking before it is adequately frozen. Thus around 100-150 m depth of water usually has to be cooled down to the freezing point to ale ice at the surface. [4, 76, 72, 77]

Figure 6 - Sea-ice floating in the Arctic [92]

Every type of ice that is formed in the sea in this manner is called sea-ice. Sea-ice can be divided into two categories, fast-ice and drift-ice/pack-ice. Fast-ice is whatever ice remains stationary along the coast, typically connected to the shoreline. Drift-ice is the term used for any ice not considered fast-ice. The differentiation of the terms drift-ice and pack-ice is defined by the concentration of ice. If the concentration of floating ice on the surface of the water is 70 % or higher, the term pack-ice is used. [4, 76, 72, 77]

It is common to separate between first-year-ice and multi-year-ice. First-year-ice will freeze in the winter and melt away in the summer, whilst multi-year-ice stay frozen for multiple years, not affected by the seasonal changes throughout the year. [4, 76, 72, 77]

2.3.2.4 Ice Accretion

The term "ice accretion" covers all processes that contribute to ice build-up on the surface of an object. When operating in cold environments like in the Arctic there is a potential risk for ice accretion on the surface of both fixed and floating offshore structures. Wind speed, wind direction, temperature, amount of surface area exposed and humidity are factors that affect the severity of the ice accretion. This phenomenon can lead to problems of different magnitudes and preventive measures should not be underestimated. There are essentially two types of ice accretion [25]:

- Atmospheric icing
- Marine icing

Atmospheric Icing

Atmospheric icing is when water droplets, freezing rain, drizzle or wet snow in the atmosphere falls down and freeze when coming into contact with a surface. These water droplets are often super-cooled, meaning they are cooled to a temperature below 0 ºC whilst travelling in the atmosphere without transitioning into a solid state (ice). Freezing rain is an example of this, although these water droplets will only partially freeze on impact with a surface, whilst water droplets in super-cooled fog will freeze completely on impact and create a porous white deposit called "rime ice". [25, 65]

Atmospheric icing can normally be classified into two different processes; precipitation icing and in-cloud icing. Freezing rain and super-cooled fog are examples of these two different processes, respectively. [25, 65]

Figure 7 - Ice accretion on an offshore vessel [91]

Marine icing

Marine icing (or sea spray icing) happens when the air temperature is below the freezing point of seawater (around -1.8 ºC). It typically forms as shown in Figure 7, after waves splash into structures and brine droplets are transported by the wind onto surfaces where ice can be accumulated. As this type of ice accretion is produced mostly from seawater, it will be softer and easier to remove due to the salt. [25, 65]

2.3.3 Visibility

Darkness for longer periods of time is not unusual in the areas of the Arctic. The periods of darkness increase whilst moving in the direction of the North Pole, where it is at its maximum. Visibility can also be affected by precipitation and these areas are known to be prone to fog. Some of the phenomena related to darkness and visibility are described in the following sections.

2.3.3.1 Polar Days/Nights

As mentioned in section 2.2.1, areas within the Arctic Circle experience the phenomenon of polar nights and polar days. During polar nights, the sun never reaches the horizon and during polar days, the sun never sets. At the North Pole this phenomena is at its most extreme, causing approximately 6 months of “winter darkness” and 6 months of sunlight during the summer. This is possible because the Earth’s axis of rotation is tilted 23.4º from the vertical axis. When orbiting around the sun, this will affect the amount of sunlight that hitting the surface of the Earth at any given time. The duration of this phenomenon is at its shortest along the line of the Arctic Circle and gradually increases the further north one moves. [26]

Although the sun never reaches the horizon during polar nights complete darkness will not necessarily be experienced throughout the entire period in all areas. Due to the Earth’s atmosphere, sunlight will be bent, spread and scattered, causing various types of twilight that will light up affected areas. [26, 27]

2.3.3.2 Summer Fog

In the summer months, the probability of fog increases significantly. The air temperature rises faster than the sea temperature, thus building up temperature contrasts between the sea and the air. The cold water will cool down any warm air flowing above at and increase the relative humidity of the air. When the air is saturated with moisture, fog is generated. Visibility during fog is dependent on the thickness of the fog and of how close to the surface it sets. [27]

3 CHALLENGES RELATED TO DRILLING AND PRODUCTION IN THE ARCTIC

The Arctic conditions described in chapter 2.3 are the main reason why this region is considered challenging for the oil and gas industry. The consequences of this type of environment is a number of added challenges to drilling and production, which must be sufficiently handled to be able to conduct operations within the same safety level as those of the less harsh areas like the North Sea.

One of the main challenges, which make the preparedness for all of the issues more difficult, is the lack of data and information in this region. Devices for measuring, weather stations, gauges, logs and detailed maps are missing partly or completely. This will be particularly challenging when approaching new areas in the Arctic.

The safety authorities can also create challenges for the industry, by introducing strict laws and requirements for activity in the Arctic. An example of this is “The Same Season Relief Well Policy”, which is a requirement from Canada stating that a relief well must be drilled in within the same drilling season as the blowout occurs. Denmark has gone one step further, requiring two rigs available per well. If a rig on location suddenly gets an out-of-control situation a well at the end of the drilling season, an ice-resistant assisting rig might be needed to be able to drill the relief well even if the water would start to freeze up. Nevertheless, ice management would be required if the drilling period was to be extended into the winter months and the subsequent harsh ice conditions. [88]

A description of how the Arctic can be classified in regards to offshore operations will be presented in the first part of this chapter. Subsequently some of the main challenges related to drilling and production will be described.

3.1 Classification

Regardless of which definition used, there will be variations of conditions within the geographical boundaries. Statoil, a Norwegian oil and gas company, proposed a classification of the offshore Arctic region based on amount of ice in the sea. It was divided into three categories, the workable, the stretch and the extreme. The areas that are completely ice-free, would be regarded as fitting for the workable category. The stretch category consists of sea areas that vary with the seasons, making it ice-free only in the summer months. The extreme category represents areas that are covered with ice all-year-round. [19]

The stretch category is considered more challenging than the workable category, but the technology present today is more than capable of handling with the additional challenges. The extreme category however, is not currently within our operational capability and would require new technology and long-term investment, thus making it a distant future option. [19]

GustoMSC has proposed another classification, which is based on the vessels suitability for sea-ice conditions. The categories are defined as:

- “High-Arctic: Suitable for areas with annual sea ice cover, with clear open water and ice seasons in an extended or year-round operational modus. This involves operations in areas such as Beaufort Sea, Chuckci Sea, Northern Greenland, Kara Sea and East Siberian Sea”
- “Sub-Arctic: Suitable for areas with occasional sea-ice cover and/or high-arctic areas in a seasonal operational modus. This involves operations in areas such as southern Greenland, Northern Barents Sea, Sakhalin and Sea of Okhotsk”
- “Winterized/harsh environment: Suitable for harsh environment areas with extreme low temperatures. This involves operations in areas such as Southern Barents Sea” [73]

3.2 Climate

The climate in the Arctic is known to be extremely harsh and unpredictable, as explained in chapter 2.3.1. The climatic conditions would affect both man and machine and can cause additional challenges in comparison with operations in less harsh regions. The combination of cold temperatures, wind and precipitation should not be underestimated and can cause a hazardous work environment. Additionally, there is an increased probability of extreme weather conditions in the Arctic, including polar lows and wind with hurricane strength. Some of the challenges related to the climate are described in the following sections.

3.2.1 Temperature

The description of the challenges related to the cold temperature environment can be divided in two:

- Challenges affecting personnel
- Challenges affecting equipment, materials and machinery

3.2.1.1 Personnel

The performance of the personnel tend to drop in Arctic conditions, as the cold environment affects the mental, the emotional and the physical abilities, causing poor decision-making and decreasing the efficiency. This also increases the risk of work-related accidents. [66]

In windy conditions, the wind chill effect increase significantly. The wind chill effect is described as the cooling from the combination of wind and temperature. This effect can be, according to the NSIDC, expressed as “the loss of body heat in watts per square meter of skin surface” [26]. The wind reduces the boundary layer that is used for isolation of the body heat, making the heat loss more excessive. Outdoor activities in the winter months would be increasingly challenging in cold arctic environments. [26, 30]

Crewmembers on a rig would be exposed to the danger of the following diseases:

- Cardiovascular disease
- Stroke
- Cold-induced asthma
- Raynauld’s disease (could lead to frostbite)
- Cold urticarial
- Diseases of the muscular and skeletal system

[76]

Another challenge would be the scenario of “man overboard”, which could occur both whilst transporting personnel by helicopter or boat and whilst personnel working on an offshore platform. The temperature of the water would be the main factor influencing the chance for survival. Only a few degrees difference would make a huge impact on the probability of surviving due to the risk of hypothermia. Severe hypothermia would be deadly within a short amount of time.

3.2.1.2 Equipment, Materials and Machinery

The cold temperature can cause failure or destruction of production equipment, personal protective equipment and safety equipment and it can cause ships to become unstable. Low ambient temperatures are challenging for the material selection used for equipment and structure of the installation. The fracture toughness of structural steels can be reduced due to a transition from ductile to brittle. When becoming brittle the probability of damages or fractures increase significantly, even with little deformation. The cold temperatures can cause liquids within pipelines to freeze and plug. Similarly, substantial formation of gas hydrates within the pipelines can cause plugs, a well-known problem experienced in conditions of low temperatures and high pressures. Failure of equipment and/or structures can be dangerous and can compromise the safety of personnel and operation. [34]

3.2.2 Polar Lows, Wind and Precipitation

The sudden occurrence of the polar lows makes it quite unpredictable and therefore difficult to prepare for. Lack of time to prepare will be challenging for operations and well control might be compromised. All outdoor activity will most likely be delayed during this phenomenon, as the wind can reach hurricane strength. The rapid change in wave height can lead to problems for floating vessels, and keeping stationary might not be possible during this high sea. The unannounced heavy storm can be followed by heavy precipitation. The combination of wind and precipitation will reduce visibility for navigation and outdoor activities. In addition to reducing visibility, precipitation is one of the main contributor to atmospheric ice accretion and can lead to a wet and cold environment for the personnel. If wind is strong enough, visibility can be reduced if snow on the surface is lifted and flown through the air, which consequently can be formed into large snowdrifts. Additionally, wind could cause high sea and increase velocity on potentially dangerous ice structures. Crane operations are typical examples of operations that are shut down during high wind and poor visibility [6, 67]

3.3 Ice

In areas where there is a risk of drifting icebergs or sea-ice, an ice management program needs to be established to avoid large ice-loads from damaging and destroying equipment, installations and operations. A thorough description of what is required of an adequate ice management program is presented in chapter 5. In the following sections, challenges related to ice accretion and sub-seabed permafrost are presented.

3.3.1 Ice Accretion

Ice accretion could cause problems for both operations and safety. Slippery decks, handrails and ladders due to light ice accretion would be challenging and dangerous for the crewmembers. Ice accumulation on antennas could block communication- and navigational systems. Safety could also be compromised by equipment for firefighting, lifeboats and first-aid-kits becoming useless or unavailable due to large ice accumulations. Failure of drilling and production equipment could cause temporary operational downtime. Accumulated ice forming on high levels of the rig would pose a threat, as the ice eventually would fall down due to an increase in temperatures. Large pieces could cause significant damage to people or structure unless managed. [25, 65, 66]

Heavy ice accretion on fixed structures could increase the weight and size of structural elements, and the extension could cause the structure to be exposed to stronger wave and wind forces. For vessels and floating structures heavy ice accretion could cause an unbalanced weight distribution and thus compromise the stability of the entire structure. The main contributor to ice accretion on vessels is sea spray generated ice. The smaller the vessel, the more brine droplets would be able to splash over deck when waves crash into the bow. [25, 65, 66]

3.3.2 Drilling and Cementation in Sub-Seabed Permafrost

All though drilling operations through permafrost in offshore locations have been successfully completed on several occasions, there are still several issues not sufficiently resolved. The main concern is regarding the potential instability in the formation around the well that may occur in these zones if conditions change, either from natural causes or by human impact.

Whilst drilling a well, several processes could cause an increase in temperature in the permafrost due to heat transfer. The increase in temperature could cause the permafrost to start thawing and the stability of the formation could thus be threatened. Warm mud circulating up and down the well could greatly contribute to an increase of the temperature in the formation surrounding the well. Kusatov (1999) states that “it is commonly assumed that during drilling, more than 99 percent of the mechanical energy (rotary and pump input) is transformed into thermal energy” This provides an indication of the significant magnitude of the potential heat transfer caused by drilling. [37, 38]

Independent of the type of sediment, instabilities in the wellbore could cause borehole sloughing, washouts and caving, thus creating problems such as mud losses, kicks and stuck pipe. If the permafrost contains gas hydrates, drilling through it could increase the probability of a kick when gasification of the mud occurs. As water expands when transformed into ice, it would consequently decrease in size when reversing the process. Thawing of frozen sediments could cause a volume reduction of 9% from the original size. This reduction coupled with exacerbated squeezing by the surrounding loads would definitely have potential of harming the borehole stability. Subsidence due to thawing of permafrost could also be harmful to bottom-supported rigs, subsea-equipment and pipelines. [37]

Whilst performing a cementing job in permafrost conditions making sure that the cement is able to build up its compressive strength is vital. In normal conditions this could take hours and if normal (e.g. Portland) cement was used in a permafrost zone, it would likely freeze prior to the compressive strength is becoming anywhere near sufficient. [80, 38]

Spacers ahead of the cement could end up in the permafrost interval if the cement top is not completed all the way to the surface. If the spacer fluids freeze, it would expand and could lead to a collapse in the casing. A successful cementing operation requires insurance of good cement bonding with the formation. Leftover mud, especially in washout zones, can easily freeze and prevent good bonding. [80, 38]

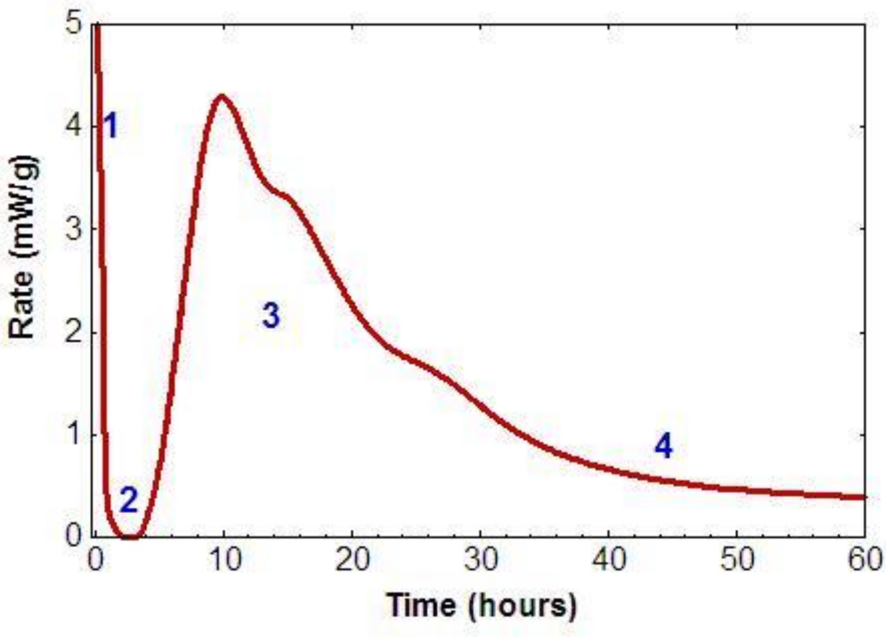

Figure 8 - The process of hydration [40]

A separate challenge would be cement hydration. This process is an exothermic reaction, meaning it generates heat to the environment. Like illustrated in the graph of Figure 8, the cement process can be divided into 4 stages, two of which are significant in regards to generating heat. [39, 40, 41, 42]

- Stage 1: Cement dissolves when cement and water are mixed, causing a fast reaction (a few minutes). The main reaction in stage 1 could be described by the following exothermic equations:

$$Eq.1: C_3A + 3C\bar{S}H_2 + 26H => C_6A\bar{S}_3H_{32}$$

$$C_3A = tricalcium\ aluminate$$

$$3C\bar{S}H_2 = calcium\ sulfate\ dihydrate\ (gypsum)$$

$$C_6A\bar{S}_3H_{32} = calcium\ aluminum\ sulfate\ mineral\ (ettringite)$$

The reaction in Eq. 1 releases 1350 Joules/gram. J/g is energy/mass and is a measure of how much thermal energy (heat) is transferred to the environment.

- Stage 2: Called the induction period. Almost no reaction occurs during this stage.
- Stage 3: A second exothermic reaction occurs and the rate of reaction increases rapidly. When stage 3 is ended, 30% of the initial cement has hydrated. The exothermic reactions during stage 3 can be described by the following equations:

$$Eq.2: 2C_3S + 7H => C_3S_2H_8 + 3CH$$
$$C_3S = tricalcium\ silicate$$
$$C_3S_2H_8 = calcium\ silicate\ hydrate$$
$$CH = calcium\ hydroxide\ (portlandite)$$

The reaction in Eq. 2 releases 500 Joules/gram to the environment.

$$Eq.3: C_2S + 7H => C_3S_2H_8 + CH$$
$$C_2S = dicalcium\ silicate$$

The reaction in Eq. 3 releases 250 Joules/gram to the environment

- Stage 4: The reactions continue but the reaction rate gradually slows down. [39, 40, 41, 42]

3.4 Remoteness and lack of infrastructure

The Arctic is regarded as one of the most remote regions of the Earth. Although covering about 30 million km^2, only about 4 million people live there. The developed infrastructure is thus limited. The following sections describes how this can affect the logistics, emergency response and communication for operations in the Arctic.

3.4.1 Logistics

Whilst developing projects in the Arctic, considering how to transport equipment, materials and people to the location of the installation is of key importance. Transportation would in many cases have to cover long distances due to the lack of supply bases in the area. The remoteness would lead to a longer response-time in comparison with traditional operations, which are closer to shore. Additionally the seasonal changes of the sea and weather conditions could cause the availability of the installation for vessels and supply-boats to be non-existing for long periods of time. Operational delays stretching for days, maybe even weeks, would prove extremely costly and could render the operation economically unviable. [17]

3.4.2 Emergency Response

The emergency response resources in the Arctic are currently scarce. Shipping accidents, oil spills, helicopter accidents and evacuation of personnel are some of the scenarios the emergency response teams could be forced to handle. If any of these scenarios occurred, time would be of vital importance. The lack of marine infrastructure limits the options and overall capability of a sufficient emergency response solution. There is a shortage of helicopters with sufficient range to cover a possible “Search and Rescue”-operation (SAR) in every part of the Arctic. [76, 63, 64]

3.4.3 Communication

North of the 74th latitude there are missing satellite coverage caused by the Earth’s curvature. This is due to the fact that most satellites are of the type called Geostationary Earth Orbit illustrated in Figure 9, which orbits around the latitude of the equator. Thus, there is a lack of necessary broadband or real-time communication possibilities. Problems with satellite coverage start occurring when reaching the 70th latitude. [72, 74]

Communication is a substantial challenge in for the oil and gas industry the Arctic. The issue is most relevant for exploration rigs, as fixed installations can cover these communicational needs through laying fiber cables. Communication, internally on the rigs and externally to the surrounding vessels, installations and onshore facilities, is imperative for safety and efficiency reasons. Miscommunication due to technical failures in the communication systems during critical drilling operations could have catastrophic consequences. The importance of adequate capacity of the communicational system must be sufficiently handled to fulfill the requirements of operations in the Arctic. Equally important is the reliability of the system, to keep safety, efficiency and quality of the 24-hours-a-day operation at a maximum. [51, 52]

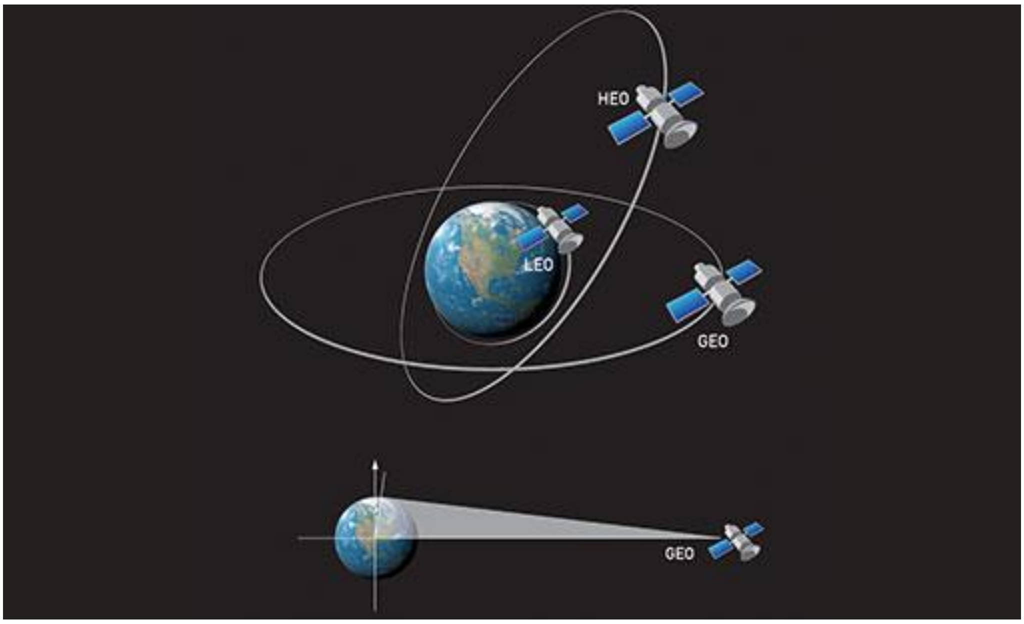

Figure 9 - Different satellite systems [52]

Floating vessels utilized for drilling or production purposes in the Arctic are expected to be kept as stationary as possible during operation. This is commonly accomplished by using a mooring system, a dynamic positioning system (hereby referred to as DP) or a combination of the two. In areas where the water is too deep for a mooring system, DPs are widely used. As the DPs are dependent on satellite signals to adjust for the environmental loads, satellite coverage would be essential for a safe and successful operation. If a vessel unwillingly drifts too far out of position, it could be forced to disconnect in order to avoid equipment damage. Scenarios like this could be costly, both operationally and economically, and could pose a threat to the safety of the operation. [51, 52]

A misleading signal or total lapse of the signal from satellites would reduce the possibility of using GPS for navigation or retrieval of personnel evacuated to sea. Additionally satellites are important in the process of tracking and detecting and for general surveillance purposes.

Numerous factors in the Arctic can interfere with the satellite signal to reduce quality of transmission:

- When the signals travel through the atmosphere, they are attenuated by atmospheric dispersion caused by rain and snow. Higher latitudes creates an angle that force the signal to travel a longer distance through the atmosphere, thus weakening the signal.
- Solar storms and other phenomena from space cause distortions in the ionosphere, which can lead to signal scintillation and attenuation. These solar storms can be seen as northern lights and may cause loss of lock to GNSS satellite signals or to signals from L-band satellites.
- The surface of the sea and the shape of the landscape can reflect satellite signals.
- Ice accretion on antennas and other receivers can reduce or block transmission.
- Floating installations with significant movement in high sea conditions may cause loss of signal or tracking of wrong satellites. [51, 52]

3.5 Visibility

Precipitation, especially in high wind, can be challenging for the visibility of personnel working in the Arctic. However, since precipitation is uncommon in many arctic areas and it usually ends relatively fast, the main concern is more of overcoming the challenges made by darkness and fog.

3.5.1 Darkness

Continuous darkness would be challenging for the day-to-day operations demanding an artificial light solution. Emergency response teams would be put to the test while searching for oil spills or attempting to rescue personnel in the water in dark conditions. Additionally, being exposed to long periods without sunlight could challenge both physical and mental health, as darkness over long periods is often associated with depression.

Figure 10 - Offshore fog [93]

3.5.2 Fog

As illustrated in Figure 10, the visibility decreases when fog occurs. The thickness of the fog determines the magnitude of the decrease, but usually fogging reduce visibility to a point that renders the helicopters ability to operate. Transportation of crews on and off the rigs would then be temporarily impossible due to strict regulations of how much visibility helicopter pilots should have to be allowed to fly. Boats and vessels may not be able to supply offshore installations due to the restricted visibility. The fog could be unpredictable and could remain for several consecutive days. Consequences of fog often comprise of expensive overtime costs and operational delay.

4 VESSELS AND INSTALLATIONS USED FOR EXPLORATION AND FIELD DEVELOPMENT

In this chapter, several rig types used for exploration and field developments will be reviewed and discussed. Some modified rigs specifically designed for the harsh arctic environments are described to show some of the specter of alternatives that is available today.

4.1 Vessels and Installations Used For Exploration

Prior to selecting the drilling structure for an exploration operation in the arctic waters, numerous parameters need to be considered to ensure a safe and efficient campaign. One of the major decisions would be which type of vessel should be used. Some of the most commonly used vessels for exploration, as well as some specific arctic designs, are introduced in the following sections. The conventional rigs typically used for exploratory drilling are:

4.1.1 Semisubmersible

Semisubmersible drilling rigs are considered in the category of Mobile Offshore Drilling Units (MODU). These rig types are the most frequently used floating units for drilling operations offshore. Only jack-up rigs, which are bottom-supported, are used more often. Semisubmersibles were originally meant to be used as bottom-supported drilling units, but as time progressed, the design was transformed into a semi-submerged type of unit. During transportation of semisubmersibles, the rigs are not sunk into the water, thus making the transportation of these units from one location to another considerably easier. Moving the semisubmersibles could be done either by the help of tugboats or barges, or by using its own self-propulsion system. The submersibles are designed with a platform-type deck that is supported by submerged floatation devices called pontoons. Two main types of semisubmersibles exists. The most noticeable difference is the way they are submerged. [32]

Bottle-type semisubmersibles

The design shown in Figure 11 allows bottle-shaped hulls under the drilling deck to be filled with water and consequently submerging. The semisubmersible would be kept stationary by mooring lines anchored to the seabed. [32]

Figure 11 - Bottle-type submersible unit [32]

Column-stabilized semisubmersibles

The design is considered the more popular of the two. Instead of bottle-type hulls, this design comprise of two horizontal hulls beneath the deck. As can be seen from Figure 12, it is attached via cylindrical or rectangular columns. Smaller diagonal columns are installed to increase structure stability. Submerging is completed by filling the horizontal hulls with water. The semisubmersibles are kept in place by either mooring lines or DP system. Especially in deeper waters, it is normal that DP either replace or supplement the mooring system. DP systems use thrusters (propellers), which are controlled by computers, to correct for disturbances from wind and waves. Adjustment are automatically made based on satellite GPS signals. [32]

Figure 12 - Column-stabilized semisubmersible unit [32]

The semisubmersibles are rated as the most stable floating unit currently available. Due to the partially submerging it reduces several of the movements described in Figure 13, such as rolling, pitching and heaving of the semisubmersibles. The outstanding stability makes the design desirable for drilling operations carried out in harsh conditions prone to rough waters. Semisubmersibles are not as depended on water depth as for instance jack-up rigs. The floating capability enables the vessel to be used in deep as well as shallow water. Reaching from shallow water depths of less than 30 m to depths of more than 3000 m, the range available for operation by the semisubmersibles is wide. [32, 33, 34, 73]

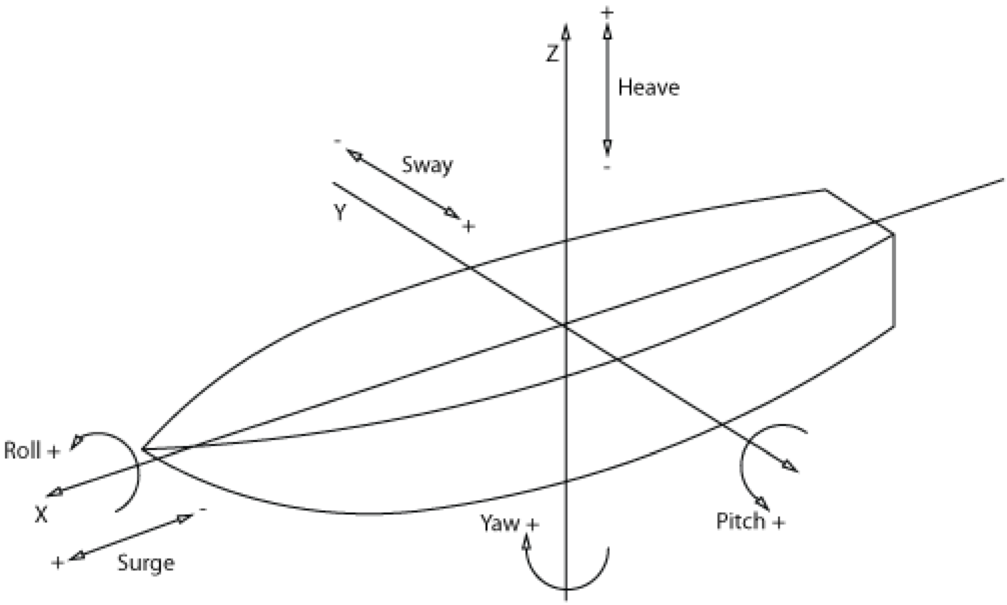

Figure 13 - Possible movement of a floating structure [99]

A limiting factor compared to a drillship would be the relatively low variable deck load (VDL) reducing the ability of storing equipment. Fluids, spare parts, operator consumables and food are examples of items it would be advantageous to store onboard. If also considering the low transit speeds, the potential for working in remote areas, like the Arctic, is highly reduced. Challenges related to the exposure of sea ice loading on equipment, which can accumulate between columns and is particularly prone to occurring in the splash zone, where the exposure is largest renders the possibility of operations in the high arctic region unrealistic. [32, 33, 34, 73]

4.1.1.1 Specific Solutions of Semisubmersibles for Use in the Arctic

Conventional semisubmersibles are not considered the most suitable choice of vessel in the arctic region due to obvious challenges related to sea-ice loads. However, in recent years semisubmersibles specialized in handling the arctic challenges have been developed. For instance, Huisman has built two types of semisubmersibles with revolutionary design mitigating some of the challenges encountered in the Arctic. These designs are presented in the following section and are named:

- JBF Arctic
- Arctic S

JBF Arctic

The design of the JBF Arctic is based on a combination of a conventional semisubmersible and an additional unit for deflection/breaking of potential ice features. It thus keep the advantage of excellent stability whilst diminishing the danger of ice by a heavily strengthened protection unit. The round structure design, seen in Figure 14, consists of a floater, eight columns and a deck box on top. If the JBF Arctic was operated in ice-free waters, it would work as a conventional semisubmersible. During operations in ice-infested water, stability is achieved by lowering the deck box partly into the water, thus protecting the riser against ice loads. A 20-point mooring system provides a stationary position for the unit. An ice resistant structure around the deck box adjacent to the water surface is installed and the round floater is designed to be able to flow through ice if supported by an icebreaker. This unit is designed to be able to drill wells in high arctic conditions throughout the entire year and to handle ice thickness of approximately 2-3 m whilst moored. Icebreaker assistance could be necessary if sea-ice proved problematic. Water depth limitation for this design is minimum 50 m and maximum 1500 m. [36]

Figure 14 - JBF Arctic [36]

Arctic S

Figure 15 shows the design of the Arctic S, which has some similarities to the JBF Arctic. The major difference being the third operating mode where the unit can act as a gravity-based structure (GBS). The round-shaped design with a floater, eight columns and a deck box is also similar. A slightly weaker mooring system is installed, using merely a 16-point solution and consequently limiting the ice resistance during mooring to ice within the thickness of maximum 1.5 meters. Operations in ice-free and ice-infested waters are equivalent to those of the JBF Arctic, though the water depth limitation is reduced in comparison to the JBF Arctic, as this design allows for operation in depths between 35-1000 m. The extra feature the Arctic provide, enables it to be placed on seabed. This option is only available in shallow water depths between 12 and 29.2 meters. The Arctic S is designed to operate in high arctic regions all year round, though it is depended on ice management programs if ice conditions exceed its limitations. [35]

Figure 15 - Arctic S [35]

4.1.2 Jack-Up

The popularity of jack-ups, both for drilling and work overs offshore, is vast. Jack-ups have been manufactured since 1954 and are frequently used for offshore exploration and development purposes all around the world. The other type of bottom-supported MODUs is the submersible rig, which is not used in the same scale as the jack-ups. The jack-up rig has floating capabilities, but when on location, the drilling deck is jacked up above the water surface, hence the name jack-up. Before jacking up, the legs are placed on the seabed, thus creating a very stable environment for the drilling operation. [83, 84, 73]

The legs can either be open-truss or columnar type. Open-truss legs are lightweight sectional tubular constructions made of steel with a zigzag shape, whilst columnar legs comprise of huge steel tubes. Although more expensive, the open-truss option is favorable due to their ability to adapt to stresses in the water and due to their overall stability being better. As can be seen in Figure 16, the hull has holes that these legs rise up through. The water depth limitations are consequently depended on the length of the legs. Due to the floating capability of the rig, it is transported without noteworthy inconvenience. The usual method of transportation is towing from a tugboat or barge, especially using barges if the jack-up needs transportation quickly or to a distant destination. [83, 84, 73]

Figure 16 - Jack-up [69]

The relatively low mobilization costs, the increased availability and the high stability of the platform design are some of the main advantages making the jack-up popular in the offshore industry. The obvious drawback is the dependence on water depth. Even though massive jack-ups have been built, some of which are able to operate in up to 167 meters of water, there will be areas with water depths far exceeding this in the Arctic. In these areas, alternatives such as drill ships or semisubmersibles are preferred. Similar to the semisubmersible, the jack-up will encounter problems when facing ice-loads. Drilling equipment in the splash zone has to be protected from ice-loads. However, if shallow water conditions are present and the challenges concerning ice-loads are addressed, they can be utilized in the conditions met in the high arctic, sub-arctic and harsh/winterized categories. [83, 84, 73]

With a conventional jack-up, drilling operations can only be completed in shallow ice-free waters. The transportation on/off location also demands ice-free waters. Therefore, valuable time, which could have been spent drilling, would be wasted on waiting for ice to diminish. The departure from location would also have to be completed before ice emerges. To extend the drilling season, the jack-up would need to be able to withstand some ice-loads, particularly during the time of decommissioning and transport away from location. [83, 84, 73]

4.1.2.1 Specific Solutions of Jack-Ups for Use in the Arctic

Two proposed concepts for extending the arctic drilling season are presented and discussed in the following sections. The first (Arctic Jack-Up 1) from Maria Urycheva and Ove T.

Gudmestad of the University of Stavanger and Gubkin University, and the second (Arctic Jack-Up 2) from Gusto MSC. [88]

Arctic Jack-Up 1

This concept is based on designing the hull of the Arctic Jack-Up 1 with enough strength to be able to break approaching ice. Compared to the conventional jack-up, this would be a more complex design, and the ice resistance capability would cause weaknesses to other parts of the jack-up. For example, the need for a larger air gap and the increased roll motion. A heavily strengthened bow with icebreaking capabilities could be installed at the front of the deckhouse and reduction of ice loads would be reduced with inclined walls. [88]

To save deck space, the legs, protective collars and equipment used for jacking up are placed within arms installed on the outside of each side of the hull. The four arms (two on each side) would, in comparison with the conventional jack-up that have legs stored inside the hull, create enlarged moment from environmental loads. In spite of open-truss legs being the preferred choice in open waters, it is suggested that a tubular design would be better equipped to handle ice-loads. Ice protective collars could be mounted on the part of the legs that are exposed to ice-loads, but should be used wisely, as they contribute to increased hydrodynamic forces applied to the legs. [88]

As the protection of drilling equipment during an operation is vital, the approach for this type of unit would be to place the derrick on top of one of the arms and consequently above one of the legs. For the derrick to be skidded over, the legs would have to be adjustable. The application of a telescopic leg is not uncommon to fulfill this requirement. Drilling can then be consummated through one of the legs and at the same time protect the drilling equipment. While transporting the unit, the derrick should be placed in the center to stabilize the hull. [88]

The jack-up legs are the limiting factor duration of the drilling season. The amount of loads the legs are able to withstand would thus determine when the MODU would be forced to leave location. The aim for the Arctic Jack-Up 1 is only to withstand low loads of ice and careful planning would have to be conducted in order to avoid encounters with rough ice conditions. Restrictions on the conventional jack-ups could shorten the drilling season to 45 to 90 days for some areas of the Arctic. However, with the technology and design of the Arctic Jack-Up 1 the operating window could be extended by approximately 4-5 weeks for drilling and an additional 4 weeks could be added to safe abandonment of the location. These extra weeks could prove the difference of whether or not a well could be drilled and tested in one season or two. [88]

Arctic Jack-Up 2

This second concept is based on several designs of GustoMSC for solutions on the range between very shallowto deep waters were floaters would be required. The primary challenges of this concept are explained in this section followed by proposed solutions to the different designs. [73]

The strategy is to design a large jack-up with enough distance between the legs to reduce the probability of ice accumulating between them and to create a stabilized platform. The large design is mainly to be able to overcome the high overturning moment that can be applied from high ice loads. Other advantages of the designs large size would be the increased variable deck load. Normally, the legs of a jack-up are a lattice type, which would be inadvisable if operating in ice-infested waters. A circle-shaped tubular leg could avoid the issue with ice accumulation inside the leg and would be more capable of withstanding the local ice loads. To diminish the effects of horizontal forces applied from sea ice, the spud can could provide an adequate solution [73]

Traditionally, jack-ups are built to withstand loads in a jacked-up position, but in the Arctic, it would be far more advantageous for the rig to be floating whilst potentially facing sea ice conditions. Thus, the arctic jack-ups should be designed with the capability of going into a floating state. Further protection from sea ice would be achieved in the splash zone, where during exploratory drilling the drill string would be highly exposed along with other equipment used in this section. To account for this, a protective sleeve can be installed. [73]

4.1.3 Drillships

Drillships are vessels that have been adapted to be capable of drilling. Some essential equipment and improvements has been added to the vessel. As shown in Figure 17, the most noticeable of which would be the drilling derrick, the helipad and the moon pool, followed by the upgraded mooring and station-keeping system typically installed. Drillships can be applied in a wide range of water depths. The available operating interval stretches from approximately 600 m to over 3000 m, though the design is considered the optimum alternative for water depths exceeding 80 m. [73, 89]

One of the advantages compared to the other MODUs is the drill ships capability of quick transportation. Due to its independency regarding outside transportation, it is able to maneuver from well to well quicker by using its own propulsion method. Drillships tend to have a high storage capacity, making them less reliant on re-supply. The biggest concern regarding drillships is their vulnerability towards waves, wind and currents. Throughout a drilling operation, it is important that the drillship is as stationary as possible. The equipment is connected to the vessel and excessive movement could cause the loads the equipment is intended to withstand to be exceeded. Thus the significance of a sufficient system to decrease movement is emphasized. [73, 89]

Figure 17 – Drillship [94]

Mooring systems could be applied in shallow waters by using 12 anchors attached to the seafloor. If water depths prevented the use of a mooring system, or the mooring system would need assistance and the DP system would be the suitable alternative. The DP system is the same as that of the semisubmersible (ref 4.1.1), with thrusters responding to an onboard computer system. In the short drilling season for some areas in the Arctic, the DP system can be favorable due to its quick set up. [89, 73]

The main advantage of the drillships is the ice-resistance capabilities and the experience available regarding vessels dealing with ice conditions. Adequate reinforcement of the vessel could make the vessel operable in environmentally harsh areas. As discussed earlier, the splash zone is particularly exposed to ice loads, although with the protection of the moonpool design the drillship offers a great solution to this problem. [73]

4.1.3.1 Station-Keeping Systems

Based on the above sections it is quite clear that this type of MODU have a great potential for operations in the Arctic. The main challenge is the susceptibility to motion. The selection and quality of the station-keeping system is thus crucial to the success of the drilling operation. There are three options of station-keeping systems to be considered:[73]

- Spread Mooring
- Turret Mooring (TM)
- Dynamic Positioning

Spread Mooring

This option is based on using anchors and mooring lines to station the ship in a fixed position without the possibility of making changes to the ships heading. Equipment for installation of the mooring system has easy access, which makes the process relatively uncomplicated. No power is needed once the set-up is completed, thus reducing fuel consumption compared to the DPS. Orienting the ship into the environment can help reduce mooring loads and motions, but due to the fixed positioning, the vessel would not be able to move freely whilst influenced by forces from ice and weather. Ice thickness would have to be closely monitored as the mooring lines have limitations on their ice resistance capabilities. If sea-ice was to become too extensive, a possible disconnection procedure would have to be available. [73]

Turret mooring

This option uses the same principal with anchors and mooring lines attached to the sea-bottom, with one major difference. The mooring lines are hooked up to a turret mounted around the area of the well, making it possible for the vessel to spin around this center-point. The design requires no additional power supply after installation is completed and thus the fuel consumption would be low. However, fuel consumption would be increased if the thrusters were to be used for assistance. The complexity of the installation process would be higher compared to spread mooring, due to the requirement of subsea access. The ability to disconnect would have to be maintained in case the mooring system was loaded beyond its capabilities. [73]

Dynamic Positioning

This option of keeping a vessel in place is based on using thrusters/propellers to adjust for forces such as ice, wind, waves and currents influencing the position and motion the vessel. The set-up is considerably less time-consuming compared to the mooring systems and mobilization can be completed without much support. Computers normally control DPS automatically, but troublesome sea-ice conditions can require the crew to manually control the DPS. Fuel consumption is relatively high for this kind of system, requiring several large thrusters with a high demand for power. The water depth is required to be at least 300-400 meters for this technique to be utilized. [73]

As harsh sea ice conditions can be expected in some areas in the Arctic, the ability of adjusting for motions and environmental loads renders turret mooring and DPS the two main options for station-keeping. The spread mooring technique is, due to the fixed positioning, not suitable for high mooring loads, and would thus be the least effective of the three options in harsh conditions. [73]

4.1.3.2 Specific Solutions of Drillships for Use in the Arctic

The NanuQ is a drillship series that was specifically designed for operations in the Arctic. GustoMSC's long track-record of designing drillships made it possible to further develop arctic drillships. Three separate units were designed:[73]

NanuQ 5000 -Turret moored

This unit is considered the top model in the series. Operationally fit for extended season, to all-year-round in conditions consisting of multiyear ice with up to 4 meters of thickness. It is classified as Polar Class 2, meaning that all arctic areas are accessible for the unit. As the title suggests, its station keeping is based on turret mooring, though it can be assisted by DPS during set-up. The turret is strategically mounted in a position for optimal ice- and weather-vaning and is thus usable in ice-infested waters as well as in ice-free waters. This unit is able to complete both exploratory drilling and development drilling. [73]

NanuQ 5000 - Dynamic Positioning

This design is also capable of exploration and development drilling and is defined as a Polar Class 2 unit. The biggest difference from the NanuQ 5000 TM is that this unit uses a class 3 dynamic position system instead of turret mooring, which makes it a more suitable option for deeper waters. The center of the well is placed in the middle of the ship. [73]

NanuQ 3500 - Dynamic Positioning

Uses the same DP system as the NanuQ 5000, though this design also provides equipment spread mooring for operation in shallow waters. The design restricts the length of the drilling season compared to the two other types. This unit would be intended for drilling in extended seasonal mode only. [73]

4.2 Vessels and Installations used for Field Developments

When selecting vessel or installation for field developments, other considerations in comparison with exploratory purposes will have to be taken into account. Primarily, there need to be thought of a long-term solution. The most widely used vessels and installations are presented in the following sections.

4.2.1 Steel Structures

Steel structures are a type of fixed gravity-based installations designed for use in shallow waters. The installations are normally floated to the assigned drilling site and then placed on the seabed by the help of their own weight. Usually weight is added to the structure by using liquids or some type of sand. This type of installation has not been the most widely used for arctic conditions and the designs have often been influenced by a lack of resources available. However, some examples of fixed steel structures are present in the Arctic. Some of the most known examples are as follows: [43, 77]

- Molikpaq: The platform shown in Figure 18 was originally designed for exploratory drilling in the Canadian arctic, the installation was sold and modified to be able to handle both drilling and production. The most significant modification was the installation of a steel spacer, which qualified the installation for deeper waters (30 m) and made it more resistant to ice and wave forces. After the alterations, the installation was approved for offshore operation in Sakhalin II’s oil field. [43, 77]

Figure 18 - Molikpaq platform [101]

- Prirazlomnoye: This stationary platform is placed at 20 m depth in the Pechora Sea south of Novaya Zemlya. The field development is based on this single platform being able to carry out almost all operations. The installation can be used for drilling, production, storage and offloading, and is the center of the field development. The platform has 40 well slots and is capable of producing 22000 tones/d of oil and 1 million m^3/d of gas. Resistance against ice loads makes it self-sustainable and it can operate all year round. [44, 77]

4.2.2 Artifcial Islands

An artificial island, like the one in Figure 19, is a concept where an island is created offshore for drilling or production purposes. The original method was based on filling up the seabed with rock or gravel until the island was visible above water. The material used for making the island could either be transported from onshore or be dredged up nearby the location of the construction. Although being a simple technique, it proved insufficient when forces from currents, waves and tides were taken into consideration. Improved techniques have been developed and there are currently five main types of artificial islands [45]:

- Sandbag retained islands
    - The island filling is contained by sandbags
    - Max water depth of 7 m
- Sacrificial beach islands

    - The edge of the island is constructed as a flat beach with low slopes to reduce erosion
    - Max water depth of 19 m
- Gravel islands
    - Steep-sloped islands filled with gravel. Requires less filling compared to the sacrificial beach islands
    - Max water depth of 14.6 m
- Caisson retained islands
    - A caisson placed upon a steep-sided sand berm below sea level. Normally ballasted with a central core filled with sand
    - Max water depth of 31 m
- Water ballasted caisson on a berm
    - Caisson ballasted on the berm by the use of water
    - Max water depth of 31 m

Several artificial islands have been constructed in the Arctic over the long period of activity in the region, thus some necessary experience has been gained. This type of approach has several advantages, some of which are listed below:[45]

- Increased space
- Limited environmental impact
- Increased safety
- Relatively inexpensive
- Number of wells/pipelines

Unfortunately, there are also some major concerns and the experience so far has discovered the following [45]:

- Material availability
    - The particular material needed to fulfill the requirements of the island may not be present locally, or if present, there might only be a limited supply. Some of the types consist of large volumes of a specific fill material.
- Season length
    - Variation in conditions can limit the available time of construction
- Erosion

    - Waves can be very erosive and need to be handled with a design of an erosion protection system
- Special equipment
    - High cost of mobilization and logistics
    - Ice management

Figure 19 - Artificial island made of gravel in the Beaufort Sea [46]

4.2.3 Concrete Gravity Based Structure

Figure 20 is an illustration of a concrete gravity based structure (GBS), which is an offshore installation with a topside facility placed upon a substructure manufactured from reinforced concrete. The installation is towed to a designated location, and is subsequently sunk to the seafloor by the use of gravitational forces created by its own weight. In most cases, fluids or solids are used as additional weight to stabilize the construction further. Before deployment, the underlying seabed has to be verified to ensure a safe and reliable landing spot. The design creates a stable substructure that is highly capable of withstanding lateral environmental loads and sufficient support for a topside structure. This type of unit is normally large and is designed for drilling, production and storage of oil, which consequently makes it suitable for field developments. [90]

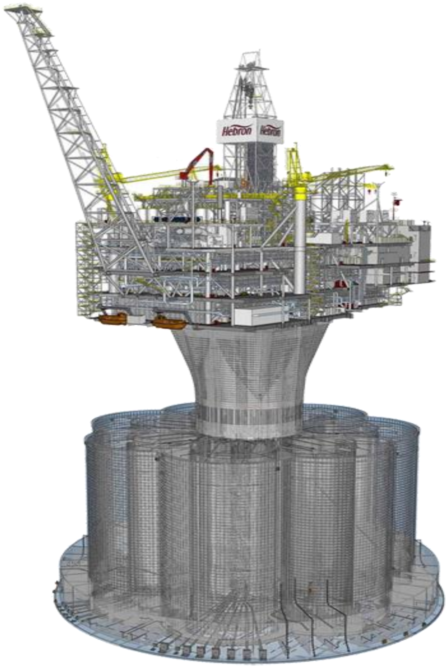

Figure 20 - Gravity Based Structure [95]

The original intent for the GBS was application in the North Sea, although the design has later been successfully used in harsh conditions such as those found in the Grand Banks of Newfoundland. The Hibernia platform, which is stationed at the Grand Banks of Newfoundland, is placed at a medium water depth of 80 m and is, with a specially designed ice-wall, able to withstand impacts of a 1 million ton iceberg. This huge structure is also capable of storing 1.3 million barrels of oil and has two drilling derricks, each of which can be skidded over 32 different well slots. [77]

4.2.4 Floating Production Storage and Offloading Unit (FPSO)

FPSOs are typically used in field developments located in deeper waters where the abovementioned designs are not able to operate. Especially FPSO’s are favorable for field development where transportation of production fluids to shore through pipelines or infrastructure is not an available option. . As suggested by the name, these installations have the ability to float and can be applied for production, storage and offloading in cooperation with a subsea system, connected via a risers and umbilicals. FPSOs have the advantage of high mobility and are considered an overall economically sound solution. [81, 47, 48]

Another essential point is the FPSO’s great track-record in regards to oil spills. Only a total of 5237 barrels of oil spread over 206 different incidents of oil spills have been reported from this type of vessel. Excluding one single oil spill of about 4725 barrels, the remaining 512 barrels spilt equals a remarkable 0.00003 % of the total oil produced from FPSOs.The large oil spill of 4725 barrels was due to a human error, which could have happened on any type of production unit, and is thus not considered as a result of design or operating conditions. The amount of spilt oil is also quite low seen in relation to the volumes that an FPSO is normally designed to store. Mooring systems, transportation methods and other specifications are dependent on which type of FPSO is used. The following five types are considered to be within the FPSO category [81, 47, 48]:

- Semisubmersible
- SPAR
- TLP (Tension-leg platform)
- Ship-shaped
- Buoy-shaped-floater

Of the five types only two designs, the ship-shaped and the buoyed-shaped-floater, are considered suitable for operating in high arctic and sub-arctic conditions. The ability to quickly and independently disconnect from the riser, umbilicals and mooring system when ice loads are beyond their ice-resisting capabilities is a significant advantage. Additionally, these two types are normally equipped with a self-propulsion system, enabling easy maneuverability on/off location whilst detached. Another advantage is the large storage capability. To further develop and prepare the FPSO’s for the arctic conditions, icebreaking capabilities and ice management support would be required [81, 47, 48]

Ship-shaped FPSO’s have been applied in arctic areas like the Grand Banks of Newfoundland, areas that are known to be prone to icebergs. The design of an FPSO in the Terra Nova field included an ice-resistant feature where the installation is able to withstand multi-year-ice and icebergs around 100 000 tons if the velocity is below 0.5 m/s. Disconnection procedures are available, although they have not been needed thus far. An ice management program for the FPSO is supporting the unit and the surrounding installations whenever large ice loads approaches [49]

As opposed to the ship-shaped and boyed-shaped-floater, the TLP and SPAR are not considered feasible options in high-arctic and sub-arctic areas as possible disconnection scenarios might emerge. The procedure of detachment is too complex and time consuming to be considered adequate. In fact, if there is high tension of tendons and top tension riser, TLPs may not be capable of disconnection. The SPAR is depended on support from a tow-boat for transportation out of the collision zone, which could prove troublesome if time was limited. In areas less prone to major ice loads and if disregarding the disconnection procedure, the TLP and SPAR would be valuable alternatives. [81]

4.2.5 Subsea Field

In a subsea field development, all the production equipment is placed on the seabed as opposed to using fixed or floating structures. The term “wet tree” is used for a subsea design were the production tree (x-mas tree) is placed on the seafloor, usually mounted on a subsea template. Production fluids are then transported to a platform, FPSO or to onshore facilities. The original idea of subsea field development was to overcome the challenges faced whilst planning to operate in extreme water depths. However, application of the subsea approach could also prove useful for locations where the harshest conditions are found at the water surface. In such a development, the subsea field has its own transportation system, which would eliminate the need of a structure above sea level. Pipelines are installed for transporting the production fluids to a safer environment onshore. Some subsea solutions are capable of processing the produced fluids subsea. Subsea field developments without the use of either fixed or floating platforms have been utilized in the Arctic. Snøhvit is a successful example of this, where unprocessed production fluids are sent via pipelines to shore. [77, 50]

For deepwater subsea production operations, ice loads from floating sea-ice or icebergs are not able to inflict any damage to equipment on the seabed. In shallower waters where keels from icebergs and ice ridges can be harmful, the need for protection is however vital. One of the major issues for a subsea field development is flow assurance. Arctic sea temperatures could cause problems concerning hydrate accumulation and prevention/elimination procedures would have to be implemented to avoid plugs in the pipeline. The decision of whether or not to construct a subsea field development, is based on numerous factors, such as water depth, ice conditions, flow assurance and distance to shore. One of the positive aspects of this design would be the reduced expenditure on topside equipment. [50, 77]

5 ICE MANAGEMENT

The oil and gas industry is moving further north into areas where sea-ice and icebergs are common, either seasonally or all-year-round. One of the largest obstacles to overcome prior to operating in the Arctic is avoiding or mitigating the strong forces these ice-structures can produce. The need for ice management is thus paramount, particularly in deep waters where fixed platforms or artificial islands are not an available option. According to Sustainable Arctic Marine and Coastal Technology (SAMCoT), the definition of ice management is “the sum of all activities in which the objective is to reduce or avoid actions from any kind of ice features”. When considering ice management, this thesis will focus on sea-ice and icebergs, as these are the two challenges that would affect offshore operations the most. [21, 82]

All offshore structures, both floating and fixed, can be exposed to ice-forces, which can be harmful or even catastrophic. Firstly, the type of ice conditions one should expect must be predicted. The amount of historical data and statistics are scarce for some of these arctic areas and conditions in general are difficult to forecast as they vary largely from one year to another. Secondly, the area around the operation would need constant surveillance to detect any potential threat to the offshore structure. Thirdly, the threats would need to be removed or mitigated to a manageable size. Lastly, a disconnection strategy would have to be in place in case of a threat exceeding the manageable. To sum up, these activities would be crucial to safely handle the ice loads in the Arctic:

- Ice surveillance
- Threat evaluation
- Physical ice management
- Disconnecting/connecting of offshore structures

[21, 82]

5.1 Ice Surveillance

The ice surveillance is an essential part of the ice management program. This part of the program is initiated long before the operation start-up, continues throughout the lifetime of the operation and can also go on after operation has ended for future usage. The ice surveillance basically comprise of detection, tracking and forecasting.

5.1.1 Detection

Although there are some similar techniques for detection of icebergs and sea-ice, it is common to distinguish between the two ice types.

5.1.1.1 Iceberg Detection

As illustrated in Figure 21, icebergs drifting in the Arctic ranges from very large icebergs of millions of tones, to smaller icebergs also known as growlers. Obviously, the large icebergs are the easiest to detect and they also cause the worst damages on impact. The use of detection equipment is important to be able to locate all potentially hazardous icebergs and thus establish a state of readiness in the case of their arrival. Detection of icebergs should never depend on a single system only. The systems can be affected by conditions such as strong winds or storms, high sea, rain, snow and fog, and the reliance of one system could consequently be insufficient.

The aerial systems mainly consist of satellite or aircraft images, which usually produce maps and snapshots of the areas they pass. Continuous tracking is accomplished by systems and observations from offshore structures. Airborne systems are typically fixed wing aircrafts using high frequency (8-12 GHz) search radars, thermal imaging and/or visual observation to locate the icebergs. The aircraft is advantageous due to its flexibility and its ability to cover large areas in a relatively short amount of time. The uncertainty of the sensors can be mitigated by using visual confirmation. [20, 22, 24]

Satellite radars can produce images that can be studied to locate icebergs. Optical sensors offer better resolution, though they fail to penetrate clouds and fogs. The challenge of satellite radars is analyzing the images correctly and extracting the relevant information. Distinguishing ships from icebergs and vice versa is not straightforward. Discovering the iceberg can prove difficult, as the returned amount of energy from the radar signals is often lower when returning from icebergs than when returning from ships due to the signals tendency to penetrate the surface of the iceberg. [20, 22, 24]

The best way to detect an iceberg would be to visually observe it, either from a fixed or floating structure or from an aircraft. However, limitations due to fog or other weather phenomena disturbing visual observation enhance the reliance on radar systems. Marine radars onboard offshore structures can detect large and medium icebergs without difficulty when weather conditions allow it. Small icebergs, bergy bits and growlers could however prove more challenging. Bergy bits are barely visible on marine radars and growlers often “disappear” when using this technology. “Sea clutter” is an expression used when echo signal cause unwanted bright spots to occur on the radar image due to waves during high sea. The bright spots can cause confusion of whether they are caused by waves or by icebergs. [20, 22, 24]

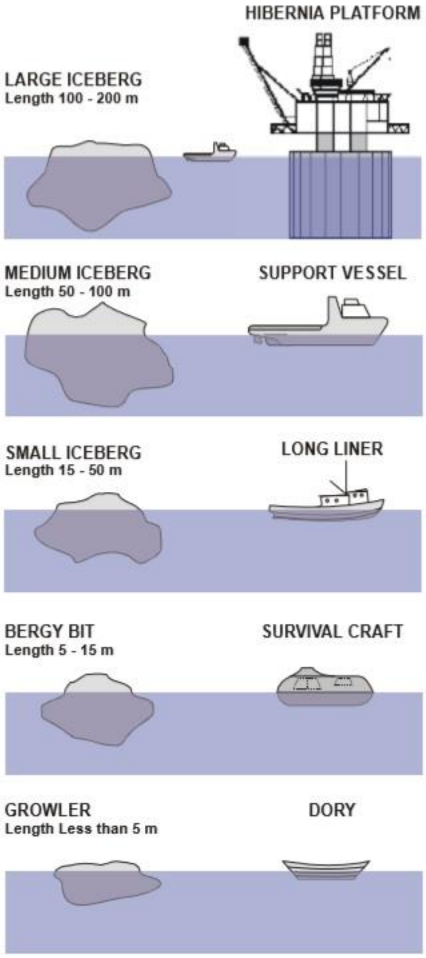

Figure 21 - Classification of icebergs [20]

5.1.1.2 Sea Ice Detection

The detection of sea-ice is often separated by information gathered locally and information gathered regionally. Local sea-ice information consists of ice concentration, thickness, size of flakes, classification of the ice and its drift velocity. This kind of information is typically gathered, provided for the users and exploited within a timeframe of a few hours. The local sea-ice data can be assembled by the use of visual observation from an on-site ice observer, for example the icebreaking vessels.

Regional information is based on detection over a larger area and at an earlier stage. The areas monitored could be located more than a 100 km away and the process of detection could take several days. The advantage of this detection method would be that the ice management program would get a longer timeframe for decision-making and the response could include physical ice management to mitigate potential harsh ice floes.

As described for iceberg detection, the use of radar, satellites and visual observation to detect sea-ice, is common in the Arctic. Helicopter ice reconnaissance has been a method used for numerous years, though the development of Unmanned Aerial Vehicles (UAVs) can hopefully replace this method. Semi-auto UAVs have several advantages compared to a helicopter reconnaissance, such as being less sensitive to weather, being able to cover larger areas, greater endurance, being immune to darkness and being safer for humans as they are unmanned. If UAVs are designed with a synthetic aperture radar imagery system, a high number of sea ice parameters can be extracted from low-resolution satellite imagery. Over 100 000 km^2 of area can be captured with these images, and in combination with high-resolution imagery the results can be of great benefit for sea-ice detection. [57, 58]

5.1.2 Tracking and Forecasting

The number of icebergs drifting in the Arctic varies significantly each year, as does the difference in size and strength. Due to these variations, it has proven relatively difficult to provide a realistic forecast of the amount of drifting icebergs to be expected. One of the reasons for these variations and the unpredictability is explained by the origin of the icebergs. As many of these are pieces fallen of large glaciers, the prediction of when and where they occur is difficult to predict. Creating a database including statistics of the occurrence of icebergs can be advantageous and has been a method used for several years. This provides an indication of the severity of icebergs in different areas.

There are examples of relatively simple methods of tracking icebergs, where drift buoys are placed on the ice to track its future movements and drifting paths. The knowledge of the driving forces of ice movements are studied, and information about currents and wind directions are of great importance in the forecasting process. Satellite images can also be used to see how ice moves as a function of time.

5.2 Threat Evaluation

After a decision to conduct an offshore operation in locations where sea-ice and iceberg can be expected, the ice surveillance would be maintained and a continuous evaluation of threats would be required. The evaluation would be based on the information gathered about the trajectory of the ice and the potential force it could apply. The force of the ice structure will be strongly dependent on drift velocity, the strength of the ice, the size of the structure, the shape of the structure and of the collision angle. There are several scenarios where decision making and threat evaluation would be put to the test once the ice-loads were detected. As is highlighted by Figure 22, the scenarios are highly dependent on which of the zones the ice-threat is detected. Some of the relevant scenarios are described below:

- If the detected ice-loads have an estimated trajectory that keeps it no closer than the observation zone, the ice will only be tracked until it has drifted passed the critical area of the field, without any physical interference.
- If the ice is detected in the observation zone and the estimation detects a possibility of the ice coming into contact with the installations, a preparation of a physical management measures will have to take place.
- If the ice structure has drifted unnoticed through the observation zone and is heading for collision, a decision has to be made on whether there is sufficient time to mitigate/eliminate the ice-loads before it enters the critical zone.
- If the ice structure which is headed for collision is either of the following the operators are forced to implement a disconnection procedure:
    - Too massive or too strong for the physical ice management techniques to handle
    - Too close to the critical zone, making the available window of physical ice management measures too short
    - Within the capabilities of the physical ice management program, but harsh conditions or failure in equipment causes the attempt to mitigate/eliminate the threat unfeasible
    - Detected inside the critical zone

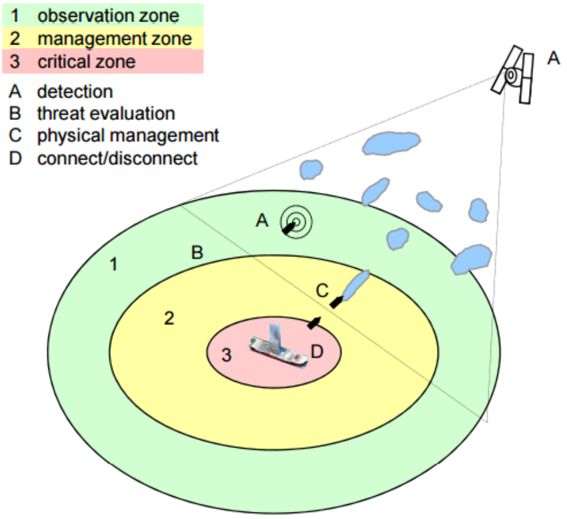

Figure 22 - Detection zones [55]

Another essential point in the evaluation of threat from ice-loads is the potential of accumulation around the installations. Especially sea-ice, considered to be within a manageable size for the installations to withstand, can accumulate and create enough force to exceed the limitations of the design. To be able to successfully evaluate the threats, the need for quality and reliable information is critical. The information must include the properties of the oncoming ice, and the availability and limitations of the techniques/equipment used for physical ice management. Risk assessments of every potential hazardous ice structures would be beneficial to avoid unwanted events.

An alert system, implemented with a purpose of heightening the safety level during operations, is common in ice-infested waters. An example of an alert system from the National Petroleum Council (NPC) is given in Table 1 below:

- Hazard Time (HT) – The amount of time before a hazardous ice-structure reaches the site of operation
- Secure Time (ST) – The amount of time required to kill the operation and to secure the well
- Evacuate Time (ET) – The amount of time required to disconnect from the mooring system and evacuate the location [57]

Alert Level	Time calculation	Action
0	HT - (ST + ET) = (> 24 hours)	Normal operations
1	HT – (ST + ET) = (< 24 hours / > 12 hours	Operate with caution
2	HT – (ST + ET) = (< 12 hours / > 6 hours	Restricted operations
3	HT – (ST + ET) = 6 hours	Secure well operations
4	HT – ET = 6 hours	Recover anchors
⬛	HT = (< 6 hours / > 2 hours)	Move rig

Table 1 [57]

5.3 Physical Ice Management

If an offshore operation is to be performed in an area of high probability of sea ice and icebergs, physical measures need to be taken in order to prevent the ice from damaging the offshore structure or causing unnecessary downtime to the operation. The application of physical ice management is only conducted after the ice surveillance and threat evaluation is completed. Once a hazardous ice structure is detected, there are two basic ways to mitigate or eliminate the ice-loads from causing direct or in-direct damage to the operation. One method is to break the ice structure into smaller pieces and thus reducing the loads to a manageable level. The other is to change the trajectory of the ice structure away from its collision course.

The amount of physical ice management required to run a safe operation and to keep costs due to downtime and repairs to a minimum, is depended on type of area, type of structure, time of year, available equipment, laws and regulations and several other factors. In the next sections, the general requirements for ice management and the different physical ice management techniques are presented. [23]

5.3.1 General Requirements for Ice Management Techniques

Physical ice management techniques are not only rated by their effectiveness in managing the threats from sea-ice and icebergs. If a specific approach would cause unacceptable damage to the environment, compromise the safety of the personnel or be extremely costly, it would not be considered a feasible technique. To evaluate the overall “rating” of each technique, these factors would be important to consider [23]:

- Safety
- Response time
- Environmental affect
- Complexity
- Limitations
- Equipment
- Cost
- Reliability

Safety

The main purpose of ice management is to ensure the safety of the personnel and the facilities. If the ice management technique endangers one of the above, the initial purpose of the system is lost and is thus meaningless.

Response time

Icebergs and sea-ice could be of such a significant threat that it would have to be mitigated/removed at an early stage, especially if the problem is detected late. It would then be imperative that the response time and speed of the threat-removal-process was sufficient.

Environmental affect

If the ice management technique has a negative impact on the surrounding environment, limitations of usage and area restrictions would probably apply.

Complexity

An uncomplicated method would be easier to implement and would save time and money on training of personnel. Low complexity would help increase the success rate

Limitations

The range in which the technique could be used. The technique would score poorly in this category if for instance environmental conditions like high waves or poor visibility were highly limiting factors.

Equipment

Low-priced, uncomplicated and easily replaceable equipment would be preferred.

Cost

The overall cost of the ice management technique would be a significant factor in the evaluation of its usefulness.

Reliability

The technique would have to be reliable in order to be of any value. [23]

5.3.2 Ice Breaking

The primary goals of the ice breaking technique is to reduce the size of the floes in moving ice up drift of a stationary installation or to make a path in front of other vessels/installations that are transported through ice-infested waters. Other usage could be in ports or terminals.

5.3.2.1 Azimuth Thrusters

The most significant advancement concerning ice breaking, following the traditionally propelled icebreakers, is the azimuth thrusters. The azimuth thrusters have been experienced to be more powerful for breaking ice than the hull of an icebreaker. The azimuth thruster method can be used both for breaking and for clearing of ice, as well as to blow away keels from first-year ridges. The method is based on exploiting the forces and the subsequent flow that the azimuth thrusters provide to break up the ice and to clear the area. Another advantage is the ability to remain stationary or move in any desired direction while managing the ice. The azimuth thrusters can be oriented in different directions and can thus be aimed towards selected spots. [56]

5.3.2.2 Patterns

In addition to the actual icebreaking capabilities, the pattern that the icebreakers choose can make a significant difference. Optimization of the shape of the patterns is highly dependent on the velocity, thickness and trajectory of the drifting sea-ice. For one ice regime, it could be sufficient to use only one pattern, while an ice regime with different dynamics could be handled more efficiently by the simultaneous use of two or three different patterns. There are several types of patterns used during an icebreaking operation, though the most commonly used patterns are as follows: [57]

- Linear Ice Management: The ice regime is broken into straight lines parallel to the ice drift direction, as can be seen from Figure 23. This type of pattern is highly suitable when the drift direction of the ice is relatively constant, when highly concentrated first-year-ice is moving quickly and when low concentrations of small ice floes have a high velocity.

Figure 23 - Linear ice management [57]

- Sector Ice Management: Figure 24 shows how the ice regime is broken up by an icebreaker moving from one side of the drift line to the other, thus creating a wider coverage inside a specific sector. This pattern is recommended when the drift direction change quickly, for pushing and breaking in thick and highly concentrated ridged ice and is a search pattern for ice in heavily reduced visibility.

Figure 24 - Sector ice management [57]

- Circular Ice Management – The pattern is based on the icebreaker running in circles, and can be performed around or up drift of the installation. The pattern, which can be seen in Figure 25, is typically used when breaking new ice near the installation, when the trajectory of the drifting ice is unknown or around the installation when ice drift is low.

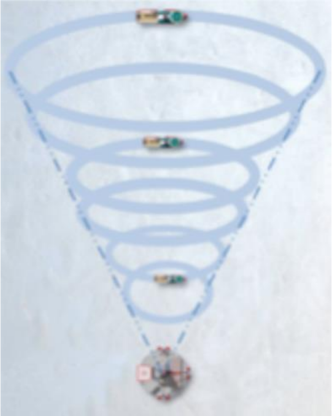

Figure 25 - Circular ice management [57]

5.3.2.3 Pushing

An alternative method to the icebreaking described above is the possibility of pushing the ice away from danger zones. In contrast to the icebreaking approach, this would remove the threat completely and would not leave smaller pieces becoming potential trouble at a later stage. By the use of one or several support vessels, relatively large ice floes can be deflected of course and out of harm's way. An important aspect of this type of physical ice management is to be certain that the removed threat does not drift back towards the sensitive areas after being deflected. [57]

5.3.3 Iceberg Towing

The purpose of iceberg towing is changing its original trajectory in cases where its path is headed towards an unwanted target. When an iceberg is detected and it is approaching a stationary offshore structure, iceberg towing is currently, and has been since the early seventies, the most commonly used method of deflection. The company owning the endangered offshore structure would normally call an independent ice management contractor to remove the threat. The towing could be done by either one or two vessels. The principle is the same, though if the iceberg is large and unstable it may require two vessels working together. The two types of vessels available are Synthetic Line Towing and Dual vessel Towing, further described in the following subchapters.

5.3.3.1 Synthetic Line Towing

In this technique only requires one vessel to carry out the towing operation. The towline is prepared at the tail of the vessel by attaching one end to a buoy and one end to the tow hawser by using shackles. The buoy is deployed and anchored at sea to increase drag and the vessel encircles the iceberg until it again reaches the buoy, as can be seen from Figure 26. The part of the towline attached to the buoy will then be connected to the same shackle as the other end. The winch will pay out a minimum of 100 m of towing hawser to sink the towing line. The hawser's purpose is threefold. Firstly, it decreases the overturning moment by allowing the tow force to be pushed closer to the iceberg's center of buoyancy. Secondly, in the event of slippage or breakage of the towline, the steel hawser would be in the water and thus reduce the recoil. Thirdly, if movement in the vessel or the sea overloads the line tension, it would serve as a shock absorber. [23, 20, 25]

A floating towline is typically 15-20 cm thick, 1200-1500 m long comprising of sections of 400 m - 500 m depending on the size of the iceberg and made of braided polypropylene. Offshore platforms are required to have a supply boat available on location and it would be advantageous if this vessel had the appropriate equipment for iceberg towing. The bollard pull on the vessel should be about 70-140 tones, which is not unusual for a supply vessel. The Anchor Handling Tug Supply (AHTS) vessels normally have bollard pull between 180-235 tones and are consequently able to tow larger icebergs. [23, 20, 25]

The process of deploying the towline is usually finished within a two-hour window, which is relatively fast. The towing process can however take up to three days due to the enormous masses of ice that occasionally emerge. The safety is upheld by keeping the vessel a great distance from the iceberg in case of slippage of the towline or the iceberg flipping over. An iceberg turnover can generate large waves that can harm the vessel. The submerged part of the iceberg can be extensive, thus be detrimental to the vessel if brought to the surface. The deck crew can be exposed to danger if the towline breaks and should stay away from the deck during towing. [23, 20, 25]

There are several advantages to this type of operation. The principles are simple and the equipment is easily obtained and repaired. If a supply vessel was used, the only cost would be to acquire the gear needed for the towing. Some extra operational costs would be required if an independent ice management contractor was hired, though the overall cost would normally be considered low in comparison to other ice management techniques. Additionally, the method has little or no negative effect on the environment. The gained experience through several decades of performing synthetic line towing-operations is a great advantage due to the increased number of personnel that is trained and familiar with the equipment. [23, 20, 25]

Unfortunately, the technique could be hindered by high sea, poor visibility, sea ice or size/shape/mass of the iceberg. If the iceberg is too large, the capacity of one vessel could be insufficient. If the iceberg is too small, there could be problems attaching the towline properly. However, smaller icebergs could be managed by using other techniques (ref. 5.3.4 and 5.3.5). [23, 20, 25]

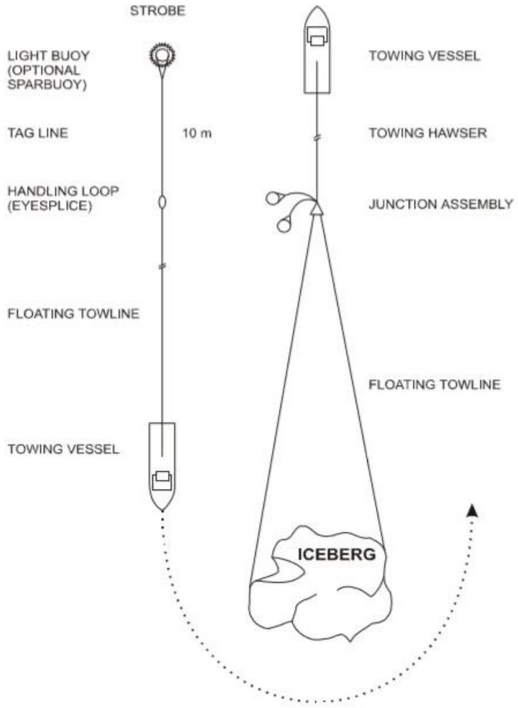

Figure 26 - Synthetic Line Towing [20]

5.3.3.2 Dual Vessel Towing

This iceberg deflection technique is similar to the synthetic line towing presented in 5.3.3.1. The major difference is the use of two vessels as opposed to one. A wire rope with approximately the same measure replaces the synthetic line and an additional steel hawser is needed for the added vessel. Dual vessel towing has the ability to tow larger icebergs due to the added force applied when adding a vessel. If the iceberg is unstable, this method is usually more effective than synthetic line towing. [23, 20]

The operation starts by aligning vessel nr 1 near the iceberg in the preferred towing direction. Vessel nr 2 backs up to vessel nr 1 and connects one end of the wire rope to the hawser on vessel nr 1. Figure 27 illustrates how vessel nr 2 circles around the iceberg and ends up next to vessel nr 1. The towing starts when the vessels are lined up and the thrust is balanced. The timeframe for the operation is similar to using one vessel, Though some increase in total time could be expected due to the the coordination of the two vessels. [23, 20]

Documentation of the reliability, effectiveness and safety of this technique is limited, though is expected to be similar to that of synthetic line towing. Compared to synthetic line towing it has two extra concerns. The balancing of the thrust from the two vessels and the depth control for the wire rope could prove challenging during the dual vessel towing. [23, 20]

The operating limits are also similar. High sea, poor visibility, sea-ice are all negative factors constraining the possibility of iceberg towing. Some additional cost due to two vessels consuming double amounts of fuel consumption are not considered significant, though the fact that the on-location supply vessel would not be adequate means that an additional vessel would have to be called upon. In most cases, the overall cost would thus be higher if using this technique as opposed to synthetic line towing. [23, 20]

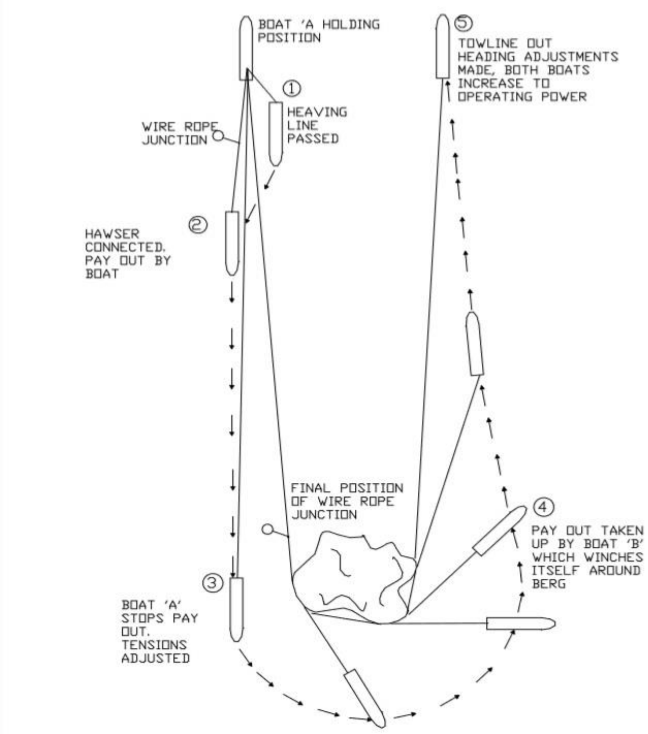

Figure 27 - Dual vessel towing [23]

5.3.4 Water Cannon

Small icebergs, bergy bits and small growlers are often difficult to tow away due to their small size. As shown in Figure 28, using a powerful water cannon as a deflection technique can thus be a sensible alternative and the approach has been proven through many years of experience. Although the water cannons original intent is to fight fire, the effectiveness on icebergs are undeniably sufficient and in later years they have been developed and installed specifically for handling icebergs. The cannons are normally installed on supply vessels and need to have a high capacity to be effective. A high capacity would mean volumes of approximately 3600 m^3/h, creating a velocity through the nozzles of almost 200 km/h. This approach can be useful for managing icebergs in several ways. Depending on the iceberg's size, shape and ice strength, the impact can break it up, deflect it into a new trajectory or start melting the ice. Also, hitting the water around it can cause forces and currents that would aid the deflection. To optimize the operation, it would be wise to direct the thrust of several cannons towards the iceberg, to have the cannons installed at the bow of the vessel and as close to the target as possible. The limiting factors are high wind speeds that can lower the applied force on the iceberg. Sea-ice surrounding the iceberg would also generally contribute negatively and the water cannons require full output from one of the vessels engines, leading to a high consumption of fuel. Otherwise this is considered a fairly inexpensive method, as the water cannons are usually already installed. [23, 20]

Figure 28 - Small iceberg deflected by powerful water cannon [96]

5.3.5 Propeller washing

Propeller washing is another deflection technique for small icebergs, bergy bits and small growlers. This technique is based on backing up to the ice mass and accelerating in the opposite way, using the backwards thrust from the water to “push” the ice mass into the desired direction. If done repeatedly, the propellers can create enough force to change the path of the ice mass. This approach does not require any extra/special equipment, is a low-cost operation and is environmentally friendly is an advantage. The operation is less effective in high sea and requires a skilled captain to maneuver the vessel. The key is to get as close as possible without actually hitting the mass. The downside of this technique is the risk of impact with the iceberg, the high fuel consumption and machine wear. [23, 20]

5.4 Disconnecting and Reconnecting Offshore Structures

If all of the preventive, mitigating or eliminating processes that are presented in the sections above have failed or been insufficient, a disconnection procedure of the installation is used as a last resort. Disconnecting from the well means downtime in operation and is extremely costly. The time spent on disconnecting/reconnecting varies between the different types of systems and rigs. Depending on the estimated time of arrival for an unmanageable ice-structure, the type of disconnection procedure is selected. It is normally differentiated between planned disconnection and emergency disconnection.

5.4.1 Planned Disconnection

A planned disconnection can be implemented if the detection and threat evaluation is completed at an early stage. The specific sequence for shutting down operation, disconnecting from the well and, in some cases, disconnecting from a mooring system would be different depending on the type of rig and the type of ongoing operation. The timeframe to stop the current activity, for most operations, would be somewhere between a few hours and a full day. One of the benefits of new designs of disconnection procedures is the reversibility option. All parts of the sequence can be reversed up to the final disconnect command, which is beneficial if there is uncertainty of whether or not disconnection would be needed. A planned disconnection should be designed so that the procedure can be completed without any damage to the equipment, and also to be able to reconnect in a safe and efficient way to minimize downtime. [59]

5.4.2 Emergency Disconnection

Having the ability to perform an emergency disconnection would provide the operation with an additional safety barrier. These disconnections should only be used if the required sequence for planned disconnection is not feasible due to lack of time. The advantage of an emergency disconnection is that it can be completed in about 15 minutes, the downside being the equipment damage and the increased time needed for reconnection. [61]

If the vessel is connected to a riser, there could be problems with potential recoil in the moment of physical disconnection. This is due to the riser being in tension during operation. Riser length and force applied would have an effect on the amount of energy rapidly released when the lower-marine-riser-package (LMRP) is disconnected. This energy could prove problematic, especially during an emergency disconnection, as there is insufficient time to reduce tension by decreasing mud-weight. Probability of stress damages to the riser would significantly increase due to lack of time to change physical variables such as sea state, riser mass and mud-weight. [61]

During a drilling operation, there might not be time to pull the drill pipe out of the hole. A shearing and dropping of the drill pipe would then be performed. The time consumed would be measured from when the operator pushes the button for emergency disconnect sequence until the LMRP is lifted of the blowout preventer (BOP). As part of this sequence, the well should be safely shut. As the drill pipe is dropped down into the well, a fishing and milling operation is often required before reconnection. In some cases, the well would be unrecoverable due to severe damages. [62]

6 OIL SPILL

Throughout the history of the oil & gas industry there has always been some kind of resistance from organizations related to environmental protection. Organizations such as Greenpeace have executed numerous protests by, for example, sending activists illegally on board oilrigs. The resistance is primarily based on the major damage a potential oil spill could inflict on the surrounding environment. The environment in arctic areas is especially vulnerable to such incidents and the battle for operating in some of these relatively undisturbed areas s tough. To get permission to operate in the Arctic, the companies have to document plans on how to prevent oil spills, recover spilt oil and minimize damages to the environment. [53]

There are several additional challenges related to an oil spill in the Arctic, compared to areas like the North Sea. The capabilities of oil spill detection, reachability, response and recovery can be significantly reduced by the presence of ice and cold temperatures. Natural evaporation of spilled oil will be dampened as a consequence of low temperatures. [54]

The oil & gas industry has performed research to develop oil spill response technologies and strategies for more than 50 years. The research consists of a large number of studies, experiments and fieldwork. To further develop the existing technology for arctic oil response, a Joint Industry Program (JIP) has been established. JIP is a group of ten international oil & gas companies that consists of Shell, NCOC, BP, Statoil, Total, ExxonMobil, Chevron, Gazprom-neft, Conoco-Phillips and Eni. A committee including representatives from each company coordinates the project and is assisted by the International Association of Oil and Gas Producers. The main objective of the program is to improve strategies and equipment, while enhancing the knowledge of the potential impacts of oil on the offshore environment. JIP has begun the process and is finished with what is referred to as “phase one”, comprising of a thorough determination of the technical existence and current standing of knowledge. “Phase two” will combine old data with new additional data for research in laboratories and in the field. To maximize the development of each individual issue, the program has been divided into ten separate projects. The projects are described in a list below [53]:

1. <u>Fate of Dispersed Oil under Ice:</u> To minimize the damage of an oil spill it can be advantageous to try to quickly dilute the oil into low concentrations. In open sea, turbulence in the water can help incorporate the oil and sweep it along its flow, consequently spreading the oil away from the initial position. In ice-infested sea, this

turbulence can be reduced due to overlaying ice protecting the water from wind forces. The project's objective is to predict the behavior of dispersed oil under ice-conditions and the possibility of unwanted oil accumulation under the ice. Predictions can be made by development of a detailed numerical model based on data gathered. [53]

2. <u>Dispersant Testing under Realistic Conditions:</u> Dispersion of oil can be increased by use of dispersant. A dispersant is a chemical mixture of solvents and other compounds that can lower the surface tension between two fluids, thus breaking the oil into smaller droplets for increased dilution. Tests have been conducted to investigate the dispersants performance level in cold waters for several different types of oil. The results were uplifting, as the effectiveness was more than 80 % in temperatures close to the freezing point. Researchers have also figured out that inorganic mineral fines along the shoreline can naturally produce oil mineral aggregates, which is helpful for oil removal. The assignment for Project 2 is to identify the operational limitations of the dispersants and fines in arctic conditions, and to establish which rules and regulations each arctic region should be required to follow in regards to dispersants and fines. [53]

3. <u>Environmental Impacts from Arctic Oil Spills and Oil Spill Response Technologies:</u> In the scenario of an oil spill, decisions between different response techniques have to be made. By using a tool called "Net Environmental Benefit Analysis", companies can be advised of which response technique is the most efficient. The purpose of Project 3 is to improve the tool and to improve the stakeholders confidence in the tool by reviewing the impacts of the oil spill and the impacts of the oil spill response technology used. The review is to include both the short- and long-term repercussions. [53]

4. <u>Oil Spill Trajectory Modelling in Ice:</u> To be able to minimize the impact of oil spill, the path of which the oil spill would move is of great importance. More importantly for arctic regions is the trajectory in ice-infested waters. This project will therefore modify a current ice-movement-model into a new model with increased accuracy on the behavior of ice. At the end of the project, it is anticipated that there will be a significant improvement in accuracy for oil spill trajectory models where ice is

present, as well as a coverage of uncertainties in the trajectory predictions. [53]

5. Oil Spill Detection and Mapping in Low Visibility and Ice: A quick oil spill response is dependent on information about the location and extent of the spill. There are many ways to detect and map the oil spill and a possibility of continuous update of the moving spill is essential. Many of the arctic characteristics, like darkness, low visibility and ice conditions interfere with oil spill detection. The task of this project is to increase and upgrade the capabilities of remote sensing and monitoring of oil spills in the abovementioned arctic conditions. There are basically two ways to perform a map-and-detect operation, either by surface remote sensing or by subsea remote sensing. Remote sensing of the surface consists of images and information given by aircrafts, vessels, satellites and installations. Subsea remote sensing is detection using Remotely Operated Vehicles (ROV) and Autonomous Underwater Vehicles (AUV). [53]

Figure 29 - Oil-Boom – Example of a temporarily floating barrier [100]

6. Mechanical Recovery of Oil in Ice: A vessel could be utilized for recovery of oil by using mechanical skimmers. The recovered oil can then be transferred to a storage vessel. This is the most preferred method of used for oil spill response as the removal of oil from the sea eliminates the possibility of the oil causing further damage. Containing the oil is important to maximize the recovered volume of oil in the water.

Containment is typically accomplished by application of floating barriers, such as the oil-boom shown in Figure 29.
The functionality of the mechanical skimmers is reduced in the presence of ice and in the cold climate, and improvements will have to be considered for maximum oil recovery. Equally challenging is the handling of the recovered volumes. The remote arctic areas are not ideal for transporting and disposal of these large quantities. [53]

7. <u>In Situ Burning (ISB) of Oil in Ice-Affected Waters:</u> The approach shown in Figure 30 is another efficient technique, where the oil is removed by controlled burning. If fire-resistant equipment is used to contain the oil causing it to form a thick layer, this technique can transform an average of 80-95 % of the oil to gas. The remaining percentages will remain as oil in the sea or as smoke (soot). The technique has been successfully used in arctic conditions and is considered one of the oil spill response technologies with the most potential for oil removal in arctic conditions. The project emphasizes the preparation, incorporation and acquired training of the technique. [53]

Figure 30 - In-Situ Burning [97]

8. <u>Aerial Ignition Systems for In Situ Burning:</u> Normally ISBs are ignited by simple devices that can be dropped by hand, but restricted arctic environments sometimes

require other techniques. The purpose of this project is to improve ignition systems to ensure that ISB can continue to be used for oil removal. New aerial ignitions solutions are expected to be developed to replace insufficient alternatives such as helicopters and fixed-wing aircrafts. The project group will bring in experts in aviation to present their views in the research process. [53]

9. Chemical Herders and In Situ Burning: The thickness of the oil layer is an essential factor when implementing the ISB technique. It can be advantageous to add chemical herders for the purpose of increasing the thickness of the oil in the 30-70 % ice concentration range. Two completed field tests in presence of sea-ice showed that chemical herders ensured an oil removal efficiency of more than 90 %. The main objective of this project is to extend the timeframe of which ISB can be applied in sea-infested waters and to simultaneously focus on the potential environmental impact of chemical herders. [53]

10. Field Research Using Chemical Herders to Advance ISB: This project will focus on further research of use of chemical herders from helicopters to enhance offshore ISB in ice conditions. Five field experiments will be executed in man-made basins for testing of ways to spray herders and ignite the released content. [53]

7 DISCUSSION

Although exploratory drilling and field developments have been conducted in the Norwegian Arctic for centuries, there are still several challenges to be handled, especially when moving further north. Examples of activity in the Norwegian part of the Arctic are:

- Snøhvit – A subsea gas field in the Southwest Barents Sea, which has produced natural gas since 2006
- Goliat – An oil field in the Southern Barents Sea expected to start production within 2015
- Johan Castberg – A discovered oil field 100 km North of Snøhvit in the Barents Sea with expected start of production 2022

The common denominator for all these fields is their location in waters considered to be ice-free year-round. Their distance from shore in regards to transport of personnel and SAR-operations are also within the range of the typical helicopters used in the North Sea. However, when operating in the region further north, the challenges will increase in size and numbers. The main challenges that have been presented in this thesis and that should be further resolved in the future of the Norwegian Arctic operations are cold, darkness/visibility, ice, distance to shore and lack of infrastructure, extreme weather conditions and communicational challenges.

The main challenges for the future operations in Norwegian part of the Arctic are:

- Ice management
- Logistics
- Emergency Response

It is important however, to understand the value of adequate communication, as communication plays a huge part in overcoming most of the challenges.

The remaining challenges that must be considered and strengthened are:

- Winterization
- Extreme weather (mainly polar lows)
- Surveillance, forecasting and collection of data
- Oil spill

In this chapter, pros and cons of some proposed solutions are presented and discussed.

7.1 Ice Management for Extended Seasonal Exploration Drilling in Ice-Infested Waters

Icebergs and sea-ice has not been a particularly troublesome problem for the operations that have been conducted in the Norwegian Arctic up until today. Thus the lack of experience regarding the handling of ice-loads in this region can prove challenging. Although icebergs are rare on the NCS, the presence of sea-ice in high-arctic and sub-arctic areas will force the need of ice management to some extent. The selection of vessel and the number of accompanied icebreakers will be decisive for the length of the drilling season. The sub-arctic conditions will be the next step in the Norwegian Arctic, and a decision has to be made regarding whether to prepare for all year round operation or to only prepare for operation during the ice-free months.

For exploratory drilling, it can be advantageous to operate in the ice-free summer months, with implementation of some ice management techniques to extend the season for as long as possible. To maximize the season length, the vessel must have the capability of quick transportation on and off the drilling site. It would be beneficial if the vessel had some ice-resistant/ice-breaking features that would allow it to move towards the drilling site whilst the sea-ice has started deteriorating. This would be advantageous towards the end of the season as well, as the drilling could continue despite sea-ice forming. [73]

The requirement of being able to drill a relief well within the drilling season must be taken into consideration. The lack of data and forecast reliability concerning sea-ice will reduce accuracy on estimated length of drilling season. This will be especially troublesome if the vessel is unable to operate in sea-ice. The drilling seasons will be based on approximate dates and this might lead the vessel to leave too early, losing valuable productive days. On the other hand, the abandonment might be too late if sea ice form earlier than expected, and the drilling of a relief well becomes impossible in case of a well incident late in the season. Therefore, will an ice-resistant capability or an adequate ice management program be advantageous for extending the season. [73]

7.2 Logistics and Emergency Response

The helicopters currently used do not have sufficient capacity to reach the outer blocks that have been opened for exploration by the authorities. This proves a problem both for transporting crews on and off the rigs, but also for the SAR-operations. An all-weather SAR

(AWSAR) helicopter is placed at Hammerfest to support the operations in the southern part of the Barents Sea. This has an operational range of approximately 340 km, though the distances required can approach 500 km for the northernmost blocks. [76]

The operational range can be extended by supply of more fuel. One way to do this is to add more fuel tanks to existing helicopters, though this would increases their weight and cuts the passenger payload. The other option is to land to refuel, which would require a helideck on either a vessel or a stationary installation. A vessel would be the most inexpensive solution, though movement of the vessel from high sea could prove to be troublesome and might lead to several unforeseen expenses in the long-term. It would thus be advantageous if the operating companies coordinated their drilling operations, such that blocks placed between the shore and the most distant blocks were drilled simultaneously, thus creating a natural possibility of refueling along the way. On the west side of the Barents Sea, Goliat has been proposed to serve as a refueling station for operations in northernmost blocks on the west side. The east side on the other hand, has no current solution for this challenge. There are possibilities of transporting personnel by boat, though this would be increasingly time-consuming, the boat could risk encountering problems at sea that the helicopter would avoid in the air. [76]

When activity is begun in areas outside the range of helicopters from the Hammerfest base, SAR-operations will become a major challenge. Rescuing people from sea can be achieved by man-over-board (MOB) boats if the accident is within the 500 m safety zone. However, if the accident is located outside the 500 m safety zone, there are currently no adequate alternatives available. Installations offshore need to consider employing a more skilled medical staff, increase equipment for medical care onboard and to be able to cooperate with hospitals for guidance. There might be a need for deployment of a dedicated emergency standby vessel, covering the areas of the helicopter routes. [6]

An international agreement, made exclusively for the Arctic region, was finalized in the spring of 2011 by the Arctic Council. The Arctic Council consists of the eight countries with boarders to the arctic region. The agreement deals with “search and rescue of aeronautical and maritime vessels and passengers” and is a way for the arctic nations to cooperate when dealing with SAR-operations. The agreement states that each nation has a specified area of which they are responsible for, which is shown in Figure 31. This cooperation will strengthen the possibility of achieving quick emergency response and efficient SAR-operations. [76, 63, 64]

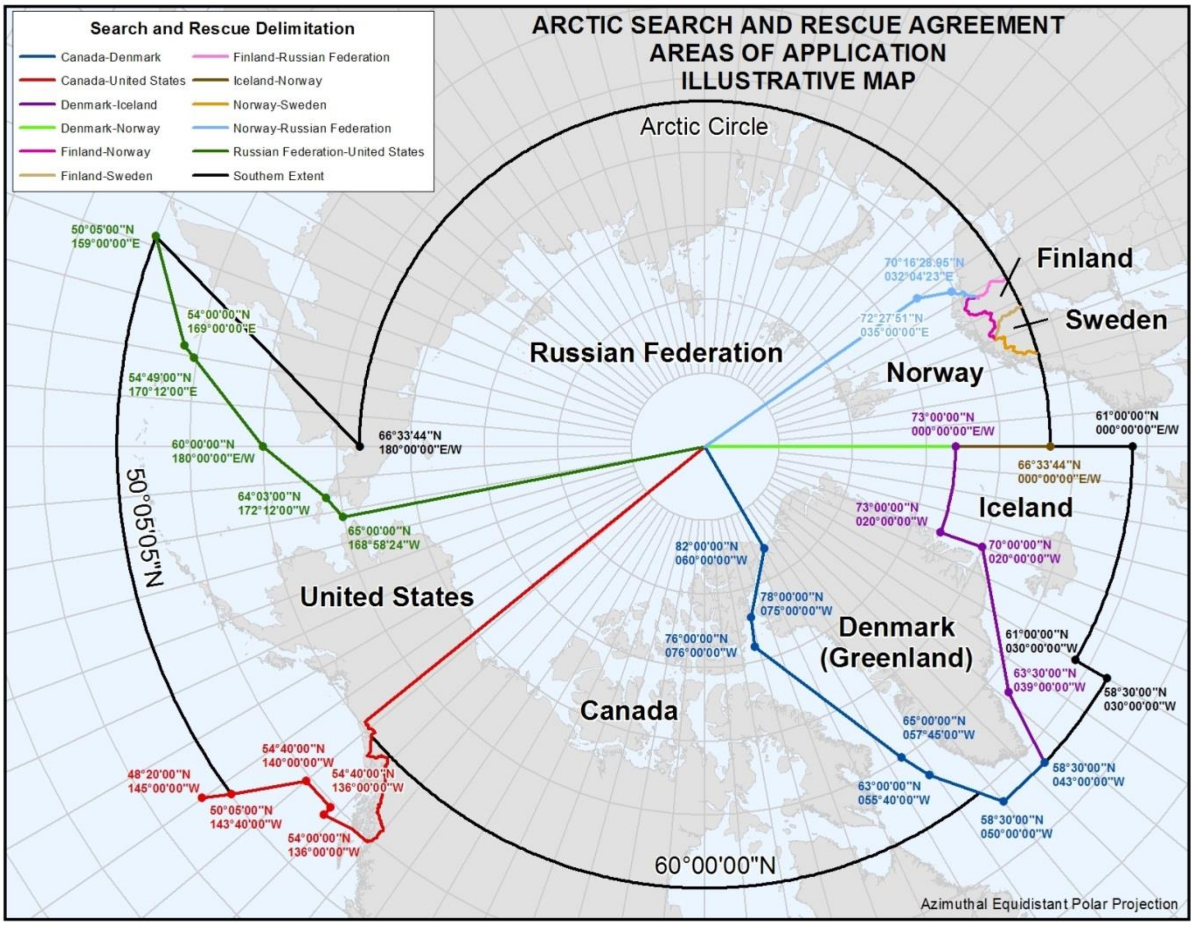

Figure 31 - Boundaries for SAR-responsibility [64]

Due to long distances, the time needed for supplying drilling consumables, spare parts, food and other equipment will be long and in some cases render supply impossible. A plan of moving all necessary equipment and materials to the location at the start-up of a project, can eliminate, or at least limit, the need for supply from an onshore base. The problem with this is that not every scenario can be planned for and unforeseen events that might require special/extra equipment, materials or personnel are bound to occur at some point. The amount of deck space available is thus decisive for the self-sustainability of the installations.

7.3 Communication

It is usually distinguished between radio and satellite systems for communicational purposes.

7.3.1 Radio System

Terrestrial radio systems like VHF (very high frequency) are used for communication purposes at sea all over the world. VHF is normally used for voice communication and the range is typically of relatively short distances, around the length of ones sight. Usually crewmembers carry one radio each, to be able to communicate during crane-operations (for example between roustabout and the crane operator) and drilling operations (driller-roughnecks). HF (high frequency) and MF (medium frequency) can be applied in the case of emergency and to transfer information about navigation, meterology and oceanology. Unfortunately, HF and MF are unable to follow the development in technology for IT and decision-support systems and lack the required digital capacity. Digital VHF and mobile phone systems, on the other hand, offer adequate digital capacity, but have to be within range of a base station. Offshore arctic locations are not within the range of such base stations and therefore this option is not available. [52]

7.3.2 Satellite Systems

Because the GEO satellites, which orbit around the equator, have little or no coverage in the Arctic, alternatives have to be established to ensure that the communication in the Arctic is stable and secure. There are currently two fully operational Global Navigational Satellite Systems (GNSS) available, namely the American GPS (31 satellites) and the Russian GLONASS (24 satellites). Two future GNSS, Europe's Galileo and China's Beidou, are in development and will be fully operational within the next few years. [51, 52]

Another satellite based telecommunication system, called Iridium, is the only system that has been able to maintain full coverage of the Arctic. This is a Low Earth Orbiting (LEO) type of satellite, orbiting much closer to the Earth than GEO-satellites (see figure). Despite of showing great potential, this has been reported to be unreliable with various shut downs and long reconnection periods. A system for offshore location positioning has been implemented by use GNSS reference stations. Precise Point Positioning can narrow down positions to within 0.1 m, and the only slight problem is the time spent to converge to this accuracy (30-45 minutes). [51, 52]

Although satellite coverage in the Arctic is currently inadequate, the future outlook is bright due to the modernization of old systems and development of new systems. It is expected that with the combination of over 100 satellites, creating a larger number of quality signals and by improving receiver and antenna hard- and software, these issues can be mitigated. [51]

7.4 Winterization and Measures for Mitigating Effects of Cold Temperature and Ice Accumulation on the Rigs

The winterization of the rigs has been successfully completed in the operations to this day. However, there is expected even harsher environments further north and the technology used today might not be adequate for the future. Emphasize must therefore be set on developing and improving the current technology while also figure out how to minimize the cost related to this.

Enclosing parts of the rig could eliminate or highly reduce the effects of the cold temperature, especially the wind chill effect. Enclosed derricks and other working areas could minimize outdoor activities and protect the personnel on the rig. Although enclosing areas is beneficial for protection, it can cause problems regarding the build-up of explosive environments. Normally the exposed areas are naturally ventilated by weather and wind, but when sheltered the natural ventilation must be replaced by a mechanical solution such as a Heating, Ventilation and Air Conditioning (HVAC). Especially in gas production scenarios, a sufficient ventilation system is highly important to prevent fires and explosions from occurring by an ignited leakage. [68]

Correct material selection for handling cold temperatures is essential. Stainless steels, titanium, aluminum and glass fiber reinforced plastic are more expensive materials, but are favorable in comparison with carbon steel. [68]

Preventive measures for ice accretion can be either to keep liquid water with freeze potential away from surfaces or to heat the surface sufficiently so that ice is not able to accumulate. There are several techniques to do this:

- Thermal methods
    - Electro thermal heating
    - Hot water
    - Infrared de-icing
- Coatings and chemicals
    - Coatings
    - Chemicals
- Mechanical methods
    - Manual removal

[25, 65, 66]

Manual removal by the personnel would seem the most inexpensive alternative, although such removal could be physically hard for the workers and the methods could damage the surfaces in the long-term. Heat tracing could be advantageous on pipelines, stairs, walkways and helidecks, especially along escape routes.

To protect the personnel from this cold environment one would have to provide warm clothing for the personnel, but as wearing too much clothes could potentially affect their work performance, it would be more advantageous to install heating and wind protection where possible. If areas were to be heated up, there would be an accompanying need for insulation and ventilation to reduce heat loss and prevent condensation build-up. Other measures could be to educate and train personnel to provide a better understanding of the conditions, as there is a high probability that the personnel has little or no experience of working in cold climates. [68]

A specialized survival suit has been made and tested in similar conditions that can be experienced in the Arctic. The timescale of locating people in such cold sea temperatures is significantly smaller compared to the North Sea. The suit is thus designed with increased isolation and the Personal Locator beacon can communicate with both the American GPS as well as the Russian GPS-system Glonass, to help rescue-teams locate people as fast as possible. [78]

7.5 Improved Forecasting and Preparedness for Extreme Weather

In the past, no models could adequately forecast polar lows due to the lack of available data and technology. To be able to deliver a detailed weather forecast with good reliability, the meteorologists need many measurements and observations, something of which is unfortunately lacking for the northern parts of the Earth. Especially the forecasting of polar lows is important for the Norwegian Arctic. The Barents Sea is considered to be one of the most prone areas for polar lows, and preparedness is key for protection against this unannounced phenomenon. Over the years, improvement in both satellite images and wind data has made it possible to make predictions of a higher quality. Although improvement has been made, there is still a need for further research to enhance awareness and confidence of forecasts. [6, 67]

7.6 Oil Spill

As for the rest of the NCS, the target for oil spills in the Norwegian Arctic is zero. Since this is a shared goal within the oil industry, there has been triggered an active cooperation between the operating companies through NOFO, the Norwegian Oil industries Oil Spill Responder, and common research and development programmes, as the Oil in Ice JIP.

7.7 Sub-Seabed Permafrost

In the Norwegian part of the Arctic, and particularly in the areas that are considered by the oil and gas industry, permafrost is not common. Although the challenges have been addressed, this subject will not be relevant in the first steps of moving further north on the NCS. However, this could be relevant in the future, when closing in on the areas around Svalbard or moving over towards onshore Russian territory in the southeast parts of the Arctic.

8 CONCLUSION

In this final chapter, a brief overview of what has been discovered during this thesis is presented, followed by a set of recommendations for the future activity in the Norwegian Arctic.

8.1 Introduction

The Arctic is considered to be the most environmentally, physically, technically and socially challenging areas in the world in regards to oil & gas operations. Due to the enormous hydrocarbon reserves that are expected to be found in this area, the industry is willing to make great efforts to overcome the challenges. The main objective of this thesis has been to present a thorough description and evaluation of the different issues and challenges the oil & gas industry is facing in the northern hemisphere, and to use this information and experience to prepare companies operating in the Norwegian Arctic.

The Norwegian Petroleum Institute is demanding, through their laws and regulations, that operations in the Norwegian part of the Arctic should be completed with same level of safety as in all other parts of the NCS. The criteria for offshore oil and gas activity in the Norwegian Arctic can be narrowed down to the following:

- Technical and operational challenges are overcome to ensure safe operation
- Social acceptance followed by political support
- Economic feasibility

Of the three abovementioned criteria, only the overcoming of the technical and operational challenges has been emphasized during this thesis. Challenges regarding ice, logistics and emergency response seems to be the toughest for future operations in the Norwegian Arctic. A common denominator for these challenges is the importance of reliable communication systems, which is a key for a successful operation. Ice management will be particularly challenging due to the fact that ice-infested waters has not yet been an issue for drilling in the Norwegian Arctic. The remaining two criteria are however equally important, as all the three criteria will have to be fulfilled simultaneously.

8.2 Recommendations

Moving the activities further north seems to be completed in a stepwise process for operators working in the Norwegian Arctic. The next phase would mainly consist of a further stepwise improvement and strengthening of personal protective gear for personnel and winterization measures that has been successfully used by the industry in today’s activities. There are however some specific challenges regarding logistics and communication of the northernmost blocks, which must be solved for exploration drilling to be started. The following considerations and recommendations might be useful for this purpose.

8.2.1 Cooperation between Government and Industry for Improvement of SAR, Surveillance and Communication

For optimization of SAR, surveillance and communication an active cooperation between government and industry is essential due to the lack of resources in the north. By working together there will be an increased possibility of finding a common solution. Creating committees and working groups where representatives from all participants from both government and industry are collectively solving the issues.

8.2.2 Coordination of Exploration Activities

Cooperation will be a key word when trying to overcome the vast challenges of the north. By coming together, the oil companies can coordinate exploration activities such that the challenges, resources and costs of emergency response, surveillance and communication are shared.

A dream scenario would be if three or four exploration rigs could conduct drilling operations simultaneously with a relatively short distance from each other. Economical potential would then increase significantly, as many of the benefits could be shared, as well as the costs.

A stationary vessel placed midway en route to the drill site with the sole purpose to provide refueling possibilities for helicopters, standby emergency response, supplies and strengthening of communication, could then be financed and utilized by all the participants. Increased number of supply vessels in circulation would mean less time waiting for consumables, spare parts and equipment sent from onshore bases.

8.2.3 Vessel selection

The essential attributes for a vessel for exploration operations in an extended season in sub-arctic environments would consist of quick transportation, ice-resistance capabilities, disconnection possibilities and an adequate self-sustainability. With these specific features in mind, a drillship would be a recommendable option for this type of operation. Especially if the concerns regarding its station-keeping abilities is emphasized and improved. A combination of turret mooring and a quality DP system would strengthen the weakness of this rig type.

There could be placed a specialized emergency response vessel, which had a designated AWSAR helicopter as well as equipment for handling a potential oil spill. Additionally, there could be placed a skilled medical staff onboard, with improved equipment for medical care and real-time communication with hospitals onshore for guidance.

8.2.4 Ice Management

The ice management program would consist primarily of icebreakers reducing the potential forces of drifting sea-ice. Although icebergs are rare and small in size in the Norwegian part of the Arctic, water cannons could be installed on the icebreaking vessels to be used for removing or mitigating an approaching iceberg. If several icebreaker are cooperating, it can be covered huge areas and thereby extending the drilling season even further.

8.2.5 Summary

To successfully fulfill the three points mentioned in the introduction of this chapter, there is no doubt that cooperation and coordination of operations in between operators and government will be of vital importance. The probability of completing safe operations will increase, and thereby save lives and protect the environment. This will win the acceptance of the society and politicians over time, by proving that operations can be conducted in a safe manner. The cooperation will also help divide the enormous costs that follows with operations in the Norwegian Arctic, making the economical aspect feasible.

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