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ENVIRONMENTAL RISK INFLUENCING FACTORS FOR PETROLEUM DRILLING IN THE WESTERN BARENTS SEA

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TEK-3900 Master's Thesis in Technology and Safety in the
High North

May 2013

PREFACE

The Master thesis is the final assignment for the two year Master of Science program, “Technology and Safety in the High North” at the University of Tromsø. The thesis is independent work and equivalent to 30 ECTS. Throughout my years of studying I have gotten a special interest for Arctic technology and the challenges regarding petroleum drilling and production in the region. This thesis will introduce environmental risk influencing factors related to petroleum drilling in the Western Barents Sea. Based on data of the environmental condition and accidents in the region, an overview of the risk influencing factors will be given. A discussion based on Acts and requirements related to the activity, existing technology, and the risk influencing factors are performed in order to evaluate the risk level related to the activity.

As a future engineer I am looking forward to take part of the Arctic technology development, and my aim is to contribute to make operations in the region as safe as possible.

I will here use the opportunity to thank for all the help that have been given me when writing and completing the thesis. Thank you, Per Olav Moslet and DNV Høvik, for giving me the honour to write my thesis in cooperation with you. I will also thank my supervisors at the university, Professor Tore Markeset and Professor Ove Tobias Gudmestad, for providing me with their knowledge about the topic and their advices in the project process. A special thank to Maneesh Singh, Kjetil Eikeland, and DNV Stavanger for giving me a desk at their office and making me feel welcome.

Tromsø, May 2013
Tina Sætrum

ABSTRACT

Offshore petroleum drilling in harsh and cold environment, like in the Barents Sea, can be challenging and risky due to the prevailing weather condition. How the physical environment affects systems, components, and working environment has to be enlightened in order to operate safely. The vulnerable environment, remoteness, and possible outcomes if an accident occurs are of great concern. The society, the regulatory authority, and involved industries such as fishery, expect and demand that the risk shall be in an acceptable limit.

The thesis will looks into one specific area in the Barents Sea; the location is south and east from the Bjørnøya Island. The main objective is to find important environmental risk influencing factors that influences the safety of petroleum drilling in the region. The purpose of this is to find vulnerable areas and to state if it is possible to achieve an acceptable risk level for drilling operation in the region. The scope will be to look at factors that may affect the drilling process. The thesis is delimited to only consider environmental risk influencing factors that may affect the topside drilling process. The methodology used in this thesis is mainly theoretical. It is a literature study where existing acts, regulations, experience, and technology regarding the topic is analysed and compared with the physical environment in the region.

The analysis performed in the thesis indicates that there is several environmental risk influencing factors that may influence drilling operations in the Western Barents Sea. The interaction of the risk influencing factors are complex and can in many situations have a negative synergy effect on systems, components, equipment, and working environment. Based on the risk evaluation performed in the thesis, the risk level for drilling operations will be within an acceptable limit if it is optimized. It is possible to reduce the risk to an acceptable limit if the drilling season is narrowed to summers or if winterized structures are used.

Keywords: Arctic, Risk, Barents Sea, Drilling, Petroleum, RIF, Influencing factors, Safety, Arctic technology, Cold climate

EXECUTIVE SUMMARY

The decrease in ice level at the poles during the last 50 years, and the increased global demand of energy supply has opened the eyes for the petroleum industry to explore in the region. Approximately 30 % of the world´s undiscovered gas and 13 % of the undiscovered oil are estimated to be located in the Arctic (Arctic Council, 2009). There is limited knowledge and experience about drilling operations in the whole Arctic, but this thesis looks especially into a region in the Western Barents Sea (WBS). The region is located southeast from the Bjørnøya Island (See Figure 1 p. 3). The main objective in the thesis is to enlighten important environmental risk influencing factors (RIF´s) when drilling in the WBS. The purpose of this is to find vulnerable areas and to state if it is possible to achieve an acceptable risk level for drilling operations in the region. This is the formulation of the problem:

What are the environmental risk influencing factors when drilling in the Western Barents Sea, and is it possible, with existing technology, to achieve a tolerable risk level in the region?

The environmental condition in the WBS varies and the weather is generally warmer compared to the rest of the Arctic. The thesis has used the weather station at the Bjørnøya Island as a reference for the environmental condition. The region has generally low temperatures and the variation can be significant. Low visibility from polar nights, cloud coverage, and fog is frequent in the region. The winter months are affected by polar lows. The occurrence of the polar lows is high and generally occurs from October to May. Sea spray is the most frequent and most hazardous form of icing on structures. Sea ice and icebergs do not occur every year in the region.

The Barents Sea contains relatively untouched marine ecosystems and the primary production is high. Several species of fish, sea mammals, and sea birds lives and breed there. This makes the environment vulnerable, especially if an oil spill occurs (WWF-Norge, 2003). Handling spilled oil in cold environment and ice-infested waters is challenging, and may to some extent be impossible (DNV Summer Project, 2012). In addition, the remoteness and lack of infrastructure in the WBS can lead to challenges regarding transportation and especially to search and rescue (SAR) and evacuation in case of accidents.

There is an underlying assumption that the petroleum operations in the Barents Sea shall be at least as safe as it is in the North Sea. This assumption demands strict monitoring and assessment of the risk level of the activity (Barents 2020, 2012). Risk combines the likelihood that a specific hazardous event will occur and the severity of the consequences of the event (Vinnem, 2007). This thesis identifies the factors that influence the risk, risk influencing factors (RIF´s). It is important to map the RIF´s in an early stage before any operation takes place. How the RIF´s influence a specific system, components, and working environment is valuable data that has to be considered (Gao & Markeset, 2007). There are 12 identified RIF´s and their occurrence throughout a year is varying. The months from October to May have 7 or more factors that can occur. July and August have only 2 possible RIF´s. The RIF´s found in the region are:

-Sea ice
-Sea spray icing
-Icebergs
-Fog
-Snow
-Atmospheric icing
-Polar night
-Icicles
-Polar lows
-Negative air temperature
-Negative sea temperature
-Wind

Throughout the years of experience with drilling in harsh and cold environment there have been developed both proactive and reactive barriers for environmental protection. These barriers are; enclosure of structure, anti-icing, reinforced hull, material and fluid selection, ice management, and de-icing. When designing for operations in the WBS it is important to consider the physical environment. Maintenance activities will for instance require proper lightning, and equipment has to be designed to tolerate high and sudden temperature changes (Markeset(b), 2008). The frequency of maintenance intervals may also be different from warmer environments. Human labour is important on a drilling structure. Low air temperatures and strong wind will set limitations for the personnel if no shielding is used (Markeset(b), 2008).

The uncertainty related to drilling activity in the WBS region is significant. The most vulnerable and exposed areas on drilling structures are:

-Open derricks
-Antennas
-Flare booms
-Windows
-Air intakes/vents
-Helicopter landing pad
-Handles, valves
-Legs and branching
-Fire fighting equipment, life rafts, lifeboats, rescue capsules, and windows

The risk analysis and evaluation in the thesis has looked into three different solutions for drilling operations. Solution 1 was for a year round drilling operation with standard structure, Solution 2 was for seasonal drilling, and Solution 3 was for a year round drilling operation with winterized drilling structure. The result from the analyse is:

- Solution 1 - The risk is in the ALARP zone, which means that it should be reduced to be as low as reasonable practicable. The environmental RIF´s can affect the availability and reliability of systems. Other challenges for this solution are: SAR operations, limitations regarding working environment, clean up of oil spills, and helicopter transportation. However, the risk during the summer months will be lower.
- Solution 2 – The risk will be within an acceptable limit. Seasonal drilling during the summer months will be less challenging If an unwanted event shall occur the SAR and evacuation will in most cases be easier to handle, and if an oil spill occurs it will be less challenging to clean up. However, annually variation should be expected.
- Solution 3 – Will be within an acceptable limit. This solution will give a better working environment for personnel and protection of technical systems. However, changes in reliability and failure rates of components due to low air temperatures can occur. Harsh weather can make helicopter transportation, SAR operations, and clean up of oil spills rough and at the same level as for Solution 1.

The risk analysis and evaluation accomplished in the thesis indicates that there are several RIF´s that may influence drilling activity, and that their interactions are complex and can in many situations have a negative synergy effect on systems, components, equipment, and working environment. Based on the risk evaluation in this thesis the risk level for drilling operations in the WBS region will be acceptable if it is optimized. It is possible to reduce the risk to an acceptable limit if the drilling season is narrowed to summers (Solution 2) or if winterized structures (Solution 3) are in use.

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TERMINOLOGY

ALARP	The risk level of a given activity should be as low as reasonable practicable. This means that the cost involved in reducing the risk shall not exceed the benefit gained
Availability	*Ability of an item to be in a state to perform a required function under given condition at a given instant of time or over a given time interval, assuming that the required external resources are provided* (Markeset(a), 2011, p.37)
Barrier	Technical, operational, organisational or other planned action that has the goal to identify and stop a chain of unwanted events
Failure	An event where a system or a component stops working or do not work as it is supposed to
Ice management	All the actions that reduce the frequency, magnitude or uncertainty from ice action
Load	Structural loads or actions are forces, deformations, or accelerations applied to a structure or its components
Major accident	*An acute incident, such as a major discharge/emission or a fire/explosion, which immediately or subsequently causes several serious injuries and/or loss of human life, serious harm to the environment and/or loss of substantial material assets* (Ptil, 2013)
Maintainability	*Maintainability is a measure that reflects how easy, accurate, effective, efficient, and safe the maintenance actions related to the product can be performed* (Markeset(a), 2011, p.31)
Reliability	A systems ability to perform its required function in a given time period and in a given physical environment (Markeset(a), 2011)
RIF´s	Factors that affect the barriers and the barrier performance
Risk	A combination of the probability of an unwanted event and its corresponding consequence
Unwanted event	Hazardous event that has the potential to damage or harm HSE, economical interest, or reputation
Winterization	To prepare a structure to the expected winter conditions
Western Barents Sea	The part of the Barents Sea that this thesis looks closer into (See Figure 1 on page 3). Bjørnøya is in the upper left corner of the region.

ABBREVIATIONS

ALARP	As Low As Reasonable Practicable
BOP	Blow Out Preventer
DNV	Det Norske Veritas
DP	Dynamic Positioning
HSE	Health, Safety and Environment
NCS	Norwegian Continental Shelf
n.d.	No data available
PR	Accretion prediction of sea spray ice
PSA	The Norwegian Petroleum Safety Authority
RIF	Risk Influencing Factor
SAR	Search and rescue
WBS	Western Barents Sea
WCI	Wind chill Index

1 INTRODUCTION

The Master thesis is the final assignment for the two year Master of Science program, *Technology and Safety in the High North* at the University of Tromsø. The thesis is independent and equivalent to 30 ECTS. In the Master thesis, the student should demonstrate knowledge about the research methodology presented in the program, as well as skills in scientific reflection and analysis.

1.1 Background

The decrease in ice level at the poles duting the last 50 years and the increased global demand of energy supply has opened the eyes for the petroleum industry to explore in new regions. The reduction in sea ice concentration has made the hydrocarbon resources in the region more accessible and easier to produce. The U.S. Geological Survey published a report in July 2008 that indicates that one-fifth of the remaining oil and gas resources in the world are located in the Arctic. Approximately 30 % of the world´s undiscovered gas and 13 % of the undiscovered oil are estimated to be located there (Arctic Council, 2009). Most of the resources are offshore at water depths less than 500 m (Løset(a), 2011). This potential great resource of hydrocarbons makes it reasonable to believe that exploration in Arctic waters will increase even more in the future, and it has already started. The Snøhvit field, owned by Statoil, has been in production since 2006, and Eni Norge is soon to start their production at the Goliat field. There is also planned production at both Stockman and Skrugard in the Barents Sea in the near future. As a result of the division of the Barents Sea in April 2010, many companies in both Russia and Norway have gotten an increased interest for the Barents Sea region and the opportunities there.

In 1859 the first oil well was drilled in Pennsylvania USA, this event has been a major contributor to form the basis of the modern drilling today. In 1966, the first drill rig came to Norway in the search of oil. The December 23rd 1969 was the first discovery of oil made on the Norwegian continental shelf (NCS), it turned out to be a giant discovery and is today called the Ekofisk field. Production from the field began in 1971. In the beginning there were no clear guidelines or safety requirements for such activities, and the companies did what they wanted and what eventually would lead to a maximum production in the shortest time possible. This struggle to get the highest profit led to numerous accidents and losses of life. The capsize of the Alexander Kielland rig in 1980 led to major changes in the Norwegian petroleum industry, and has probably been one of the reasons why Norway today is a leader in safety in the industry (Norsk olje og gass, 2010). Accidents like Piper Alpha in 1988 (Cullen, 1990) have also been contributor to the priority of safety and emergency preparedness for the industry. The fatal consequences and damage to HSE, reputation and financial assets has been an eye-opener for people's perception of risk and industry priorities for risk reduction.

Operators at the Norwegian continental shelf is responsible to verify that they are within the requirements set by the government, and have since 1985 been based on internal regulations and functional requirements. In the 1970s, the system was made up of detailed requirements that were set by the Norwegian Petroleum Directorate. A minimum risk, an event rate of less than 10^{-4} came in the 1980s, and a strong focus on methodology and requirements became a trend. In 1990s the focus was on using risk analysis to make decisions and solutions. This led to a greater focus on the ALARP (as low as reasonable practicable) principle and risk reduction over time, in terms of the technological innovation and experience. In the 2000s it became a greater focus on major accidents and today operators have to formulate risk acceptance criteria for major accidents (Aven & Vinnem, 2007).

Moving the drilling activity from the NCS and further north to the Arctic will introduce new and additional challenges and new strategies might be needed. Extreme environmental conditions such as: low temperatures, icing, sea ice, and long periods of darkness can lead to operational challenges. Insufficient oil spill preparedness resources and long distances to infrastructure will also present operational challenges. Unless all these above factors are compensated for, they are likely to increase the frequency of accidents and the environmental consequences. In worst case the consequences to the environment and subsistence economy activities may be irreversible (Hasle et al., 2009). One of the main topside challenges will be regarding protection of personnel, equipment, and operation systems and components. These challenges are taken care of through winterization actions. These winterization challenges demand new innovation, knowledge and experts in the field. In addition, the lack of infrastructure and generally remoteness is dominating, this will give helicopter transportation, search and rescue operations a higher lead-time.

When performing operations in harsh and cold climate and in ice-infested waters, reliable information about the surrounding environment is essential to perform safe operations (Haugen et al., n.d.). The vulnerable environment, remoteness, and possible outcomes if an accident occurs are of great concern. The society, the regulatory authority, and involved industries such as fishery, expect and demand that the risk shall be within an acceptable limit.

1.2 Objectives

The main objective in the thesis is to enlighten important environmental risk influencing factors when drilling in the Arctic, more specific in the Western Barents Sea. The purpose of this is to find vulnerable areas and to state if it is possible to achieve an acceptable risk level for drilling operation in the region.

Sub-objectives for the thesis is to find the safety requirements for drilling operations and what technology in form of barriers that are used in the industry today. Study the: vulnerability, remoteness, operational and maintenance challenges, together with previous accidents from the region are also sub-objectives for the thesis.

1.3 Research Questions and Formulation of the Problem

Based on the presented background information, gaps in the existing knowledge and information have been found. This thesis will look closer into some of the gaps. The location that this thesis looks into is in the Western Barents Sea. Five research questions have been developed, and they are:

- How is the environmental condition in the Western Barents Sea?
- What are the safety requirements for offshore drilling in the Norwegian sector?
- How does the physical environment affect topside drilling operations in the Western Barents Sea?
- Is it possible, with today’s technology, to achieve an acceptable risk level when drilling in the Western Barents Sea?

Based on the research questions and objectives for the thesis a formulation of the problem has been developed. The formulation of the problem is:

What are the environmental risk influencing factors when drilling in the Western Barents Sea, and is it possible, with existing technology, to achieve a tolerable risk level in the region?

1.4 Delimitations

This thesis looks into the environment and risk influencing factors of a specific region in the Western Barents Sea. The Western Barents Sea is a part of what ISO 19906:2010, classifies in category 1, West Barents Sea. The red section in Figure 1 illustrates the specific region that this thesis especially will enlighten. Bjørnøya is in the upper left corner of the marked region. The total area is approximately 176 km². This specific region is selected because of the increasingly activity further north in the Barents Sea, and the selected region is today in the zone of being explored in the near future.

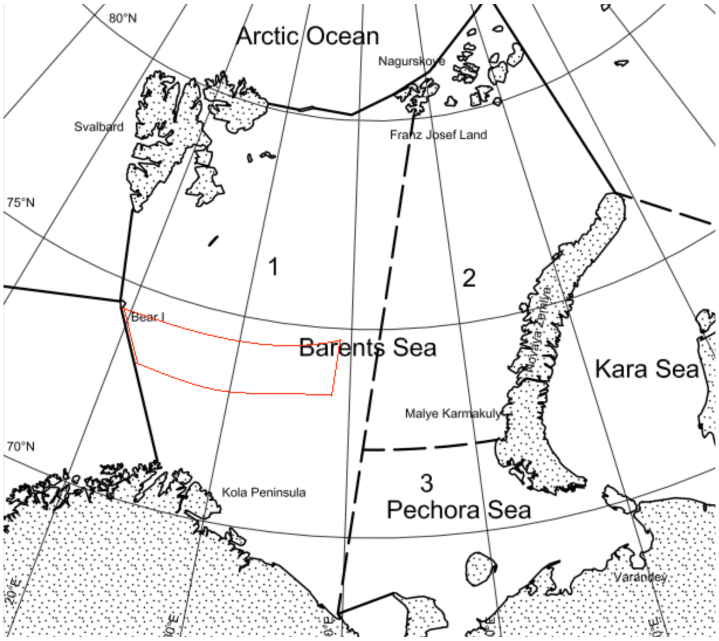


Figure 1: The Barents Sea divided into different sections (International Standards, 2010, p.404).

The thesis is also delimited to only consider the additional risk to topside operations due to the physical environment. Challenges regarding well and well control in the region will be excluded. The list below introduces other delimitations for this thesis:

- The thesis will only consider environmental risk influencing factors related to the drilling process, and not risk influencing factors such as organisational or human related.
- The thesis will focus on challenges related to topside. Environmental loads in the well and on the equipment there will not be analysed.
- The thesis will not evaluate the risk related to major accidents from earthquakes and tsunamis.
- The thesis will not consider risk perception in the local communities or the society.

1.5 Limitations

Limitations for the thesis are due to the field of study of the author and available information regarding the topic. The author is a safety and risk engineer and the scope of the thesis will enlighten the knowledge gained throughout the study. As a result of the limited data and experience available related to drilling activity in the Western Barents Sea, there have been challenges regarding establishment of data and the performance of in-depth analysis. The thesis has only used public available data with no restrictions.

The weather data used in the thesis do in general present the weather condition in the Western Barents Sea region during the last decade. Regarding the wind speed, only data from the previous year (2012) have been found and used. These relatively short time periods that present most of the weather data, may have resulted in that not the most extreme situations that can occur in the region have been presented.

Since the Arctic petroleum development is a relatively new and hot topic it is reasonable to believe that there exist more information regarding the topic than what is published and presented in this thesis. It is assumed that there exists confidential information about design of new technology and how to, in a safely way, withstand the environmental loads.

The validity of the analysis is relying on the educational experience of the author and the available data used in the research. The scientific papers and other sources used in the thesis are evaluated to be reliable due to their authors or publisher’s acknowledgement and previous work or experience.

1.6 Method

The methodology used in this thesis is mainly theoretical. The thesis is a literature study where existing experience and technology regarding the topic is analysed and compared with the physical environmental in the region. Both quantitative (quantifiable data) and qualitative (descriptive data) data have been used. The quantitative data is mainly weather data from the Western Barents Sea and the quantification in the performed risk analysis.

The thesis has used both primary and secondary data. Primary data is the data collected by the author to conduct the analysis in the thesis. The primary data in thesis are personal conversations with experts. Most of the data used is secondary data. The secondary data is collected by someone else than the author and often has a different scope or intention (Blumberg et al., 2011). The secondary data used in this thesis are: relevant books, reports, published papers, weather data, standards and regulations, and lecture materials. Both the primary and secondary data are important resources and contributors to the thesis.

The thesis has a deductive approach for the adaption and development of data. This approach is characterized with that theory is used as a basis to make empirical data (Jacobsen, 2005). The thesis uses the statement, that drilling operations in the Arctic region are more challenging compared to operations in warmer climate, as a basis when collecting data and find factors that improves this. Presenting empirical data in form of weather data from the region, experience data, and accident data, will confirm this statement.

Calculations have been done to quantify how harsh and cold the environment in the Western Barents Sea is. The calculation is used to exemplify how the conditions in the region can be and how much it can influence the safety and operations on a drilling structure.

Based on the collected information about the environmental condition in the Western Barents Sea region, risk and barriers, experience, and existing technology a risk evaluation of drilling operations in the region has been accomplished. The analysis of the risk is both qualitative and quantitative and is presented in a risk matrix. The already existing data from the literature, the weather data, the regulatory requirements, and the risk analysis together, is the foundation for the conclusion. The result of the analysis is used as a basis for evaluation of the acceptance of risk level for drilling activity in the Western Barents Sea.

1.7 Thesis Outline

In the beginning of the thesis the topic will be presented in general and after divided into different sections. The Western Barents Sea challenges, drilling challenges and regulations, and risk will be explained separately. In the evaluation the different topics will be discussed and evaluated all together in order evaluate the risk level of drilling operations.

In *Chapter 1* an introduction with objectives and delimitations to the thesis is presented. *Chapter 2* presents the necessary theory for topside drilling operations in the Western Barents Sea. Important terms and factors that affect the safety and vulnerability for the region will be introduced. Information about barriers, risk, environmental condition in the Western Barents Sea and topside drilling systems will be presented. Information about previous offshore accidents in the region and drilling experience will also be given. *Chapter 3* will state how harsh the physical environment in the Western Barents Sea is. The chapter contains information about the expected environmental loads and the risk influencing factors will be discussed. Some calculations will be presented. *Chapter 4* will present information about existing barriers for environmental protection for drilling structures in use today. For illustration a bow tie will be shown in the end. *Chapter 5* will present operation and maintenance challenges for drilling operations in the region. The chapter will also include information about working environment and support. Analysis and evaluation of the risk level for drilling operations in the region will be presented in *Chapter 6*. Comparison with physical environment in the North Sea, existing barriers, and risk picture of today’s situation will be presented. To finish the thesis the conclusion and recommendations is presented in *Chapter 7*. References and appendices are in the end of the report.

2 DRILLING OPERATIONS IN THE WESTERN BARENTS SEA: EXPERIENCE, KNOWLEDGE, AND CHALLENGES

This chapter will present necessary theory for topside drilling operations in the Western Barents Sea (WBS). Important terms used in this thesis will be introduced. Information about the environmental condition in the WBS, barriers, risk, and topside drilling systems will be presented. Information about previous accidents in the region and drilling experience will also be given. The quote below is from IMO´s *guidelines for ships operating in Arctic ice-covered waters* (2002), and states some of the operational challenges in the region. Many of the factors are applicable for drilling structures too.

> *Ships operating in the Arctic environment are exposed to a number of unique risks. Poor weather conditions and the relative lack of good charts, communication systems and other navigational aids pose challenges for mariners. The remoteness of the areas makes rescue or clean-up operations difficult and costly. Cold temperatures may reduce the effectiveness of numerous components of the ship, ranging from deck machinery and emergency equipment to sea suctions. When ice is present, it can impose additional loads on the hull, propulsion system and appendages* (IMO, 2002, p.2).

2.1 Drilling Experience

This section will present information about drilling experience from the Arctic region. Information about winterized drilling structures that are in use today and a brief introduction of different environmental loads that a drilling structure can face will be given. As a result of the limited drilling experience from the Western Barents Sea (WBS) region, information about the whole Arctic will be given.

There is a large extent of equipment, regulations and procedures involved in a drilling process. This section will only introduce the basic and most important aspects in order to have the terms clarified when used later in the thesis. Since the thesis only consider the topside loads from the environment, details regarding drilling operations and well stability will be excluded.

2.1.1 Drilling in the Arctic

Offshore drilling and production activities in ice-covered waters started in the 1960's, more site specific in the Cook Inlet, Alaska. In the region the sea surface routinely freeze for a couple of months every winter. After the first step of exploring the Arctic, different types of offshore structures like oil platforms and vessels have been deployed and used in high latitude seas (Yue, n.d.).

Compared to drilling operations in other regions, drilling safely in the Arctic require a different strategy regarding decision of structure. To protect and enclose exposed working areas and equipment from harsh and cold environment is essential. In most Arctic operations (including drilling, production, and offloading of hydrocarbons) moored floating vessel concepts tend to be the most attractive solution. Effective ice management and reliable shut down procedures reduces the challenges with ice conditions. One main challenge is to extend the operability time and the reliability of the concepts (Bonnemaire et al., 2007). Management tasks of drilling operations in the Arctic have to be in place at an early stage of a project. The management includes selection of contractors for ice management, drilling operations, core handling and curation, identify safety hazards and develop contingency plans, and organise logistics (Hovland, 2001).

Gudmestad and Quale (2011) have stated some challenges regarding development of new fields in the Arctic region. This increased uncertainty will require more research in the planning phase for the field development.

> "*… There may be technical challenges with well positioning and directional drilling in new areas with unstable formations and little knowledge of rock behaviour. Well positioning based on magnetic and gyroscopic directional technique in High North regions is associated with 4x the uncertainty at equator and 2x the uncertainty in the North Sea"* (Gudmestad & Quale, 2011, p.14).

2.1.2 Drilling structures and systems in general

There are two main types of structures that can be used to drill a well offshore, fixed structures and mobile structures. Mobile structures or drill ships are basically designed as the fixed structures, except that here the wellhead and the *blowout preventer* (BOP) are mounted on the sea bottom, below the floating platform. The BOP is a safety valve used when drilling. The BOP consists of a stack of different closing mechanisms to close or shut down the well, if needed. If a moveable drilling structure drifts off the drilling location, the riser can be disconnected rapidly from the BOP in such a way that the flexible connection and the riser are not damaged. The unwanted drifting can happen due to bad weather or errors in the navigation system. Before the disconnection starts, the BOP will be activated and closes the well completely. This is the main reason why the wellhead and the BOP are mounted on the sea bottom (Skaugen, 2012). Figure 2 shows a sketch of a drilling structure and the typical placement of equipment and modules. It is normal to place the drilling and production systems in one part of a structure and the living quarters, evacuations stations, and helideck in the opposite.

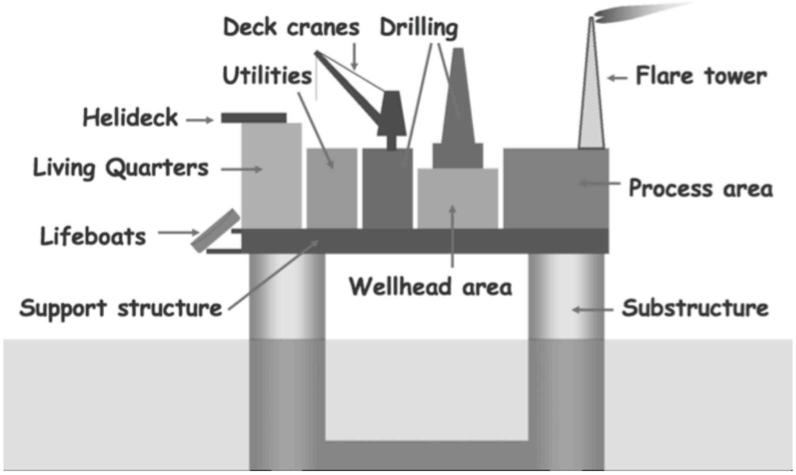


Figure 2: Sketch of a drilling and production structure (Odland, 2012, p.23).

Figure 3 shows roughly the equipment placed on the *drill floor*. In traditional drilling a steel beam tower, called derrick, is used. The derrick is mounted on the drill floor, and the height of a derrick is typically around 60 m. All equipment for handling, storing and operating the drill string is in, on or above the drill floor. Below the drill floor is the *pump floor*, where equipment to mix, clean, store and pump drill mud is found (Skaugen, 2012).

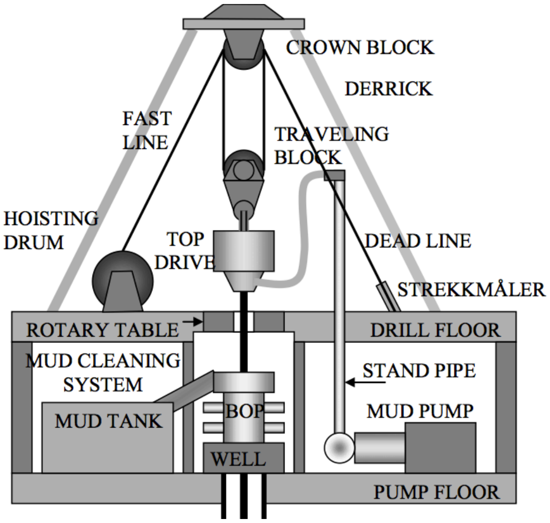


Figure 3: Sketch of equipment on the pump and drill floors (Skaugen, 2012, p.4).

2.1.3 Winterized drilling structures

In order to select an adequate drilling structure for operations in harsh and cold environment, the environmental condition at the given location has to be analysed closely. Hovland (2001 p. 29) have presented a list, which include general requirements for a drilling structure capable of operating in the Arctic sea ice. The list is as follows:

> "*1. Dynamic positioning (DP)*
> *2. High-Arctic ice-class*
> *3. An adequate moon pool with a reinforced deck capable of supporting a drill rig*
> *4. Sufficient deck space for drilling, coring, logging equipment, and tools*
> *5. Provision for modular laboratory containers, including provision of services (water, fuel, power etc.)*
> *6. Sufficient accommodation for crew and scientists*
> *7. Helideck and other appropriate navigation and safety features for Arctic work*"

The DP is especially needed in deep waters where mooring is not an option. Presence of ice may affect the stability of a floating unit. Ice-class is mainly reinforced hull at the unit. Drilling in drifting ice require careful planning and ice management. One of the main considerations is movement of the drilling structure. The maximum allowable lateral movement of a unit should be calculated. This factor decides how much response time the operator has before a decision has to be taken. A unit with low acceptance of movement requires fast decision-making (Hovland, 2001).

It is important to distinguish between exploration drilling and production drilling. If production drilling is the goal a more permanent solution might be desirable, whilst for exploration drilling a moveable structure is the best solution. Other factors that influence the choice of solution is the water depth, expected ice load, and expected lifetime of the production well. There are several winterized drilling structure in use today and they are especially designed for the expected challenges in the Arctic region. Figure 4 shows pictures from different floating drilling structures that are in use today. The units are partly or fully enclosed in order to protect the working area and equipment.

Figure 4: Winterized floating drilling structures, Arctic Semi-rigid Floater, Henry Goodrich, Kulluk, Tempera, and Ocean Odyssey (IMVPA, 2008, pp.72,77,135,107,137).

Table 1 presents all types of drilling and production units that have been or are in use in the Arctic waters. The list is from 2008 and may not be fully updated. The characteristics and concepts of the different solutions will not be explained in detail. The only units that had been in use in the Barents Sea by that time were the floating structures, SPAR and Tension-leg. These solutions are often used in regions where the water depth is several hundred meters. Both of the solutions are moored to the seafloor and can quickly disconnect if needed.

Table 1: Summary of Arctic Cold Regions Exploration & Development Options (IMVPA, 2008, p.151).

	Region												
	US Beaufort Sea	Chukchi Sea	Bering Sea	Cook Inlet	Can. Beaufort Sea	Can. High North	Can. East Coast	Offshore West Greenland	Barents Sea	Kara Sea (Gulf of Ob)	Pechora Sea	Baltic Sea	Sakhalin Island
Bottom-Founded & Fixed Type Structures													
Gravity-based structure	X	X	X		X		X			X	X		X
Mobile bottom-founded	X				X					X			
Barge			X		X								
Jacket / Monopod			X	X			X						
Jack-up			X	X			X						X
Gravel Island	X				X								
Caisson-retained island					X								X
Ice Island	X				X								
Floating Structures													
FPSO / FSO			X				X	X					
SPAR platform							X		X				
Tension-leg platform							X		X				X
Semi			X	X			X	X					X
Drillship	X	X		X	X		X	X					
Floating ice pad						X							

2.1.4 Loads on structure

Environmental loads on drilling structures have to be considered before any drilling operations can be done. It is normal to divide the different loads in different categories. This thesis will only consider the categories that the environmental loads belong in. Figure 5 shows a scheme of a structure design. The figure also shows how the environmental loads are considered in the design of a structure.

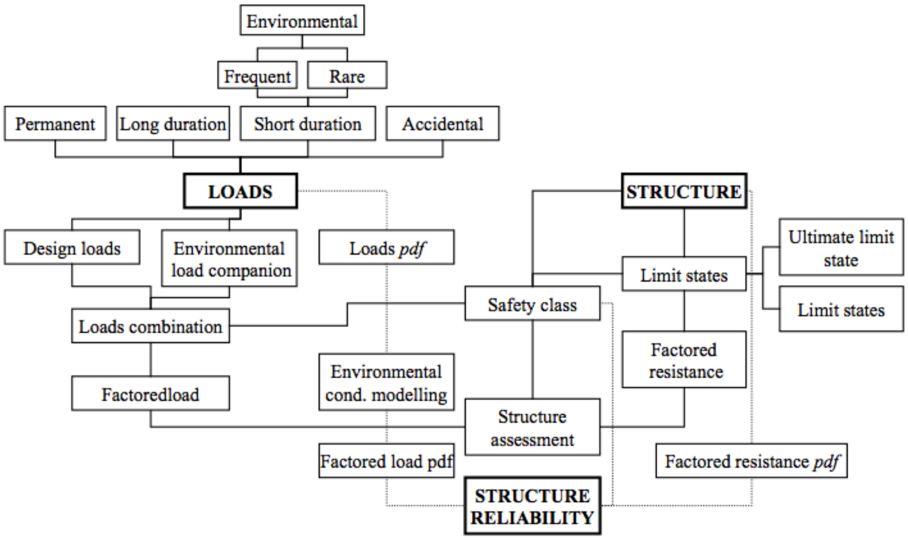


Figure 5: Scheme of structure design (Løset & Høyland, 1998, p.94).

Environmental loads are a part of the category *Short duration loads*. These loads occur with duration of seconds, minutes or hours. The category is divided into two sub categories, *Frequent Environmental Processes* and *Rare Environmental Processes*. The frequent category includes loads from wind, waves, currents, tides, and snow and ice accumulation. Rare processes include earthquakes, icebergs, sea ice, and tsunami. The categories are also divided in groups according to the annual probability of exceedance (APE). The frequent processes should not have an APE grater than 10^{-2} and the rare processes should have an APE in the range between 10^{-4} - 10^{-3}. Special (accidental) loads is a category that includes collision, explosion, dropped objects, etc. (Løset & Høyland, 1998).

Snow and ice accumulations expose structures for loads. Figure 6 shows in general where different ice types can be expected on a drilling structure. Heavy ice and snow concentrations can clog important and vulnerable systems, and in worst case it can clog ventilation systems or change the centre of gravity on the structure. Changes in the centre of gravity can lead to capsizing.

Figure 6: General locations where atmospheric icing and sea spray icing would be expected to occur on a drilling structure such as Eric Raude in the figure (Ryerson(b), 2008, p.12).

Figure 7 shows the different motions that a floating structure is exposed to. The oscillatory rigid-body translator motions are surge, sway, and heave. Roll, pitch, and yaw are the oscillatory angular of the different axis. The motions impact differently depending on type of structure (Faltinsen, 1990). Heave motion is a limiting factor for drilling operations. The vertical motion of the riser has to be compensated and there are limits to how much the motion can be compensated. According to Faltinsen (1990) the heave motion should be less than 4 m. In order to be available to drill most of the time it is important to design the structure so that it will not exceed this value.

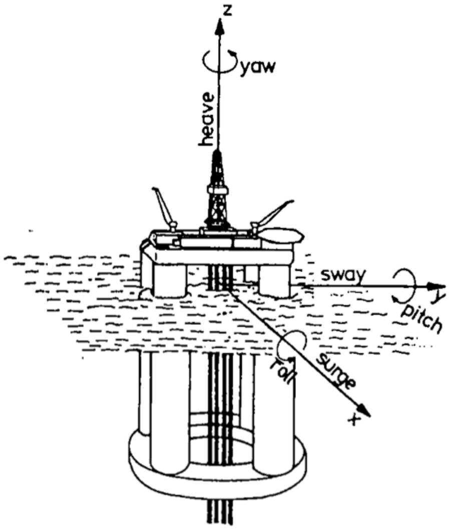


Figure 7: Motions of a floating structure (Faltinsen, 1990, p.3).

2.2 Physical Environment

The climatic condition in the Western Barents Sea (WBS) varies and the weather is generally warmer compared to the east and northern parts of the Barents Sea and the rest of the Arctic (Thelma, 2010). The water depth in the WBS is varying from 0 at Bjørnøya to around 450 m. The average water depth is between 250 m and 350 m (Google Earth, 2013).

Regarding environmental conditions in the region, measurements from the Bjørnøya Island will be used. Bjørnøya is located at 74.30 ° N 19.01 ° E, about midway between mainland of Norway and Svalbard. Detailed information about the environmental condition will be presented in the following sections.

2.2.1 Temperature

The temperature is generally higher in the WBS than in other regions in the Arctic, this is mainly as result of the Norwegian Atlantic Current, which is transporting heat from the southern Atlantic, along the Norwegian coast, and up to the Barents Sea (Sundsbø(b), 2011). The effects of temperature shall be evaluated when selecting structural materials, machinery lubrication, sealants, or topsides winterization. The effects of thermal changes on structural behaviour shall be considered as part of the design and operation of the structure (International Standards, 2010).

In order to illustrate how harsh the weather can be in the WBS, the lowest air temperature measured at Bjørnøya in the time period from 2002 to 2012 is presented in Table 2. The lowest air temperature is defined as the lowest measured air temperature in the time period. The month normal air temperature from 1961 – 1990 is also presented. The normal air temperature is average temperature over a specific 30-year period (normal period) (met.no, n.d.).

Table 2: Lowest measured air temperature in the given month and month normal air temperature, at Bjørnøya (met.no, n.d.).

Lowest air temperature [°C] at Bjørnøya												
Year	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
2002	-18	-19,4	-17,5	-4,9	-5	0,9	2,6	3,4	-1,9	-4,5	-6	-16,1
2003	-22,6	-13,4	-20	-16,7	-10,1	-3,1	1	0,9	-0,7	-7,1	-4,1	-19,1
2004	-16,5	-22,7	-10,6	-1,1	-5,4	-0,9	3,3	3,1	1,1	-2,8	-10,9	-8,2
2005	-6,9	-10,7	-17,1	-9,4	-3,6	0,8	2,5	4,2	0,7	-5,5	-6,2	-7,6
2006	-4,8	-10,1	-15,7	-3,8	-2,7	1,4	3,1	4,8	0,1	-4,3	-4,9	-6
2007	-13,2	-11,1	-7,7	-9,6	-5,2	-0,2	2,1	2,8	1	-1,2	-4,2	-5,7
2008	-6,4	-8,4	-15,4	-11,4	-4,2	-0,3	1,1	2,7	1	-5,6	-5,9	-10,1
2009	-18,5	-12,1	-18,9	-14,6	-1,6	-0,1	2	1	1,1	-2,2	-1,1	-9,1
2010	-9,4	-8	-13,7	-6,5	-1,6	-0,7	2	1	1,3	-5,3	-10,9	-10,1
2011	-15,7	-13,3	-11,4	-2,8	-5,4	-1	2,9	2,3	2,9	-4	-5,7	-8,9
2012	-6,5	-7,9	-6,6	-7	-2,3	0,4	3	3,4	0	-3,2	-5	-9,3
Minimum	-22,6	-22,7	-20	-16,7	-10,1	-3,1	1	0,9	-1,9	-7,1	-10,9	-19,1
Year	2003	2004	2003	2003	2003	2003	2003	2003	2002	2003	2010	2003
Month normal 1961-1990	-8,1	-7,7	-7,6	-5,4	-1,4	1,8	4,4	4,4	2,6	-0,5	-3,7	-7,1

The seawater temperature varies with the air temperature and presence of ice in the region. Table 3 shows the average seawater temperature at Bjørnøya. The temperature is generally cold and is negative throughout the winter months. The low temperature is an effect of the inflow of polar seawater from the north (NOFO(a), 2007).

Table 3: Average seawater temperature at Bjørnøya (NOFO(a), 2007).

Sea water temperature [°C] at Bjørnøya											
Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
-1.50	-1.65	-1.55	-1.20	-0.20	1.80	3.15	3.60	3.25	1.85	0.10	-1.00

2.2.2 Visibility

The visibility in the WBS can be impaired by darkness, cloud coverage, fog, rain, and snowfall. Insufficient visibility can lead to increased risk related to grounding or collision of structures and vessels, or challenges related to detection of heavy sea ice concentration and icebergs. Low visibility can be challenging for personnel, who are fully dependent on their vision to operate, and it can also limit the ability for a helicopter to operate.

The phenomenon *fog* is formed when water vapour condenses into tiny liquid water droplets in the air. Offshore, the main ways water vapour is formed into the air is when cold or dry air moves over warmer water (Kjerstad, 2011). Horizontal visibility of 1 km or lower it is called fog (met.no, n.d.). The principle of formation of fog over sea is shown in Figure 8. Fog is normal in the WBS (Kjerstad, 2011).

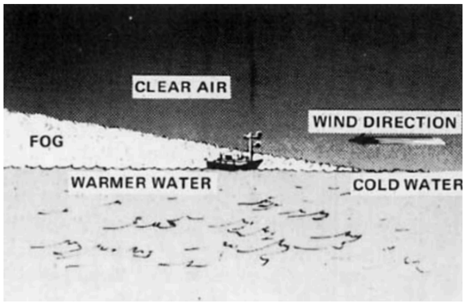


Figure 8: Formation of fog at the sea (Pilie et al., 1979, p.1276).

The winter months are dominated by darkness since the sun is under the horizon for several months. The length of the *polar night* season varies in the Arctic, at higher latitudes the season is longer than in lower latitudes. The polar night at Bjørnøya lasts from 8th of November until 3rd of February, and the period of midnight sun from May 2nd until August 11th (met.no, n.d.).

High cloud coverage can also be challenging for operations. Cloud coverage is often measured in *oktas*. The oktas scale ranges from 0 to 8, where 0 is free of clouds and 8 is completely cloudy. Cloud coverage is not directly convertible with fog; the fog is located at sea level whilst the cloud coverage can be several metres above sea level. Table 4 shows the amount of days that had an average cloud cover of 6 oktas or more at Bjørnøya from every second year from 2002-2012. The data is collected and calculated from The Norwegian Meteorological Institutes service, *eKlima*. The cloud data was measured 4 times a day, every day of a month. For simplification, the data is presented as an average value. The calculations are shown in Appendix A. As can be seen from the table, it is relatively high cloud coverage the whole year in the region. The summer months have in general higher cloud coverage than the winter months. In addition, the table also shows the month normal of hours with sun at the location from 1961 – 1990. It should be noted that it is above 3 months with no sunlight so the visibility will be low independent of the cloud coverage. Table 5 shows the distance in average horizontal view at Bjørnøya in the time period 1997-2006, the table also shows how high percentage of the time the visibility is lover than 800 m.

Table 4: Cloud coverage and hours of sun at Bjørnøya (met.no, n.d.).

Days with cloud coverage above 6 oktas [Oktas] at Bjørnøya												
	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
2002	13	15	19	23	20	20	19	28	26	22	17	19
2004	24	15	22	21	21	25	12	18	25	23	19	17
2006	23	17	21	20	19	25	28	25	17	20	18	14
2008	21	19	19	17	19	24	21	21	21	24	23	22
2010	16	13	16	19	23	26	19	28	26	23	17	20
2012	17	14	16	18	21	24	24	19	22	18	22	8
Average	19	16	19	20	21	24	21	23	23	22	19	17
Month Normal of hours with sun [h] for Bjørnøya 1961 – 1990												
Hours with sun [h]	0	6	57	105	116	105	79	70	42	15	0	0

Table 5: Horizontal view at Bjørnøya (1997-2006) (DNV, 2008).

Average horizontal view at Bjørnøya (1997-2006) [km]			
June	July	August	September
26.8	18.5	17.5	22.5

Horizontal view below 800 m at Bjørnøya (1997-2006) [%]			
June	July	August	September
8.2	14	17	7

2.2.3 Wind

In general, the wind profile is much stronger offshore than onshore; this is because of less resistance at sea (Sundsbø(c), 2011). According to International Standard (2010), the most prevailing wind direction is northeast during the winter and west during the summer. The occurrence of the northeast during the winter is 27 % and the west wind occurs 19 % during the summer. Table 6 shows the average and strongest wind condition at Bjørnøya the previous year. The wind speed is measured at 10 m elevation.

Table 6: Wind condition at Bjørnøya 2012-2013 (met.no, n.d.).

Wind speed [m/s] at Bjørnøya 2012		
Month	Average [m/s]	Strongest [m/s]
January (2013)	8.3	19.6
February (2013)	7.3	20.3
March	7.9	18.0
April	6.6	20.1
May	6.4	17.0
June	6.0	14.0
July	6.0	16.3
August	5.7	14.0
September	7.8	17.2
October	7.4	18.6
November	6.4	15.3
December	7.9	18.6

The winter months in the region are affected by a phenomenon called *polar lows*. Polar lows are formed when cold air flow over warmer water and creates an atmospheric instability. The atmospheric instability can grow such that low-pressure centres of up to a few hundred kilometres in diameter. The frequency of the phenomenon is high in the Barents Sea, especially in the western part (International Standards, 2010). Polar lows do in general occur from October to May (Gudmestad(a), 2009). The lows are characterized by heavy snowfall and icing, they normally lasts from 6 hours to 1-2 days, and the highest wind speed measured is 36 m/s (Thelma, 2010). As a result of the relatively small size of the lows and lack of extensive observation systems in the region, polar lows are difficult to observe and forecast (International Standards, 2010). However, today the forecast technology is continually improved and will likely be more accurate in the future. Figure 9 is a satellite image of a polar low at the coast of northern Norway in 1987.

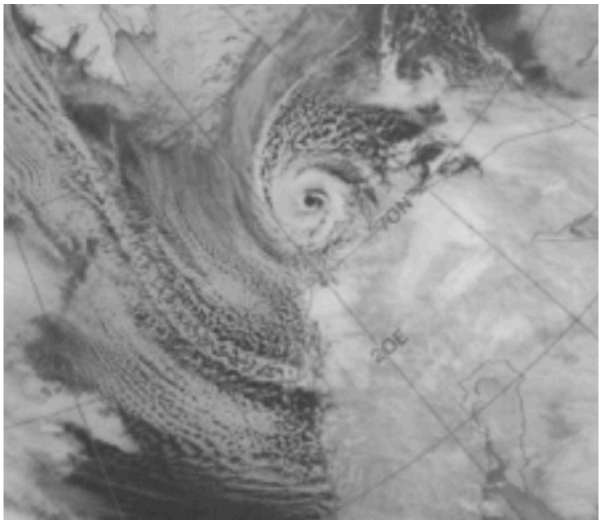


Figure 9: Polar low on the northern coast of Norway, satellite image from 27. February 1987 (Kolstad, 2005, p.349).

The effect of wind in combination with low air temperature gives an extra cooling effect when exposed to bare skin on humans. The effect is often measured in a *Wind Chill Index* (WCI) that expresses the effect on exposed areal (W/m^2) (Standards Norway, 2004). The wind speed and air temperature are the variables, and their effect are synergic. The acceptable working time limits for personnel are presented in Table 7. The equation that can be used is (Woodson, 1992):

$$WCI = \left(10 * \sqrt{U} - U + 10.5\right) * (33 - T)$$

Where	WCI	Wind chill index [W/m^2]
	U	Wind speed [m/s]
	T	Ambient air temperature [°C]

Table 7: Acceptable working time per hour for personnel (Standards Norway, 2004).

WCI [W/m^2]	Restrictions
1500 > WCI > 1000	Acceptable working time per hour for an individual personnel is from 33% to 100%
1600 > WCI > 1500	Acceptable working time per hour for an individual personnel is from 0% to 33%
WCI > 1600	No outdoor work for personnel is accepted

2.2.4 Sea waves and currents

The waves in the Barents Sea are dominated by a prevailing south-westerly weather influxes. The Norwegian Coastal Current ends in the Barents Sea, which also affects the waves and currents. These two factors are the main reasons of why the largest waves are in the western part of the Barents Sea. There is a current around Bjørnøya, the Bear Island current, which is a narrow, cold, and weak current. The current tend to transport sea ice southwards. North of the Bear Island Current the East Spitsbergen Current is located. This current transports Arctic water downwards and it transports sea ice (Fugro, 2005). Figure 10 shows the significant wave height, period, and the 100-year maximum tidal current in the WBS.

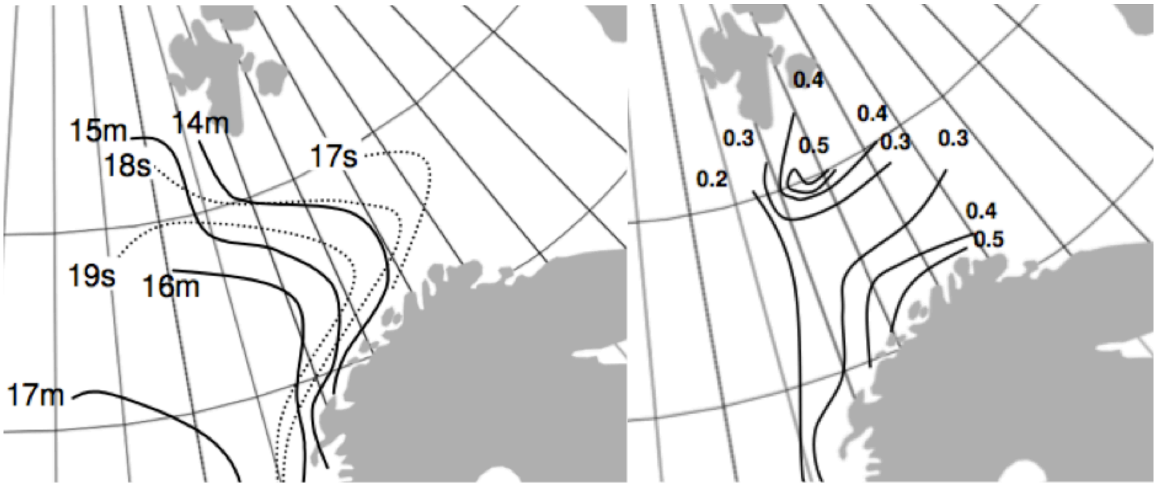


Figure 10: To the left: The significant wave height [m] and period [s] in the Western Barents Sea (Standards Norway, 2007, p.13). To the right: Maximum 100-year tidal surface current [m/s] in the Western Barents Sea (Standards Norway, 2007, p.17).

2.2.5 Precipitation

Bjørnøya has, on average, 393 mm precipitation (rain, sleet, snow or hail) annually and approximately 33 mm each month. There are 219 days annually that have greater than 0.1 mm of precipitation. The month with the less precipitation is April, where on average 22 mm of precipitation falls across 17 days. However, the month with most precipitation is September, when on average 48 mm precipitation falls across 21 days (Climatemps, 2012). Combination of wind and snowfall often lead to unwanted snow depositions in lees where wind has reduced transport capacity. Snow transport is mainly driven by this interaction between wind, topography, vegetation, and interaction between moving snow particles, humidity, and temperature affects the overall transport (Sundsbø(a), 2011).

2.2.6 Atmospheric icing

Super-cooled fog, sea smoke, and cloud droplets are humidity in the air that is all so small that it freezes rapidly upon contact with cold objects, this is called atmospheric icing. Atmospheric icing is in other words a result of humidity in the air in combination with low air temperature (Ryerson(b), 2008). At Bjørnøya, the average mean relative humidity over a year is recorded to be 87.8%, and ranges from 85% to 90%, which makes a good environment for atmospheric icing (Climatemps, 2012). Atmospheric icing normally occurs when the air temperature is between 0 °C and -20 °C, and the wind speed is less than 10 m/s (Løset et al., 2006).

The ice that forms from atmospheric icing is rime or glaze (there are other types too but they are not included in this thesis). *Rime* is relatively weak in strength and is brittle, but makes a foundation for snow and ice to attach to the surface. *Glaze* forms from freezing rain at attaches to surfaces and is stronger than rime. *Icicles* are a type of glazier. *Icicles* occur when cooled water flows over a curb, and parts of the water freeze on the boundary of a cold surface. Typically, an icicle will form when snow or ice is melted by changes in the air temperature (Ryerson(b), 2008).

2.2.7 Sea spray icing

Sea spray generated ice has a great impact on facilities and especially on vessels safety. Sea spray is the most frequent and most hazardous form of icing (Løset et al., 2006). The ice is formed when droplets from waves splashes against structural elements, typically below main deck level. For moving vessels, spray attaches first and most frequently in the bow/wave interaction, and some droplets is carried over the ship by wind. According to International Standards (2010), the spray icing begins to occur at wind speed is above 8 – 10 m/s. Most sea spray occurs 15–20 m above the sea level, but can be as high as 60 m (Ryerson(b), 2008). In order to limit the risk related to maritime activity in cold regions it could be helpful to calculate expected ice accretion. The equation below is used to calculate expected ice accretion. Table 8 presents classification of ice accretion from light to extreme. This classification is according to NOAA (National Oceanic and Atmospheric Administration of the USA) (Løset et al., 2006).

$$PR = \frac{U_A\ (T_F - T_A)}{1 + 0.4\ (T_W - T_F)}$$

Where	PR	Accretion prediction [m°C/s]
	U_A	Wind speed [m/s]
	T_F	Freezing temperature of sea water with salinity 34 ppt (- 1.9°C) [°C]
	T_A	Air temperature [°C]
	T_W	Sea water temperature [°C]

Table 8: Amount of icing (Løset et al., 2006, p.197).

	Light	Moderate	Heavy	Extreme
Icing rate (cm/h)	< 0.7	0.7 – 2.0	> 2.0	> 5.0
PR (m°C/s)	< 20.6	20.6 - 45.2	> 45.2	> 70

2.2.8 Sea ice

There are many types of sea ice. The sea ice can either be landfast or in floes, and the age of the ice has a big influence on its properties. It is common to characterise the ice after the age. Newly formed sea ice is weaker and less compact than old ice, and this is mainly due to presence of salt and other foreign particles that is extracted from the ice over time. Ice that is less than one year old is referred to as first-year ice and ice that is more than two years old is referred to as multi-year ice. First-year ice and multi-year ice can be referred to as FY and MY ice (Kjerstad, 2011). There exists many different types of sea ice but this thesis will not present them.

Pressure ridges are an accumulation of ice (Figure 11). The ice accumulates like this as a result of movements (from waves, currents, and wind) in the sea. The ice is forced on top or below other flows and freezes together. In the FY ridge the different original floes can be identified, and the MY ridge is more compact and more like one piece of ice (Løset(c), 2012).

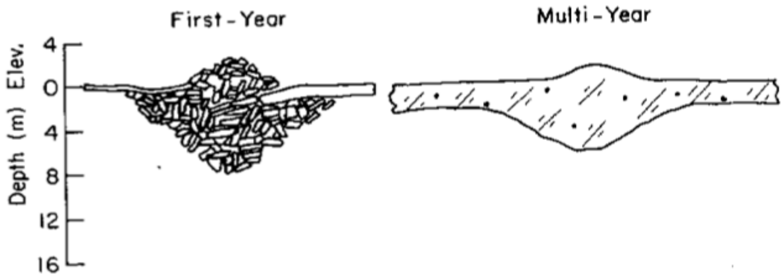


Figure 11: Pressure ridges. The multi year pressure ridge is much stronger and compact than the first year pressure ridge (Løset(c), 2012, p.74).

Table 9 shows the ice concentration in the WBS in the winter months 2005-2012. Ice charts from The Norwegian Meteorological Institutes service, *Polarview*, have been analysed. Only ice charts from the last day of each month have been used. None of the ice charts that has been analysed have shown high ice concentration at the location, just a little ice around Bjørnøya. The month that has most occurrence of ice is March. However, the ice edge is often placed right above Bjørnøya. The ice chart in Figure 12 illustrates a typical shape of the ice concentration in the region for the given period (2005-2012). The ice is shaped like a triangle and goes downward from the north and ends around Bjørnøya.

Table 9: Sea ice concentration at the given location (PolarView, n.d.).

Sea ice concentration in the Western Barents Sea (2005-2012)								
	2005	2006	2007	2008	2009	2010	2011	2012
January	0	0	0	0	1/10-4/10	0	0	0
February	0	0	0	0	1/10-4/10	0	0	0
March	0	0	0	4/10-7/10	4/10-7/10	9/10-10/10	1/10-4/10	0
April	0	0	0	0	1/10-4/10	0	0	0
November	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0

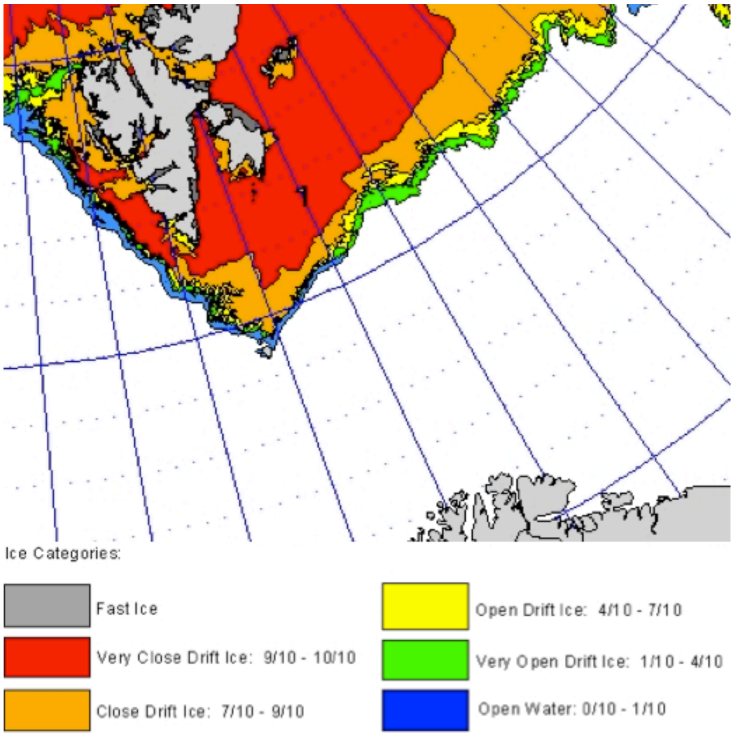


Figure 12: Typical shape on the ice edge around Bjørnøya. This chart is from January 31st 2011 (PolarView, n.d.).

Figure 13 shows the 10-year, 50-year, and 100-year extreme ice edge limit in the Barents Sea. The study is from 1990 but it is reasonable to believe that there have not been any significant changes during this period.

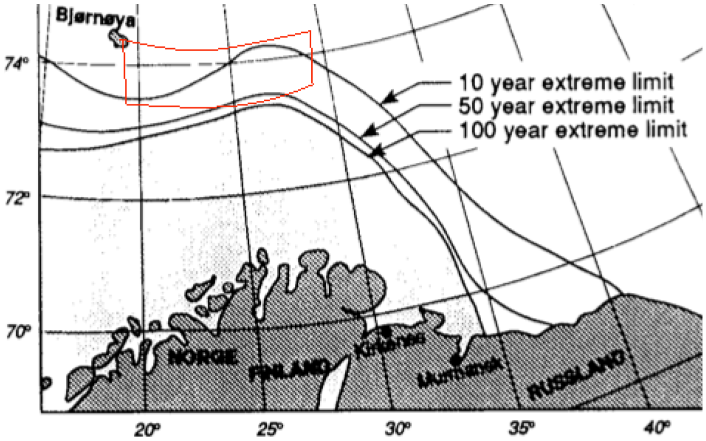


Figure 13: Extreme ice limits in the Barents Sea (Vefsenmo et al., 1990).

2.2.9 Icebergs

Icebergs are bites of ice that have been loosened from glaciers and drifts away from the glacier front. The size and density varies with terrain and surrounding environment (Kjerstad, 2011). Some shapes that an iceberg can take, like wellrounded, can be difficult to identify in very thick ice cover and can cause dangerous situations(Løset(b), 2012). If an iceberg collides with an offshore structure it can lead to a major accident with severe damages on the hull.

There have been done researches on the drift of icebergs in the northeastern Barents Sea. In one specific research done by Løset (2012), it was figured out that the mean value for drifting speeds of icebergs is 0.25 m/s. From a specific study 1987 an iceberg was observed to drift with a mean speed of 1.13 m/s for 31 hours. The maximum speed measured for that research was 1.38 m/s (Løset(b), 2012).

Figure 14 shows the annual expected occurrence of icebergs in the region. For the given location in the WBS the highest percentage is set to 10% but will be lower in most parts of the region (around 5%) (Abramov, 1996). This means that an iceberg may occur pass by in the region between every 10th and 20th years. Normally icebergs occur in the spring, April and May, when the ice melts (Gudmestad(c), 2013).

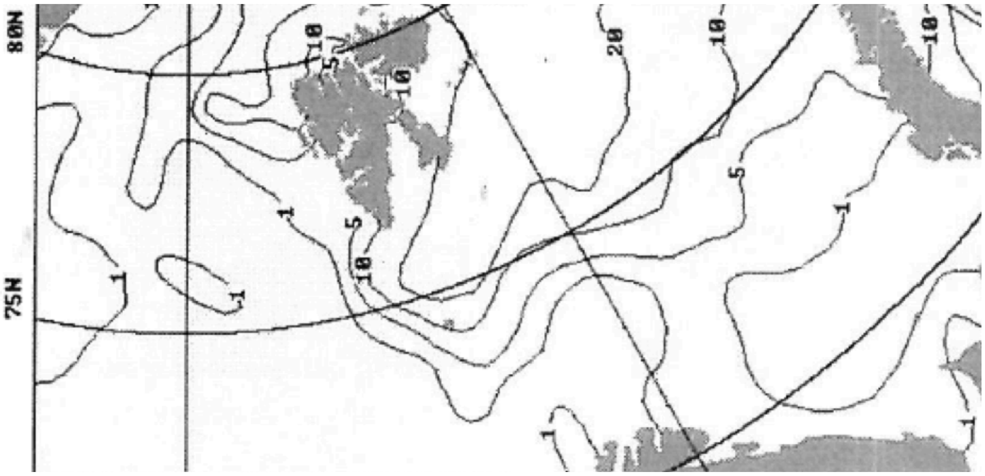


Figure 14: Annual occurrence of icebergs in the Western Barents Sea. At the bottom of the map the coast of Northern Norway is located (Abramov, 1996, p.3.37).

2.3 Vulnerability and Remoteness

Many of the challenging factors with offshore drilling operations in the Western Barents Sea (WBS) are linked to the remoteness and vulnerable ecosystem. The vulnerability and uncertainty linked to the consequences of an accident is significant due to the lack of experience in the region. What is known is that the outcome has the potential to be severe. Vulnerability is defined as the ability of a system to maintain its function when it is exposed to stresses. The vulnerability expresses the hazards related to that a barrier wills stop functioning as a result of the load that it is exposed to (Aven et al., 2011).

2.3.1 Ecosystem

The Barents Sea contains of one of Europe's largest clean and relatively untouched marine ecosystems. There is an extremely high primary production in the region. The Barents Sea has a rich biological diversity including some of the world's most numerous colonies of seabirds. In addition, it also has a unique variety of marine mammals such as walrus, bowhead whales and polar bears. The seafloor contains numerous of deep-water coral reefs (WWF-Norge, 2003).

Figure 15 illustrates a simplified food web from the Barents Sea. Unfortunately, the illustration is in Norwegian language. The figure presents a huge diversity and all the different species are depending on each other to live and breed. Phytoplankton is food for zooplanktons, and the zooplankton is an energy source for scrimps, seals, sea birds, and fish. Fish is an important energy source for bigger fish, seals, whales, sea birds, and humans. The energy from the sun, wind, sea currents, and nutrients at the sea floor, are all important factors that affects the uniformity of the chain. Ice edges may be considered as a separate ecosystem where it gradually shrinks northward in the spring and summer. The ice edges create favourable production conditions for phytoplankton and zooplankton (Berg, 2006). Disturbance in the diversity's balance can lead to severe consequences.

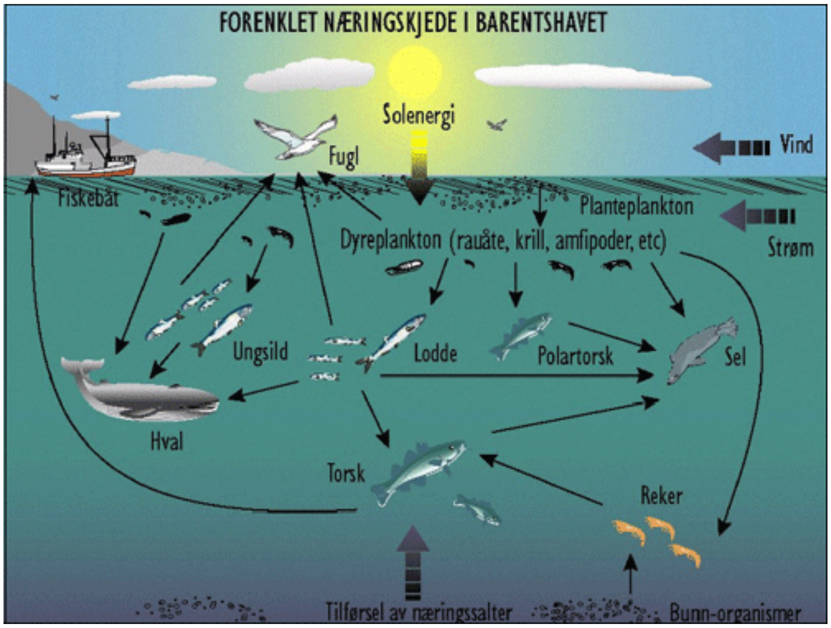


Figure 15: Simplification of the food web in the Barents Sea (Berg, 2006).

2.3.2 Oil spill

The Arctic conditions pose other challenges for oil spill response compared to temperate waters. The presence of sea ice will have a great effect on oil spill response. Whether the oil is spilled on top or under the ice, the form and stage of the ice and other prevailing conditions (darkness, remoteness, and low temperatures) all have a significant effect on oil spill response operations (Sørstrøm et al., 2010).

The requirements of a clean environment are of severe importance in the Arctic (Gudmestad & Løset, 2004). Global experience shows that uncontrollable influx of fluids from wells poses a danger to fixed and mobile drilling structures. These influxes are referred to as open flows and blowouts and are one of the main sources of oil pollution to the marine environment. Experts have calculated the volume of probable oil spill in a dramatic situation, where a failure on the well is accompanied by damage to the drilling structure, an amount of 300 m^3 oil and 50 m^3 of drilling mud can leak into the sea (Gudmestad et al., 2007).

Handling spilled oil in cold environment and ice-infested waters is challenging. The process of natural dispersion of oil in water takes longer time in cold environment compared to warmer environment (DNV Summer Project, 2012). Today there exist some methods that ease the clean up after spills. It is possible to use mechanical recovery, in-situ burning, and chemical dispersion. The selection of method will be dependent on site-specific conditions (near shore, shallow water, sensitivity of the receiving environment, ice coverage, weather and ice drift forecasts, etc.). *Mechanical methods* are developed for open water. The method has several limitations for operations in ice. Some of the main challenges in ice compared to open water are: icing and freezing of equipment, limited access to the oil, limited flow of oil to the collecting equipment, separation of oil from ice and water, forces in the ice field, and increased oil viscosity. For *in-situ burning* the different crude oils can have very different ignitability due to their original chemical composition and the effect this has on the rate of weathering. In order to have an effective in-situ burning the oil slicks has to be thick or else it can be hard to ignite. Fire booms can collect and keep slicks thick in open water. The addition of a *chemical dispersant* to spilled oil increases the potential for oil to be dispersed. The smaller the oil droplets are the more available they are for microorganisms in the water mass to naturally biodegrade the oil (Sørstrøm et al., 2010).

On the other hand, sea ice does not necessarily only cause extra problems. It have been experienced that ice can aid in oil spill response operations; it slows down oil weathering, it dampens the waves, it prevents the oil from spreading over large distances, and it gives more response time. In some situations oil spill response in ice-covered waters can be easier than in open water, although this does not imply that it will be simple (Sørstrøm et al., 2010).

To the left in Figure 16 an illustration of how the oil mixes with seawater and seawater with present of ice. As can be seen, the oil may be trapped under the ice. This offers significant challenges to the clean up, and may to some extent be impossible. In addition, oil has the tendency to clog and penetrate brines and holes in the sea ice; this also makes the clean up challenging (DNV Summer Project, 2012). To the right in Figure 16 a picture of usage of in-situ burning in an oil boom is shown.

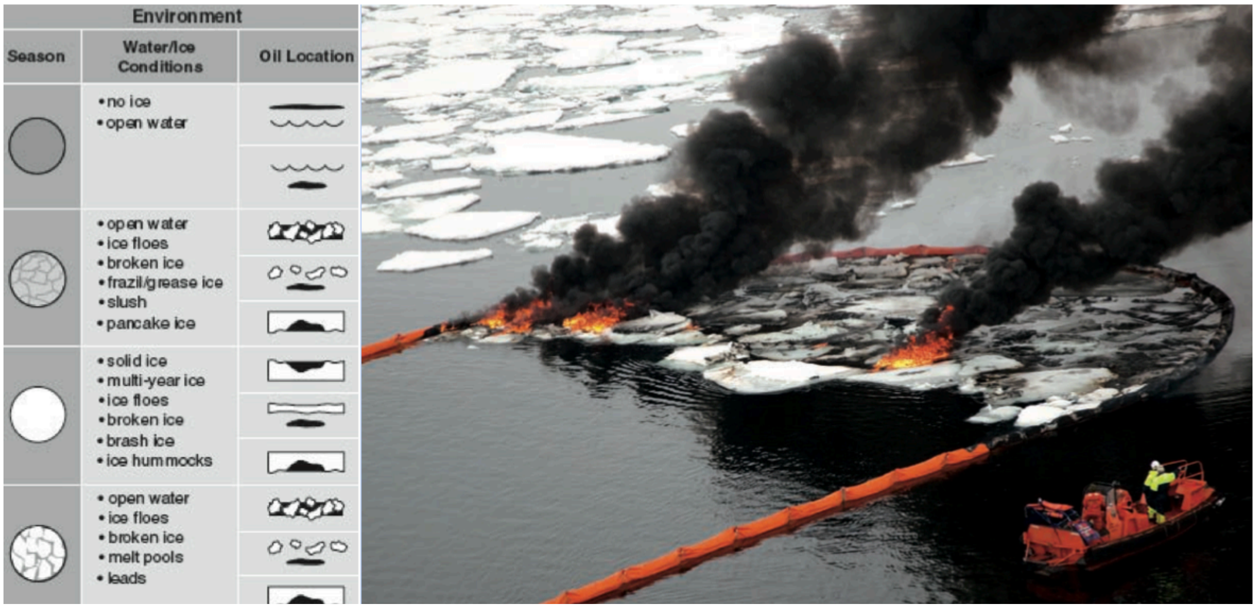
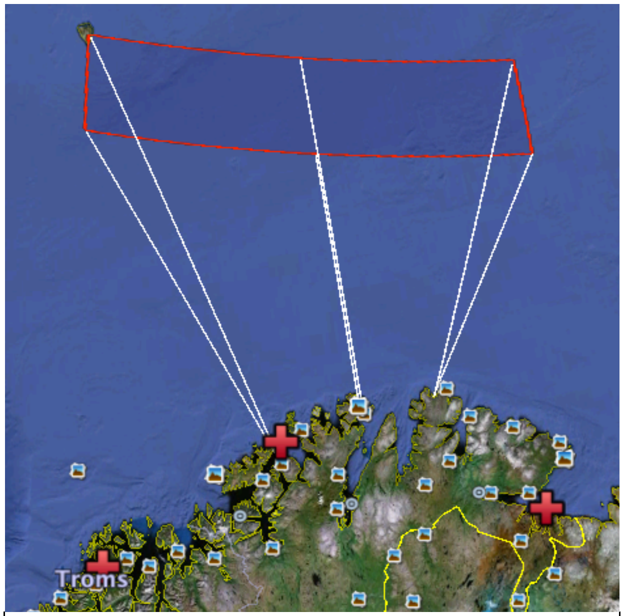


Figure 16: To the left: Ice conditions and mixing with spilled oil (Sørstrøm et al., 2010, p.8). To the right: Oil boom and in-situ burning (Sørstrøm et al., 2010, p.13).

2.3.3 Remoteness

The limited infrastructure and long distances combined with the climatic conditions in the Barents Sea offers significant challenges if an accident occurs. These challenges require special consideration and management. Icing on lifeboats and scarce of helicopters in the region makes evacuation and rescue a high-risk operation where the likelihood of success is low. The long response time might lead to fatale consequences (Jacobsen, 2012). Because of the challenging environment, Jacobsen (2012), suggest in his Master thesis that every effort should be made to prevent need for emergency preparedness resources. Furthermore he states that if it is needed; evacuation, survival and rescue equipment should function as required in order to eliminate or reduce injury and loss of life. International Maritime Organization (IMO) (2002), *Guidelines for ships operating in Arctic ice-covered waters*, presents requirements related to emergency equipment and winterization of vessels. These requirements have to be met when operating in polar waters such as the WBS.

Figure 17 shows the distances from the drilling location in the WBS to the Norwegian coast. The distances are long and helicopter transportation and search and rescue (SAR) will require long-range flights. The hospitals in the region are marked with red crosses; from the left we have Tromsø, Hammerfest, and Kirkenes. Tromsø is the specialist hospital in the region and has the largest capacity and expertise.



Distances		
North-West	Hammerfest	444 km
South-West	Hammerfest	364 km
North-Middle	Honningsvåg	341 km
South-Middle	Honningsvåg	247 km
North-East	Mehamn	331 km
South-East	Mehamn	250 km

Figure 17: Distances from the locations to the Norwegian coast. The marked red crosses are locations for hospitals in the region (Google Earth, 2013).

Figure 18 shows the estimated SAR coverage with helicopter. The figure shows the range within two hours for the different helicopters from the different SAR bases. There are some parts of the drilling location in the WBS that is not covered. In order to have a sufficient coverage with helicopter improvements is strongly needed and the helicopter bases can for instance be located further north on the coast. If the helicopters from the Norwegian coast are used in SAR operations at the drilling location they probably have to refuel at Bjørnøya (or other refuel stations) because of the long distances.

Figure 18: Estimated search and rescue coverage (Kvamstad & Berg, 2012, p.15).

In addition to the helicopters from the Norwegian coast, helicopters from Svalbard can be used for SAR operations. In 2014 new rescue helicopters are planned to be located at Svalbard. The ranges of the helicopters are 222 km, and since they will be located in Longyearbyen at Svalbard they will have to refuel at Bjørnøya (or other refuel locations) if they will be used as aid in accidents at the drilling location. The helicopters will be especially equipped for SAR operations and have good communication and safety systems (TU, 2012).

2.4 Previous Accidents

Existing information about previous accidents in the Western Barents Sea (WBS) region will be used as a tool to find influence factors for drilling operations. The overall drilling experience in the region is poor compared to the Norwegian continental shelf (NCS) and other well-explored drilling regions. Due to the scarce experience, accident data from other activities will be included.

The increased investments in better technologies during the last years have reduced the risk related to maritime activity. Ships certificated with proper class for their voyages, better navigation systems such as detailed maps and satellite GPS, and improvements of the weather forecasts have increased the safety and reduced the amount of accidents. Increased safety for operations has become important. For instance, during a cold break in winter of 2012 fishing vessels were not allowed to leave harbours in Finnmark County because vessel icing was highly probable with high potential for ships to loose stability as a result of winds, low temperatures and waves (Njå & Gudmestad, 2012).

During the 20th century 56 vessels were lost and 342 people lost their lives in accidents in Norwegian waters. Many of the losses are most likely a consequence of polar lows and its strong winds, heavy snow and large waves. The Norwegian Coastal Steamer (Hurtigruten) has been traveling along the Norwegian coast since 1893 in almost any weather conditions. Over the years 15 Coastal Steamers have been lost. Table 10 shows a list over accidents that have occurred in Norway and in Eastern Greenland since 1848. Many of the accidents are most likely caused by large waves, potentially combined with low freeboard and icing causing flooding and loss of vessel intact stability. For cases with sudden strong winds combined with snow, emergency response is very difficult. Not all the accidents are a result of bad weather condition; some of the accidents are from human failures such as navigation error (Njå & Gudmestad, 2012).

Table 10: Vessel accidents as a result of harsh weather in the Norwegian and Greenland coast (Njå & Gudmestad, 2012).

When	Location	Vessels down	Fatalities
Feb. 1848	Lofoten Islands	-	500
April 1917	Vestisen (East Greenland)	6	84
April 1933	Vestisen (East Greenland)	7	13
April 1939	Vestisen (East Greenland)	2	28
April 1952	Vestisen (East Greenland)	5	72
Oct. 1962	Norwegian Coast	1	41
Feb. 1974	Bjørnøya	1	36
Feb. 1978	Offshore Steinfjord	1	9
1988	Vestisen (East Greenland)	1	-

The Joint Rescue Coordination Centre in Northern Norway (Hovedredningssentralen Nord-Norge) has data from reported unwanted offshore event in the northern part of the Norwegian coast. Table 11 shows event data from 4 different categories in the time period 2005-2010. The category "offshore" includes incidents and accidents at both permanent and mobile petroleum facilities. The category "missing vessel" includes events where vessels have been reported missing. This involves both vessels that have been recovered and those who have not been recovered. The outcomes of the events in this table are unknown (Wangsfjord, 2013).

In total there was 182 reported events in the time period 2005 – 2010. Most of the reported events were in the summer months July and August. The winter months, especially from November to March, had the fewest reported events. This can be a result of less activity in the region during these months.

In total there were 48 "capsizing" accidents during the period. 1 of them was drowning, and the 47 other were due to list on the vessels. If a vessel looses its stability it might lead to capsizing and is most likely the reason for the events. However, the reason it have lost its stability is unknown. The capsizing events are evenly distributed over the year, but has a slightly increase in the summer months.

The total amount of reported "offshore" events during the time period was 16. 11 of the events occurred from October to April. This increase in events in the winter months can be a result of increased challenges because of more challenging operation environment, but on the other hand, it can be a coincidence.

With a total of 118 reported events, most events are from missing vessels. This category contains all kind of vessels from fishing boats to leisure and commercial vessels. Today it is not likely that missed vessels are not found again, the reported events are most likely from concerned co-workers or family that cannot get in contact with the vessel. The limited reach of the communication system in combination with harsh weather can make people concerned and ask for help to track them.

Table 11: Accident data from The Joint Rescue Coordination Centre in Northern Norway, in the time period 2005 – 2010 (The Joint Rescue Coordination Centres, n.d.).

The Joint Rescue Coordination Centre in Northern Norway		January	February	March	April	May	June	July	August	September	October	November	December	**Total**
2005	Capsizing - drowning	0	0	0	0	0	0	0	0	0	0	0	0	0
	Capsizing - list	0	0	0	0	2	2	0	1	0	0	0	0	5
	Offshore	1	0	0	1	0	0	0	0	2	0	0	0	4
	Missing vessel	2	1	1	2	3	1	2	4	1	2	1	1	21
2006	Capsizing - drowning	0	0	0	0	0	0	0	0	0	0	0	0	0
	Capsizing - list	0	0	1	1	0	1	0	0	0	2	1	0	6
	Offshore	1	0	1	0	0	0	0	0	0	0	0	1	3
	Missing vessel	0	0	1	1	1	4	5	4	0	2	1	1	20
2007	Capsizing - drowning	0	0	0	0	0	0	0	0	0	0	0	0	0
	Capsizing - list	1	0	0	1	0	0	0	2	1	0	0	0	5
	Offshore	1	1	0	0	0	0	0	0	0	0	0	0	2

The Joint Rescue Coordination Centre in Northern Norway		January	February	March	April	May	June	July	August	September	October	November	December	**Total**
	Missing vessel	1	2	0	2	0	1	4	5	1	2	1	0	19
2008	Capsizing - drowning	0	0	0	0	0	0	0	0	0	0	0	0	0
	Capsizing - list	0	0	1	0	0	2	1	0	1	0	1	0	6
	Offshore	0	0	0	0	0	0	0	0	0	0	0	0	0
	Missing vessel	0	1	1	3	2	0	4	1	0	0	1	0	13
2009	Capsizing - drowning	0	0	0	0	0	0	0	0	0	0	0	0	0
	Capsizing - list	0	0	3	1	0	1	2	2	3	1	0	0	13
	Offshore	1	0	0	1	0	0	0	0	1	0	0	0	3
	Missing vessel	1	3	3	1	0	2	4	2	4	1	1	1	23
2010	Capsizing - drowning	0	1	0	0	0	0	0	0	0	0	0	0	1
	Capsizing - list	1	1	2	2	0	1	1	1	1	2	0	0	12
	Offshore	0	0	1	0	1	0	0	0	0	0	0	2	4
	Missing vessel	2	1	4	3	1	3	3	4	0	0	1	0	22
Total		12	11	19	19	10	18	26	26	15	12	8	6	182

Table 12 shows all vessel accidents from Bjørnøya, Svalbard, and Jan Mayen from the time period January 1995 to Mach 2012. In total there where 40 accidents. There have not been any major accidents during the time period, but 2 injuries occurred. The environmental conditions when the accidents occurred are specified in the table, however the air temperature and sea ice condition is not specified. In some of the accidents data is missing, where data is missing the field is marked with "-". The majority of the accidents are grounding, and only 1 accident is categorized to be a cause of harsh weather condition. However, challenging weather can also be the cause of more accidents due to that they are categorized by the "type of event". 4 of the accidents occurred under a wind speed of above 13.9 m/s and 3 accidents occurred when the wave height was above 2 m. 8 of the accidents lead to severe damages on vessel or total losses.

Based on this data there cannot be drawn any exact parallels to that the accidents are caused by harsh weather condition. Several of the accidents occurred in relatively calm wind and wave conditions and with light and good visibility.

Table 12: Vessel accidents around Bjørnøya, Svalbard, and Jan Mayen from January 1995 to March 2012 (The Norwegian Coastal Administration, 2012).

Vessel accidents at Bjørnøya, Svalbard, and Jan Mayen (1995-2012)																		
Nr.	**Date**	**Accident type**	**Near accident**	**Fatalities**	**Injuries**	**Latitude**	**Longitude**	**Water**	**Wind direction**	**Wind speed m/s**	**Wave height (m)**	**Light**	**Visibility (Nautical mile)**	**Name of vessel**	**Vessel type**	**Length (m)**	**Nationality**	**Damage on vessel**
1	14.01.1995	Grounding	No			79,9	17,6	Open sea	North-East	17.2 - 20.7	0.50 - 1,24	Dark	2,1 - 5	BARENSTRÅL	Fishing	34	Norway	Small damages
2	15.09.1995	Environmental pollution	No			78,2	15,7	Harbour hub	-	-	0.00 - 0,24	Light	Above 5	SYNSRAND	Fishing	27	Norway	Small damages
3	16.12.1995	Other	No			79,8	18,0	Open sea	North-East	13.9 - 17.1	0.50 - 1,24	Dark	Below 0.25	BJØRGVIN SENIOR	Fishing	47	Norway	Small damages
4	18.12.1995	Leakage	No			80,1	16,1	Open sea	North-West	3.4 - 5.4	0.00 - 0,24	Dark	2,1 - 5	ATLANTIC PRAWN	Fishing	59	Norway	Total loss
5	02.07.1996	Grounding	No			79,8	26,6	Outer coast	North-West	10.8 - 13.8	1.25 - 2,4	Light	Above 5	POLAR STAR	Passenger	46	Norway	Serious damages
6	09.07.1996	Grounding	No			78,6	16,4	Outer coast	South-West	1.6 - 3.3	0.00 - 0,24	Light	Above 5	NORDSTJERNEN	Passenger	80	Norway	Small damages
7	19.07.1996	Grounding	No			78,1	13,7	Close to harbour	Varying	-	0.00 - 0,24	Light	Above 5	SPINELL	Passenger	17	Norway	Small damages
8	20.07.1996	Grounding	No			79,6	12,6	Close to the shore	Calm	0.0 - 0.2	0.00 - 0,24	Light	0.5 - 2	SVALBARD	Passenger	33	Norway	Small damages
9	20.07.1996	Grounding	No			78,2	15,7	Close to harbour	South-West	0.3 - 1.5	0.00 - 0,24	Light	Fog and snow - Below 0.5	RIGNATOR	Cargo	55	Norway	Small damages
10	13.07.1997	Grounding	No			80,0	18,3	Close to the shore	Calm	0.0 - 0.2	0.00 - 0,24	Light	Above 5	HANSEATIC	Passenger	123	Bahamas	Small damages
11	11.11.1997	Grounding	No			78,1	13,0	Outer coast	North-West	13.9 - 17.1	2.5 - 3,9	Dark	Above 5	VIKATRÅL	Fishing	39	Norway	Serious damages
12	26.07.1998	Grounding	No			79,0	11,9	Close to harbour	Calm	0.0 - 0.2	0.00 - 0,24	Light	0.5 - 2	POLARBOY	Passenger	53	Norway	Small damages
13	24.08.1998	Grounding	No			77,5	16,2	Close to the shore	South-East	8.0 - 10.7	0.50 - 1,24	Light	Above 5	ORIGO	Passenger	39	Sweden	Small damages
14	16.09.1998	Grounding	No			78,2	14,1	Outer coast	East	8.0 - 10.7	0.50 - 1,24	Twilight	Above 5	ARTIC CORSAIR	Fishing	60	-	Serious damages
15	04.07.2002	Grounding	No					Outer coast				Light	Above 5	SOUTHERN STAR	Passenger		France	No damage
16	10.12.2002	Harsh weather damage	No			-	-	-	-	-	-	-	-	NORBJØRN	Cargo	77	Norway	Small damages

Vessel accidents at Bjørnøya, Svalbard, and Jan Mayen (1995-2012)																		
Nr.	**Date**	**Accident type**	**Near accident**	**Fatalities**	**Injuries**	**Latitude**	**Longitude**	**Water**	**Wind direction**	**Wind speed m/s**	**Wave height (m)**	**Light**	**Visibility (Nautical mile)**	**Name of vessel**	**Vessel type**	**Length (m)**	**Nationality**	**Damage on vessel**
17	08.04.2003	Leakage	No			67,5	-	-	North-East	8.0 - 10.7	2.5 - 3,9	Light	2,1 - 5	POLARSYSSEL	Cargo	51	Norway	Serious damages
18	09.05.2003	Fire/Explosion	No		1	-	-	Open sea	North	3.4 - 5.4	0.00 - 0,24	Light	Above 5	LYSNES	Fishing	27	Norway	Small damages
19	09.05.2003	Grounding	No			-	-	Outer coast	North-East	3.4 - 5.4	0.50 - 1,24	Light	2,1 - 5	LANCE	Cargo	60	Norway	Small damages
20	04.07.2003	Grounding	No			79,6	10,9	Close to the shore	North-East	3.4 - 5.4	0.50 - 1,24	Light	Above 5	H.U. SVERDRUP	Cargo	46	Norway	Small damages
21	25.07.2003	Grounding	No			79,6	10,6	Outer coast	Varying	1.6 - 3.3	0.50 - 1,24	Light	Above 5	MONA LISA	Passenger	-	Bahamas	Small damages
22	31.05.2004	Grounding	No			-	-	Close to the shore	Calm	0.0 - 0.2	0.00 - 0,24	Light	Above 5	LANGØYSUND	Passenger	27	Norway	Serious damages
23	12.06.2004	Grounding	No			-	-	Close to the shore	-	-	0.00 - 0,24	Light	Above 5	LANCE	Cargo	60	Norway	Serious damages
24	27.06.2005	Grounding	No			-	-	Close to the shore	-	-	-	Light	Above 5	POLAR STAR	Passenger	86	Barbados	Small damages
25	06.09.2007	Grounding	No			-	-	Outer coast	-	-	-	-	-	Oosterschelde	Passenger	50	Holland	-
26	11.11.2007	Grounding	No			74,4	18,9	Outer coast	-	-	-	-	-	Amerloq	Fishing		Russia	-
27	05.03.2008	Grounding	No			78,3	12,8	Close to the shore	South-East	1.6 - 3.3	0.00 - 0,24	Dark	2,1 - 5	LANCE	Cargo	61	Norway	Small damages
28	23.07.2008	Grounding	No			79,6	18,4	Close to the shore	Calm	0.0 - 0.2	0.00 - 0,24	Light	0.5 - 2	ANTARCTIC DREAM	Passenger	83	Panama	No damage
29	19.11.2008	Stability failure	Yes			72,6	15,0	Open sea	North-East	17.2 - 20.7	6.0 - 8,9 m	Light	-	FISKENES	Fishing	39,9	Norway	No damage
30	23.02.2009	Collision	No			71,0	23,2	Open sea	-	1.6 - 3.3	0.50 - 1,24	Dark	Above 5	FLØGRUNN	Fishing	20	Norway	Small damages
31	23.02.2009	Collision	No			71,0	23,2	Open sea	-	1.6 - 3.3	0.50 - 1,24	Dark	Above 5	MYREFISK	Fishing	21	Norway	No damage
32	11.05.2009	Grounding	No			74,3	19,1	Open sea	-	-	-	-	-	PETROZAVODSK	Cargo	67	Russia	Serious damages
33	21.07.2009	Grounding	No			79,7	11,0	Close to the shore	South-East	5.5 - 7.9	-	Dark	Above 5	KONGSØY	Cargo	38	Norway	No damage
34	23.08.2009	Fire/Explosion	No		1	74,1	18,2	Open sea	-	0.0 - 0.2	0.50 - 1,24	Light	Above 5	ATLANTIC VIKING	Fishing	55	Norway	Serious damages
35	25.08.2009	Contact damage	No			78,2	15,0	Outer coast	-	-	-	Light	Below 0.25	ANTARCTIC	Passenger	83	Panama	Small damages

Vessel accidents at Bjørnøya, Svalbard, and Jan Mayen (1995-2012)																		
Nr.	**Date**	**Accident type**	**Near accident**	**Fatalities**	**Injuries**	**Latitude**	**Longitude**	**Water**	**Wind direction**	**Wind speed m/s**	**Wave height (m)**	**Light**	**Visibility (Nautical mile)**	**Name of vessel**	**Vessel type**	**Length (m)**	**Nationality**	**Damage on vessel**
														DREAM				
36	02.07. 2011	Leakage	No			69,0	6,2	Open sea	South-East	5.5 - 7.9	-	Light	Above 5	MAURSUND	Cargo	61	Norway	No damage
37	03.07. 2011	Grounding	No			80,0	18,3	Outer coast	South-East	1.6 - 3.3	0.00 - 0,24	Dark	2,1 - 5	PLANCIUS	Passenger	89	Holland	Small damages
38	20.07. 2011	Other	Yes			78,3	13,9	Close to the shore	Calm	0.0 - 0.2	0.00 - 0,24	Light	Above 5	LANGØYSUND	Passenger	28	Norway	No damage
39	04.08. 2011	Collision	No			-	-	Open sea	-	-	-	-	-	KV BARENTSHAV	Cargo	93	Norway	Small damages
40	04.08. 2011	Collision	No			-	-	Open sea	-	-	-	-	-	ROSENBORG	Fishing	40	Norway	Small damages

2.5 Risk and Risk Management

There is an underlying assumption that the petroleum operations in the Barents Sea should be at least as safe as it is in the North Sea. This assumption demands strict monitoring and assessment of the risk level of the activity (Barents 2020, 2012). Since the environmental condition in the Western Barents Sea (WBS) deviates from the Norwegian continental shelf (NCS) the risk has to be analysed even more carefully. The WBS can introduce new and more challenging risks compared to the NCS.

2.5.1 Risk and uncertainty

The term risk is expressed in many ways depending on who defines it. In this thesis, *risk* is defined as a combination of the probability of an unwanted event and its corresponding consequence. In other words, risk combines the likelihood that a specific hazardous event will occur and the severity of the consequences of the event (Vinnem, 2007). An operational practical calculation of risk is expressed in Vinnem (2007, p. 15):

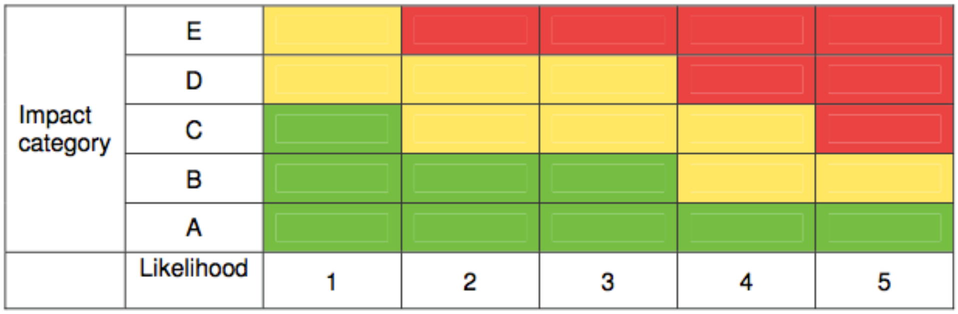
$$R = \sum_i (p_i \cdot C_i)$$

Where R Risk
p Probability
C Consequence
i The specific accident sequence

In the petroleum industry it is normal to assess the risk in order to ensure acceptable risk levels that are in accordance with the regulatory authorities´ requirements. However, there is always an *uncertainty* related to risk. There is an uncertainty to if an unwanted event will occur or not, and what the consequences will be (Aven et al., 2008). Uncertainty reflects insufficient information and knowledge available to do a risk analysis, and the uncertainty will be reduced if more information is gained (Vinnem, 2007). For petroleum operations in new and almost untouched regions, such as in the WBS, the uncertainty is higher. The lack of operational experience and knowledge from the region can introduce challenges that have not been foreseen.

When analysing risk it can be practical to look at it as a big picture where all the involved barriers of an unwanted event are included. Risk picture is often presented in a *bow tie*. The name bow tie comes from the shape of the illustration. In the middle of the picture an unwanted event is placed. To the left the causes (failure of proactive barriers) of the event are located, and to the right (failure of reactive barriers) the consequences are located (Aven et al., 2008).

Another way to express risk is through a risk matrix. A *risk matrix* is often suitable for risk assessment in early project phases where limited information is available. The probability and consequences are arranged in different axis and together represent the risk. The matrix is usually divided into three zones: high risk (red), medium risk (yellow), and low risk (green). In the red zone risk reduction is needed, and in the yellow zone the ALARP principle (read more about ALARP in 2.5.3 Risk influencing factors and acceptance) should be used. The green zone indicates broadly acceptable risk (Standards Norway, 2010).



Impact category	E	🟨	🟥	🟥	🟥	🟥
	D	🟨	🟨	🟨	🟥	🟥
	C	🟩	🟨	🟨	🟨	🟥
	B	🟩	🟩	🟩	🟨	🟨
	A	🟩	🟩	🟩	🟩	🟩
	Likelihood	1	2	3	4	5

Figure 19: Example of risk matrix (Standards Norway, 2010, p.66).

2.5.2 Risk management

In ISO 31000:2009 (p. 2) risk management is defined as the "*…, coordinated activities to direct and control an organization with regard to risk*". The management is all about balancing the conflict where exploration of opportunities is desirable, and on the other side avoidance of loss and accidents are important (Aven et al., 2008).

Risk management is a continuous management process and shall ensure that the drilling processes is conducted safely and in accordance with regulations and requirements. The risk is a dynamic term and can change over time, it is therefore important to continuously monitor and assess. The process typically includes risk assessment, risk treatment, risk acceptance and risk communication (Aven(b), 2008). The goal of the process is to identify, analyse, assess, and evaluate possible risks related to the drilling activity, and come up with actions that will limit or reduce the severity of the consequences (Rausand & Utne, 2009).

The risk management process is illustrated in Figure 20. The risk assessment is an essential part of the process and includes risk identification, analysis, and evaluation. Figure 21 shows roughly how the loop should be conducted. The loop is based on Deming's PDCA (Plan, do, check, act) cycle, which is a well-known quality assurance cycle. The goal of the loop is to identify changes in the risk and where improvements are needed (Aune, 2000). As a result of the increased uncertainty in the WBS region it is especially important to have a good risk management system in order to avoid major accidents.

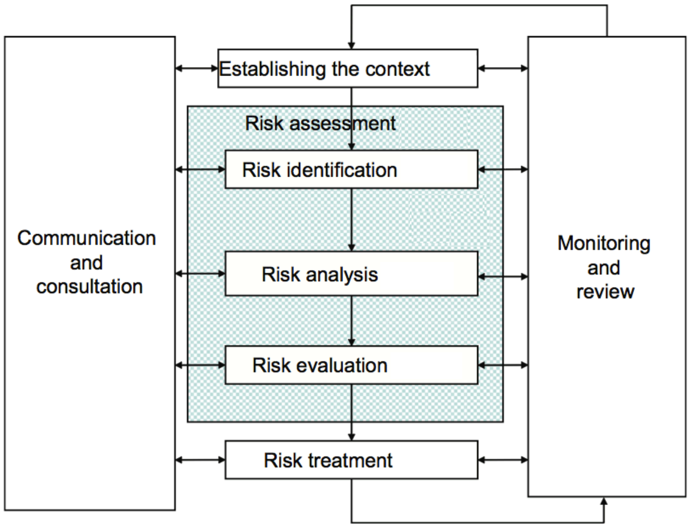


Figure 20: Risk management process (International Standard, 2009, p.14).

Figure 21: Risk management cycle (Barents 2020, 2012, p.112).

2.5.3 Risk influencing factors and acceptance

Risk influencing factors (RIF´s) are factors that affect barriers and barrier performance (Aven et al., 2008). The RIF´s are often divided in different groups such as: technical, human, organisational, environmental, regulation, and social. Examples of technical RIF´s are design, material characteristic, and technical condition. Human related RIF´s are for instance competence, workload, and working environment (Rausand & Utne, 2009).

This thesis will look closer into environmental RIF´s. It is known that the environmental condition in the Barents Sea can be challenging because of its cold temperatures, strong winds, reduced visibility, precipitation, and icing. These factors are environmental RIF´s and it is important to map them in an early stage before any operation takes place. How the RIF´s influence a specific system and how important they are is valuable data that has to be considered (Gao & Markeset, 2007).

2.5.4 Risk tolerance and acceptability

Criteria for risk tolerance and acceptability is a central part of risk management process. The risk tolerance limits defines the risk levels that are unacceptable and acceptable with respect to HSE (health, safety, and environment) and financial values (Barents 2020, 2012).

Risk acceptance criteria is used to express acceptable and unacceptable risk level. That a risk is acceptable means that the risk level is tolerable in a given period of time or in a given phase of an activity. The criteria give an evaluation of the selected solution and the need of risk reduction measures (Aven et al., 2011). If the calculated risk is lower than a predetermined value the risk is acceptable. The requirements regarding acceptance criteria in the petroleum industry is presented in 2.7 Regulations and Requirements.

The *ALARP* principle states that the risk level of a given activity should be *as low as reasonable practicable*. This means that the cost involved in reducing the risk shall not exceed the benefit gained (Aven et al., 2008). The ALARP principle is built on the statement that infinite time, effort, and money could be spent to eliminate the risk. When applying the principle it is normal to divide the risk into three categories:

”*1. The risk is so low that it is considered negligible*
2. The risk is so high that it is intolerable
3. An intermediate level where the ALARP principle applies” (Aven(a), 2011, p.8)

To verify ALARP, procedures such as engineering judgement, check lists and codes, or cost-benefit analyses are applied (Aven(a), 2011).

2.6 Barriers and Barrier Management

A barrier is a technical, operational, organisational or other planned action that has the goal to identify and stop a chain of unwanted events (Rausand & Utne, 2009). Barrier management is an important part of a risk management process. The main objective with barrier management is to establish and maintain safety barriers. The management is important to ensure that the barriers, at any time, can handle the involved hazards by preventing incidents to happen or reduce loss and mitigates the consequences if the incident occurs (Barents 2020, 2012).

The Barents 2020 (2012) report states that the management of safety barriers shall include the management processes, systems, and measures. This is to ensure necessary risk reduction and comply to the requirements set to safe design and operation. The report also presented a barrier management list of what it should contain:

- *“ Which function the different barriers shall maintain*
- *Which performance requirements have been placed on the technical, operational or organisational elements that are necessary to ensure that the individual barrier is effective*
- *Monitoring - which barriers are non-functioning or weakened, and the effect on the risk level*

- *How to implement necessary compensating measures to restore or compensate for missing or weakened barriers"* (Barents 2020, 2012, p.124)

Safety barriers can be either physical or non-physical means, and every barrier has its own function. The barrier function is a function to prevent, control, or mitigate unwanted events (Sklet, 2005). It is normal to distinguish between passive and active barriers, and proactive and reactive barriers. Passive barriers are barriers that are integrated in the design and are independent from operational control systems. Active barriers are barriers that are dependent on the operator actions or technical control systems to function. Proactive barriers are barrier that reduces the frequency of an unwanted event. Reactive barriers are barriers that limit the consequences if an unwanted event has occurred (Rausand & Utne, 2009).

Barriers are widely used to ensure safe operations in the petroleum industry. For drilling operations in the Western Barents Sea (WBS) it can be important for the industry to add barriers to protect vulnerable systems, working area, and personnel from the physical environment. Essential systems like escape routs and fire fighting systems have to be protected. Today it exist both de-icing and anti-icing methods that are used as barriers (Ryerson(a), 2010), different weather shielding systems to protection from wind and precipitation is also used (Sætrum et al., 2011).

From time to time it occurs that the barriers do not function as originally planned. The reasons for their failure or malfunction can be many, and it is important to avoid and detect it. James Reason´s *Swiss cheese model* illustrates that a chain of holes (failure or malfunction) in barriers eventually will lead to an unwanted event, if the barrier failures is not identified. A barrier alone does seldom lead to an accident, but a sequence of several barrier failures together can lead to unwanted events. Reason also states that many of the gaps are contingencies and are hard to identify (Reason, 1997).

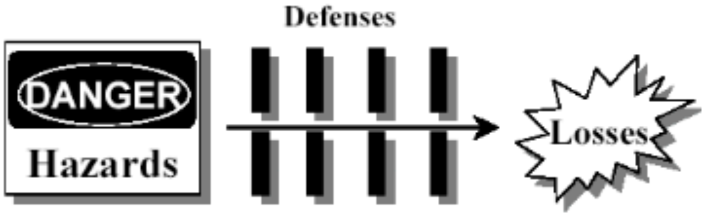


Figure 22: Swiss cheese model where holes in the barriers lead to unwanted events (Reason, 1997, p.1).

2.7 Regulations and Requirements

This section will introduce relevant Acts and regulation for drilling operations in the Arctic region. At first the Norwegian situation will be presented and after a short summary for the rest of the Arctic will be given.

2.7.1 Norway

When drilling in the Western Barents Sea (WBS) there are a number of laws and regulations that have to be fulfilled and followed at any time. The Norwegian Petroleum Safety Authority (PSA) is the regulatory authority for technical and operational safety, including emergency preparedness and working environment. The regulatory role covers all phases of the petroleum industry, from planning, design through construction, and the whole operation to possible removal (Petroleum Safety Authority Norway, n.d.).

The regulatory approach for offshore drilling in Norway is performance-based. Performance-based regulation identifies functions or outcomes for regulated entities, and allows petroleum operators considerable flexibility. The flexibility is to determine how the operators will undertake the functions and achieves the outcomes (Dagg et al., 2011).

The concept of well barriers and the control of barriers are essential in the Norwegian regulation. As already mentioned, barriers are used to reduce the probability of failures, hazards and accidents. The barriers are selected based on its potential to reduce risk, with prioritization of barriers that reduce collective risk rather than individual risk. The regulations do not require a specific number of barriers in a system, but what is required is redundancy. More than one barrier is necessary and each barrier shall function independently (Dagg et al., 2011).

There are five *Acts* from the PSA that concerns drilling activity in Norwegian sector:

Petroleum Activities Act
Health Personnel Act
The Pollution and waste Act
Working Environment Act
The Fire and Explosion Prevention Act

The Petroleum Activities Act (Act November 29th 1996 No. 43) regulates the management of the Norwegian petroleum resources. The purpose of the Act is to ensure the best possible utilization of resources (Lovdata, 1996). The purpose of *The Working Environment Act* (Act June 17th 2005 No. 62) is to ensure a working environment that gives personnel full protection against physical and mental risk. The Act also provides the basis for the businesses to solve their problems in partnership and supervision by public authorities and organisations (Lovdata, 2005).

The petroleum industry also has additional *regulations* to follow, established by the PSA since 2002 (PSA, n.d.). The regulations are as follows:

Framework HSE Regulation
Information Duty Regulations
Activities Regulation
Management Regulation
Facilities Regulations
Technical and Operational Regulations

The Management Regulation, Section 9, *Acceptance criteria for major accident risk and environmental risk*, state:

"The operator shall set acceptance criteria for major accident risk and environmental risk.
Acceptance criteria shall be set for:
a) The personnel on the offshore or onshore facility as a whole, and for personnel groups exposed to particular risk,
b) Loss of main safety functions for offshore petroleum activities,
c) Acute pollution from the offshore or onshore facility,
d) Damage to third party…" (PSA, n.d.)

The Framework HSE Regulation is a high level regulation that includes the overall principles which is elaborated further in other regulations. In the regulation, Section 11, *Risk reduction principles*, state:

> "*… the risk shall be further reduced to the extent possible. In reducing the risk, the responsible party shall choose the technical, operational or organisational solutions that, according to an individual and overall evaluation of the potential harm and present and future use, offer the best results, provided the costs are not significantly disproportionate to the risk reduction achieved*." (PSA, n.d.)

There exist numerous of different *standards* related to drilling operation, which the petroleum industry is recommended to follow. Both ISO and NORSOK standards have several recommendations and requirements in all parts of the process, from recommended use of drill bits, to use of different drilling fluids, and to equipment that should be used in different sediments. Drilling operators is encouraged to use a risk assessment approach as defined by NORSOK D-010 standard. The advice is to minimize risk to personnel and of pollution, and to calculate the probability of failure (Dagg et al., 2011).

2.7.2 Other places in the Arctic

In 1996 the Arctic Council was established as a high-level intergovernmental forum to provide a means for promoting cooperation, coordination and interaction among the bordering countries in the Arctic. Involvements of the Arctic Indigenous communities and other Arctic inhabitants on common Arctic issues have been of importance for the council. A sustainable development and environmental protection in the Arctic are desirable. The member states are: Canada, the kingdom of Denmark, Finland, Iceland, Norway, Russian Federation, Sweden, United States of America (U.S.A) (Arctic Council, 2011).

There are no common regulation for petroleum drilling and production in the Arctic region, and each bordering country may have its own way to rule and regulate. The overall regulatory approach of offshore drilling can either be prescriptive requirements or performance-based regulations. Many regimes include elements of both approaches. In contrast to the performance-based regulation used in Norway, the Prescriptive regulation sets specific technical or procedural requirements that shall be followed. This type of regulation is for instance used in the U.S.A. (Dagg et al., 2011).

However, even though there are many different ways to regulate, there are still some similarities between the countries. What is common for the offshore drilling acts and regulations are that they include environmental protection, safety, employment standards and work environment, health protection, emergency planning, oil spill response, and liability of accidents. The given topics are usually covered by either a single act and associated regulations or several different acts. In order to avoid overlap between the different acts, a separate drilling act may be established for clarification. The Canadian Arctic is regulated by one main Act, but there are many regulations under that Act. In Greenland most aspects related to drilling is gathered in one Act. The United Kingdom (U.K.) and the U.S.A. each have one principal Act governing offshore drilling. The U.K. has in addition several regulations under the different Acts (Dagg et al., 2011).

3 ENVIRONMENTAL LOADS AND RISK INFLUENCING FACTORS FOR DRILLING OPERATIONS IN THE WESTERN BARENTS SEA

This section will state how harsh the physical environment in the Western Barents Sea (WBS) is. The environmental loads will be presented. A list over the risk influencing factors (RIF´s) and their importance will be given, and in the end of the chapter the physical environment in the North Sea will be presented for comparison with the WBS.

3.1 Environmental Loads

To identify safety issues caused by snow or ice on offshore structures requires a good understanding of snow and ice types, where it forms, and how it affects different operations. It also requires identification of technologies currently used to combat ice hazards (Ryerson(b), 2008). When designing an offshore structure it is important to consider and calculate expected loads from ice, and also evaluate other environmental factors like wind, waves and sea currents. Different types of ice give different loads and cause different challenges. In addition, not all kinds of ice are present in all regions of the Arctic, and the ice condition varies in the different places (Yue, n.d.).

3.1.1 Environmental loads

The experience data presented (2.2 Physical Environment) indicates that there is harsh and cold weather in the WBS region. Low air and sea temperature in combination with high wind speeds makes good foundations for ice accretion. Sudden occurrence of polar lows can be extremely dangerous if it introduces heavy snowfall and high frequency of sea spray icing.

In a personal conversation with Gudmestad (2013), he stated that structural stability could be of great risk if loads from ice or snow are present. The possibility of a major accident if a structure collides with floating ice or if the ice concentration on the upper parts of a structure is high, is of great concern (Gudmestad(c), 2013).

Sea ice is expected in the region. Based on the presented data the occurrence is varying from year to year. In several of the analysed years the ice edge is shaped like a triangle with one of the corners is centred right north of Bjørnøya. This makes the drilling location free for ice. However, according to Figure 13 (page 21) the ice edge is expected to be in the drilling zone from time to time. The expected ice is first year ice and is not significantly thick. However, the load form the sea ice should be estimated. If a drilling structure should operate in the region during winter months it should be prepared for sea ice conditions and be designed to withstand the load. Another challenge with sea ice for drilling structures is that it may be difficult for structures to move away from location after disconnecting. Disconnection can, as already mentioned, be used if there is a high danger of for instance collision with an iceberg. If a structure cannot move from the location dangerous situations can occur and therefore management to remove ice is needed.

Sea spray icing is present when there is limited amount of sea ice and when the environmental factors allow it. The sea spray icing will in the extreme cases be a significant safety hazard for a drilling structure. Ice accretion with a rate of more than 5 cm/h can be expected in many situations. The ice will however attach the lower surfaces of a structure. The ice attaches itself to horizontal surfaces and to small diameter surfaces. This will increase the total weight of a structure, and in worst cases it can affect the stability by changing the centre of gravity. The expected amount of sea spray icing in the region will be presented in 3.1.2 Calculation of environmental factors.

Figure 23: Heavy ice loads from sea spray on vessel (Gudmestad(b), 2010, p.5).

Icebergs are not frequent in the region but may occur from time to time. Collision with a drilling structure can lead to catastrophic consequences. If the iceberg is of great size and the drifting speed is high the damages can destroy the structure and capsize the structure, and several fatalities and spill of hydrocarbons can occur. The potential consequences make it extremely important to avoid collision by having proper ice management.

Intrusion of *Snow* presents a risk. Snow deposits and snow penetration in working areas are therefore not desirable. Arctic snow has usually smaller grains than regular snow; this is because the snow normally has longer transportation. Small grains of snow can easily entrain small gaps. Wet snow can be heavy and expose structures for unwanted loads that may lead to damages. Blowing snow reduces the visibility and can penetrate small gaps and openings of a structure. Snow can clog important systems such as ventilation systems, which lead to insufficient ventilation rate. Surfaces with snow can also be very slippery and be hazardous for personnel.

Atmospheric icing can occur practically everywhere at a drilling structure and is not affected by the sea spray-generated ice. Atmospheric icing is assumed to occur at all surfaces of a drilling structure during the winter months in the region. The ice can cause damages or delays if it freezes on windows, cranes, hatches, or other essential systems.

Icicles normally have a narrow shape at the edge and can be a major hazard for personnel and equipment. Icicles can fall off because of changes in air temperature or if it gets too heavy. If icicles fall off and breaks sensitive equipment, maintenance or replacement might be needed. The drilling structure may in some situations expect more downtime if sensitive areas are damaged. The formation of icicles should be prevented.

Polar lows introduces a great hazard for drilling operation during the winter months. Its sudden occurrence and extreme wind and snow loads may damage structures and make good conditions for icing. Based on the accident data presented, it is reasonable to believe that many of the previous vessel accidents in the Norwegian region are a consequence of the effect from polar lows.

Negative air temperature is one of the main reasons of formation of snow and ice. Water freezes if it is cooled down to the freezing point (0 °C). The temperature affects the type of formed ice and snow. Human limitation related to operation in cold climate is strongly influenced by the air temperature. If the weather is too harsh it can delay important maintenance activities. Negative air temperatures should be expected in most of the months throughout a year in the region.

Negative sea temperature increases the chances of getting sea ice and icing on structure from for sea spray. The winter months have negative sea temperatures.

Wind and Waves can together generate motions that can have a significant effect on the stability of a drilling structure. Motions of a floating drilling structure are important to measure and consider. Too much motion may damage the riser and equipment at the seafloor and drill floor.

Previous accidents from the region do not indicate that there is a direct connection between the physical environment and the accidents occurrence. However, some of the accidents are caused by harsh and cold weather from for instance polar lows and loss of stability as a result of sea spray icing.

3.1.2 Calculation of environmental factors and loads

By using the presented environmental data in 2.2 Physical Environment, calculation of expected loads on the structure will be presented. Examples from the calculation are shown in Appendix B. The accretion predictor (PR) is calculated below by using the sea spray icing accretion equation. Table 13 presents the accretion predictor based on average seawater temperature, the average and extreme air temperature and wind, for Bjørnøya. The data was presented in 2.2 Physical Environment. The freezing point of the seawater was set to be -1.9 °C which is the freezing point of water with salinity of 34 ppt. The table shows that on an average basis it can be expected to have sea spray icing from November to the end of April. Table 8 (page 19) shows the categorisation of accretion. In most of the months with average values there will be moderate icing (0.7 – 2.0 cm/h). In extreme conditions there may be sea spray icing from October to June. Many of the months presents a significant higher PR number than the "Extreme" situation in Table 8, which is set to be 70 m°C/s (> 5.0 cm/h).

Table 13: Expected amount of sea spray icing at the given location.

Month	Average PR [m°C/s]	Extreme PR [m°C/s]
January	44,36	349,76
February	38,49	383,85
March	39,50	285,79
April	18,05	232,41
May	No icing	82,98
June	No icing	6,77

Month	Average PR [m°C/s]	Extreme PR [m°C/s]
July	No icing	No icing
August	No icing	No icing
September	No icing	No icing
October	No icing	38,69
November	6,40	76,50
December	30,21	235,24

Additional mass from snow and ice formation can affect the stability of a structure if the amount is significant. Sea spray ice and snow accumulates mainly on horizontal surfaces. The calculation in the table below shows roughly how much more mass that can be expected from sea spray icing and snow. The amount of sea spray icing is 5 cm. This is categorized as an extreme situation for one-hour accretion. On an area of 10 m^2 it can be expected to have 463 kg extra mass after one hour. The additional mass from snow is calculated from the maximal precipitation in a month, 4.8 cm. Ice and snow will not always be evenly distributed over a surface in actual situations. However, the snow will most likely not affect the stability of a structure according to this data, the ice mass can on the other hand be of consideration due to this mass after just one hour.

Table 14: Expected additional mas son structure. Density data are from: (Løset & Høyland, 1998).

Month	Density [kg/m^3]	Accretion [cm]	Kg on 10 m^2
Sea spray icing	926	5	463
Snow	400	4.8	192

Based on the presented drift speed of icebergs and the horizontal view of 800 m, the drifting time for the distance is calculated. Table 15 shows that on average an iceberg uses 53 minutes to drift the distance, however, under the right circumstances the iceberg can drift the distance in 10 minutes. 10 minutes is a short time to make important decisions and actions, such as whether or not to disconnect from the riser. When it is dark it is harder to detect icebergs. Ice management such as detection and tracking of icebergs may be a solution.

Table 15: Time for iceberg to drift 800 m by using drift speeds measured by Løset (2012).

Horizontal view [m]	Drift speed [m/s]	Time [min]
800	0.25	53
	1.13	12
	1.38	10

The wind chill index (WCI) is calculated by using the average and maximum values for air temperature and wind speed for the WBS. The green zone is below the restriction limit and 100 % work every hour for all personnel is allowed. The yellow zone is between 1000 and 1500 W/m^2 and 33 % - 100 % work is allowed. The orange zone has 0 % - 33 % acceptance per hour. The red zone is restricted to no work outdoor. In worst case it can be expected to have working restrictions for personnel the whole year, but on average the personnel will be able to work outside 33 % - 100 % of an hour.

Table 16: Calculated wind chill index in the Western Barents Sea.

Month	Average WCI [W/m^2]	Extreme WCI [W/m^2]
January	1274	1956
February	1230	1964
March	1247	1851
April	1136	1751
May	1011	1497
June	905	1224
July	829	1106
August	820	1089
September	931	1214
October	1015	1405
November	1079	1506
December	1231	1825

3.2 Risk Influencing Factors (RIF´s)

The potential harsh and cold environment in the region has been presented in the thesis. Based on the presented data, this section will introduce the environmental risk influencing factors (RIF´s), which might present a hazard to systems and components of a drilling structure.

Table 17 shows when the different RIF´s can be expected during a year. The table can possible contributes as a foundation to have a better preparedness for the expected environmental conditions. The winter months presents the highest number of RIF´s. The months from October to May have 7 or more factors that may occur. July and August are the only months with only 2 RIF´s. To the right in the table the load category is placed. The load category indicates how the often the RIF´s will affect structures in the Western Barents Sea (WBS), the rare processes will seldom occur in a year whilst the frequent processes must be expected several times throughout a year.

Table 17: Environmental risk influencing factors (RIF´s) for the Western Barents Sea.

Environmental RIF´s	January	February	March	April	May	June	July	August	September	October	November	December	Load category
Sea ice	X	X	X	X							X	X	Rare Environmental Processes
Sea Spray icing	X	X	X	X	X	X				X	X	X	Frequent Environmental Processes
Icebergs				X	X								Rare Environmental Processes
Fog						X	X	X	X				Frequent Environmental Processes
Snow	X	X	X	X	X	X			X	X	X	X	Frequent Environmental Processes
Atmospheric icing	X	X	X	X	X	X			X	X	X	X	Frequent Environmental Processes
Polar night	X	X								X	X	X	Frequent Environmental Processes

Environmental RIF´s	January	February	March	April	May	June	July	August	September	October	November	December	Load category
Icicles	X	X									X	X	Frequent Environmental Processes
Polar lows	X	X	X	X	X					X	X	X	Frequent Environmental Processes
Negative air temperature	X	X	X	X	X	X			X	X	X	X	Frequent Environmental Processes
Negative sea temperature	X	X	X	X	X							X	Frequent Environmental Processes
Wind chill restrictions	X	X	X	X	X	X	X	X	X	X	X	X	Frequent Environmental Processes

The impact from different ice types on structure function is shown in Table 18. The cross-tabular methodology used in the table is developed by Ryerson (2010). The different ice types (RIF´s) are ranked by the expected hazard that they might inflict on structure safety. The structure functions are ranked by the relative importance of each function to overall structure safety. For instance, frost as an icing type has less impact on helicopter landing pads compared to snow. However, the helicopter pad has a greater impact on the overall structure safety than for instance railings, if both are iced. The coloured classification is raked like this: 70-100 red, 30-69 yellow, and 0-29 green.

The hazard rating is the hazard from the different types of ice, the raking is from 1 to 10 where number 10 is the highest threat. For instance, sea spray ice is the highest threat, and is more dangerous than frost and sleet.

The safety rating indicates the impacts on structure safety. The ratings are based on the importance of functions or components. Threats to the safety of an entire structure are of greater importance than threats to the entire crew, which again are more important than threats to individuals. Threats to individuals are more important than threats to work tempo. A rating of 10 signifies a high threat and a rating of 1 indicates a least threatening condition.

Table 18: Joint safety impacts by ice type and component or functions, with large numbers denoting a more serious safety hazard (Ryerson(a), 2010, p.98).

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

3.3 Physical Environment in the North Sea

In order to evaluate how harsh and cold the environment in the Western Barents Sea (WBS) is, data from the Norwegian continental shelf (NCS) will be presented for comparison. Icing is not a problem a problem in the region and is therefore not described further.

Table 19 presents weather data from the production structure Gullfaks C in the North Sea. The structure is located northwest for Bergen, 121 km from shore (NOFO(b), 2007). The temperature is generally warm and the minimum temperature measured in the time period was -3.6 °C, which was in January 2004. The air temperature is much warmer compared to the environment in the WBS. The winter condition in the North Sea (November to March) is close to the summer condition in the WBS (from June to the end of September). The average seawater temperature in the North Sea is also presented in the table. The temperature in the region is approximately 8 °C warmer than in the WBS throughout an average year. The presented wind speeds are average values for 2012. The maximum wind speed is expected to be significantly higher than the presented values. The average values are approximately the same as the average values for the WBS. Throughout the year it is on average much more sun in the North Sea compared to WBS.

Table 19: Gullfaks C in the North Sea - Minimum air temperature, average wind speed, average hours with sun (met.no, n.d.), and average seawater temperature (NOFO(a), 2007).

Minimum air temperature at Gullfaks C [°C]												
Year	January	February	March	April	May	June	July	August	September	October	November	December
2003	-0.7	0.7	1.8	2.6	2.5	8.0	11.5	11.3	6.7	3.3	5.0	-1.5
2004	-3.6	-1.6	2.6	3.0	6.5	7.4	9.3	11.8	7.6	6.1	-0.1	-1.6
2005	2.6	1.7	-0.1	-0.3	3.5	5.5	10.0	9.8	5.9	2.5	-0.8	-2.8
2006	2.1	-0.8	-0.6	2.2	3.6	6.3	10.3	11.3	10.2	5.8	3.3	3.7
2007	0.1	-0.3	1.9	-0.2	3.1	6.5	9.4	8.0	5.2	4.2	0.5	3.0
Average seawater temperature at Gullfaks C [°C]												
	8.8	8.3	8.0	7.9	9.0	10.3	12.5	13.3	12.5	10.8	9.8	9.1
Average wind condition at Gullfaks C [m/s]												
2012/13	7.4	7.7	6.6	7.4	7.0	7.5	7.8	5.4	8.1	7.3	8.1	8.2
Month Normal of hours with sun [h] for Gullfaks C 1961-1990												
	19	56	94	147	185	189	167	144	86	60	27	12

The significant wave height, period, and maximum 100-year surface currents for the North Sea (Figure 24) are not that different from the condition in the WBS. The most significant difference is the wave periods, which are around 2 seconds shorter in the North Sea.

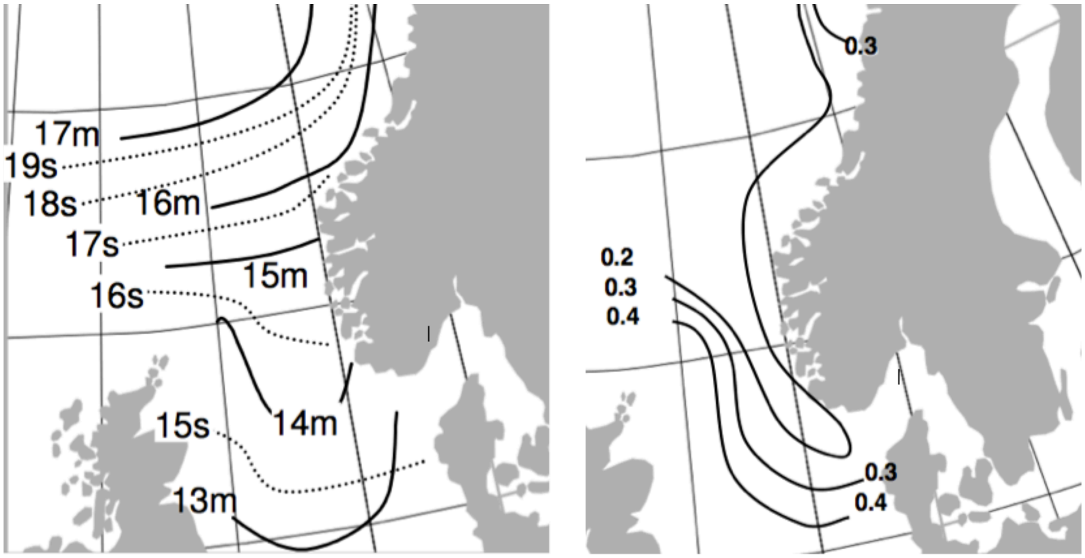


Figure 24: To the left: The significant wave height [m] and period [s] in the North Sea (Standards Norway, 2007, p.13). To the right: Maximum 100-year tidal surface current [m/s] in the North Sea (Standards Norway, 2007, p.17).

When evaluating the presented data it is clear that the physical environment in the North Sea is much warmer and less harsh than the condition in the WBS. However, the environment in the North Sea during winter months has similarities with the summer conditions in the WBS.

4 EXISTING BARRIERS FOR PROTECTION FROM PHYSICAL ENVIRONMENT

This section will introduce information about existing barriers on winterized drilling structures. In the end of this section a simplified bow tie will be introduced for illustration of the presented barriers.

Throughout the years of drilling experience in harsh and cold climate there have been introduced barriers to limit the operational risk. In this thesis the barriers will be divided into three categories: design, ice management, and de-icing. Figure 25 shows the different existing barriers under the given categories.

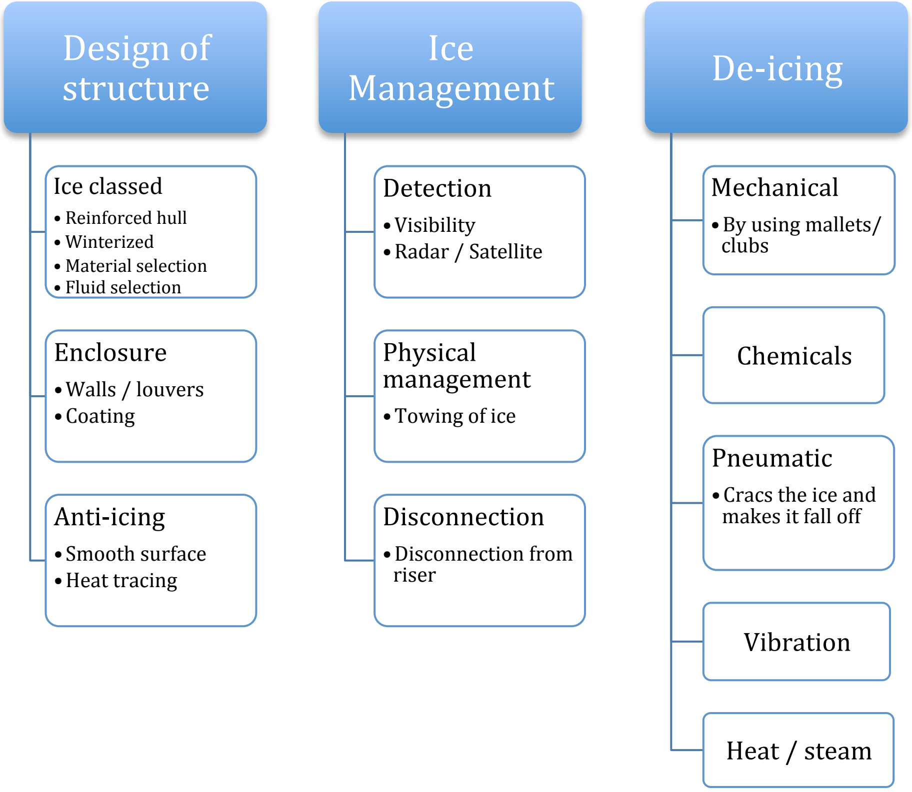


Figure 25: Existing barriers for environmental protection.

4.1 Design of structure

Consideration of environmental loads in the design phase of a structure is essential. To reduce the amount of ice accretion and loads on structure limits the risk of major accidents and makes ice management easier.

In order to get protection from the physical environment a drilling structure can be partly or fully enclosed. Open structure with large amount of small diameter bracing, such as on jack-up rigs, have the potential to allow large icing loads on superstructure. Facilities with complex structure, with many small surfaces and areas for the ice to attach, will most likely have serious icing problems if operating in cold waters (Ryerson(b), 2008). The figure below shows vulnerable areas for icing on a structure that is not enclosed.

Figure 26: Complex cellar deck on the structure Pentronius that would accumulate ice easily if located in colder waters (Ryerson(b), 2008, p.24).

4.1.1 Enclosure of structure

In general, decreasing the magnitude and height of spray generated is the most effective solution to reduce icing. This can be done by reduction of surface areas where ice can attach and accumulate. Reduction or enclosure of small diameter surfaces will limit formations (Ryerson(b), 2008).

Enclosure of structure to protect vulnerable areas and to make a desirable working environment for personnel is effective proactive barriers. Evaluation of environmental factors in the design phase can optimise the quality of solutions. However, a risk related to insufficient ventilation and explosion pressure has to be considered if a structure shall be partly or fully enclosed. Standard explosion relief panels that are used today can freeze and will not be able to ventilate gas clouds or explosion pressures sufficiently, which may lead to fatal consequences (Sætrum et al., 2011).

Figure 27 illustrates the principle with enclosure of structures. The illustration to the left is of a derrick. This shielding barrier provides good protection form environmental loads from ice, snow, and wind. The open solution to the left in the picture has many small diameter surfaces that make a good base for high ice concentration to accumulate. The enclosed solution also limits the consequences of falling ice. The illustration to the right is of the winterized and enclosed Goliat production facility that is soon to start up the production 85 km northwest of Hammerfest, Norway.

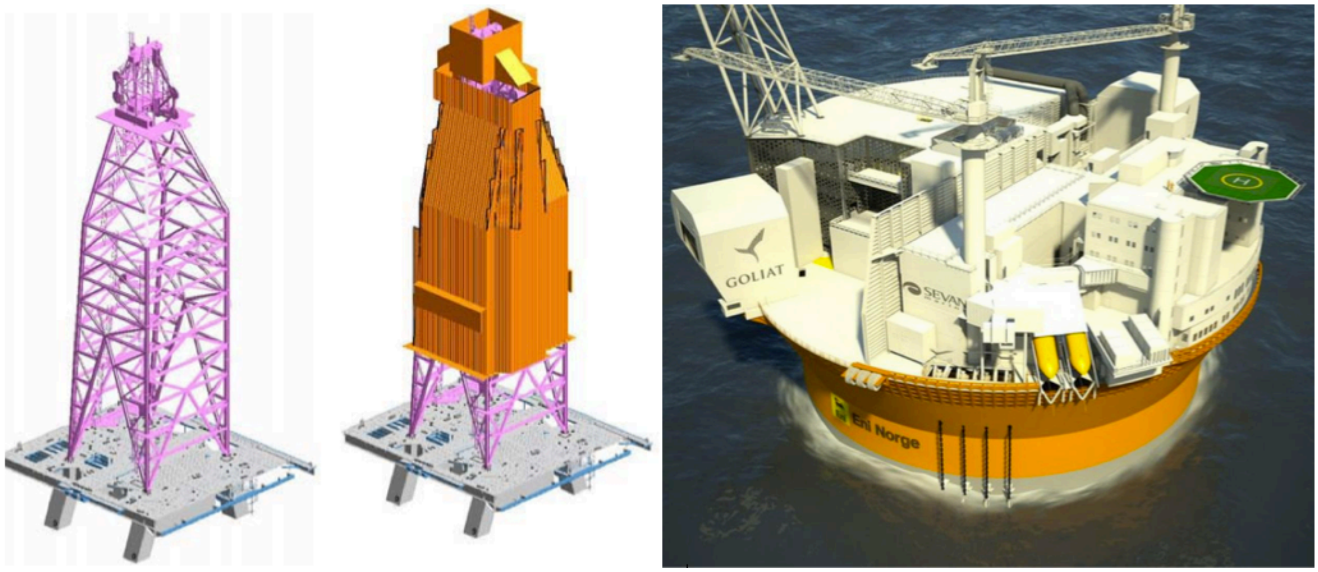


Figure 27: To the left: Derrick with and without wind shielding (Gudmestad(b), 2010). To the right: The winterized Goliat production facility (TU, 2012).

4.1.2 Anti-icing

Anti-icing measures are proactive barriers that limit the accretion of ice on structure. Derricks, flare booms, and cranes on deck can be kept free of ice by means of anti-icing mitigation measures such as heat tracing. However, limited power supply makes it is unclear to foresee to which extent this can be achieved. The barriers have to be less energy consuming than equipment used today. There are also other anti-icing measures. Ryerson ((b), 2008, pp. 48-124) have described 6 different methods in his report and they are listed below. The different methods will not be elaborated in detail in this thesis.

1. *Coatings*
2. *Design*
3. *Heat*
4. *Electrical*
5. *Ice detection*
6. *Windows*

4.1.3 Reinforced hull

According to regulations, structures have to be classed for the intended operational environment. This means for instance that a reinforced hull is needed because of the expected sea ice condition during some winters. DNV has developed different standards regarding design of structures. The offshore standard, DNV-OS-E101 - Drilling plant, is applicable for designing drilling structures.

4.1.4 Materials

When operating in the WBS it is also important to use materials (metals, polymers, concrete, etc.) that do not lose its intended properties in cold temperatures. For instance, metals like steel and iron becomes brittle in cold temperatures. If rubber is exposed to lower temperatures than it is designed for it will crystallise and get porous. These processes that the materials are exposed to are irreversible which means that they by a short period of time will lose their characteristics, fail to perform its required function, and will not be able to go back to have its original properties. However, today it exists different alloys that can be used in sub zero temperatures, and more robust solutions are under development. The polymers that is most used in low temperatures are PTFE (polytetrafluoroethylene) and FEP (ethylene-propylene copolymer) (Freitag & McFadden, 1997). Aluminium is one of the few metals that get stronger in cold temperatures without loosing its quality, and due to its relatively low density it can be a good material for offshore use in cold environment (Sætrum et al., 2011).

4.1.5 Fluids

Use of fluids in machinery and hydraulics has to be adapted for use in cold environment. In low temperatures oil becomes more viscous which makes it more difficult to supply lubricant. At some point, if the temperature continues to fall, it will reach a point where the lubricant will no longer flow. Temperatures below the pour point of oil risks increased wear of machinery as a result of metal-to-metal contact. In order to keep the wear of machinery to a minimum, engines and other systems is also recommended to run permanently. Slow and uniform heating of machinery is desirable in cold temperatures. Freeze protection for liquid based cooling systems is mandatory for machinery operating in temperatures below 0 °C. If a system is not protected from freezing, the coolant can expand because of freezing and damage or rapture systems. Today, the most commonly used antifreeze fluid used for this purpose is ethylene glycol or a fluid with similar properties (Freitag & McFadden, 1997).

4.2 Ice Management

Ice management includes all the actions that reduce the frequency, magnitude or uncertainty from ice incidents. Figure 28 shows the typical components that an ice management system consist of, and its distance from the drilling structure. Zone 1 is the detection zone where the ice are first observed. Zone 2 is the management zone where the ice can be towed with physical management. Zone 3 is the critical zone where the ice is close to the structure. If the ice reaches this zone disconnection is the right solution. All of the barriers in the illustration are proactive barriers that reduce the probability of a collision to occur.

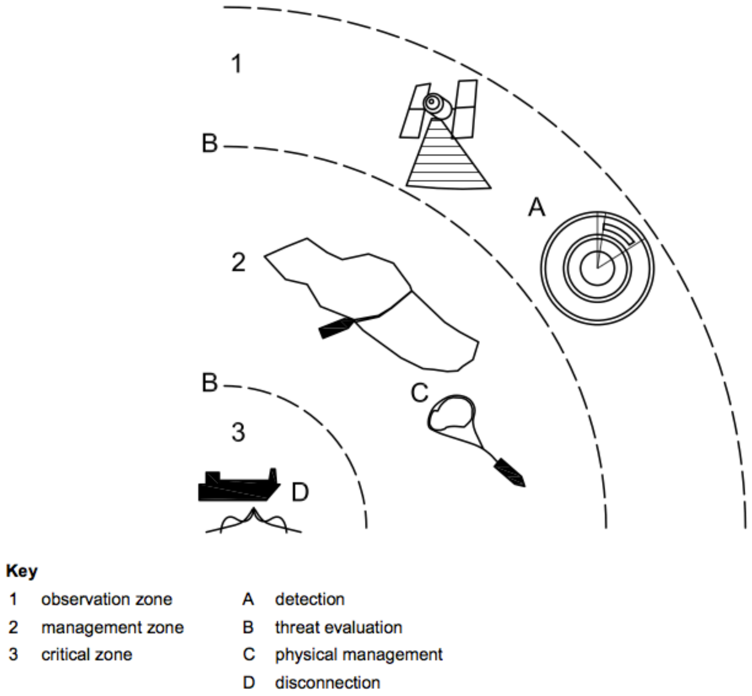


Figure 28: Typical components of an ice management system (International Standards, 2010, p.300).

4.3 De-icing

There exist several different de-icing measures. Some of the de-icing measures, like heat, are also used as anti-icing. De-icing measures are reactive barriers that remove ice from structures. Some of the measures are both proactive and reactive since they are used as both anti-icing and de-icing. Ryerson ((b), 2008, pp. 48-124) have described 12 different de-icing methods in his report and they are listed below. The different methods will not be elaborated further in this thesis.

1. *Chemicals*
2. *Milimetre wave*
3. *Electrical*
4. *Explosive*
5. *Heat*
6. *Hydraulic and steam lance*
7. *Mechanical*
8. *Piezometric*
9. *Pneumatic*
10. *Vibration*
11. *Windows*
12. *Infrared*

Barriers that melt snow and ice can in worst case just transfer the accumulation problem to other parts of the structure if the water is not steamed or collected. If the water is transferred to other parts of the structure it may freeze again.

4.4 Bow tie

To illustrate the arrangement of the existing barriers the author has presented them in a simple bow tie. The unwanted event is ice accumulation on structure and its proactive and reactive barriers are also given. Figure 29 shows the bow tie that includes the existing barriers. To the left in the picture the risk influencing factors (RIF´s) are shown. The RIF´s influences the barrier performance. Today it exists more proactive than reactive barriers. This is most likely a result of the increased operational risk if icing occurs. In other words, the consequences of icing can be of so severe that it is better to avoid it completely.

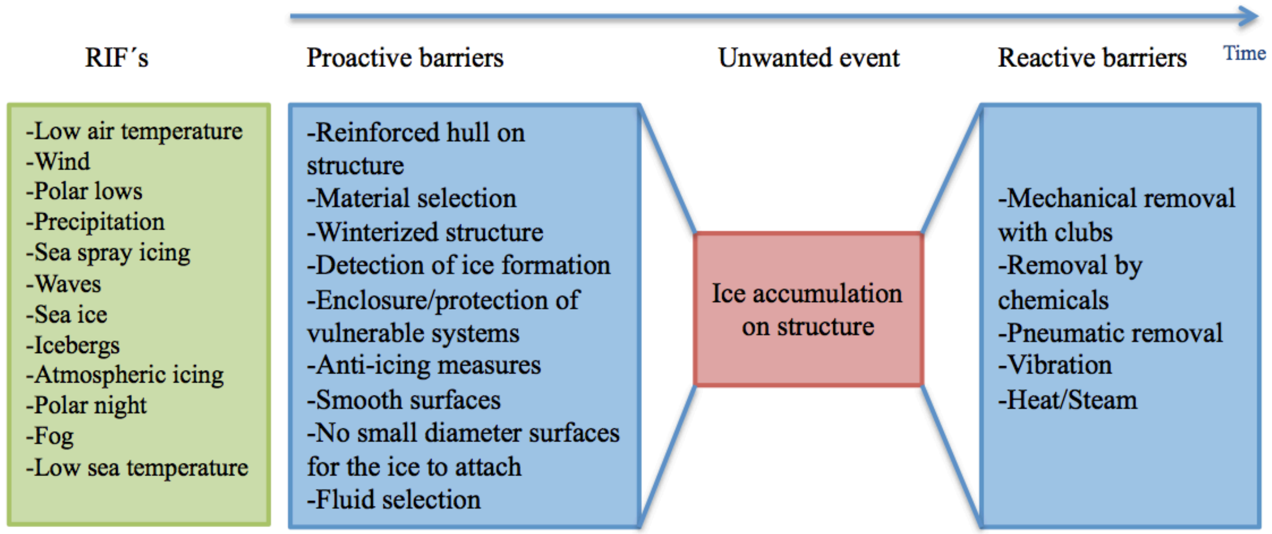


Figure 29: Bow tie with the unwanted event; ice accumulation on structure.

5 OPERATION AND MAINTENANCE CHALLENGES IN THE WESTERN BARENTS SEA

This section will present operation and maintenance challenges for drilling operations in the Western Barents Sea (WBS). Only site-specific challenges related to the environmental condition will be considered. Working environment for personnel and operational support will also be included here.

5.1 Operation and Maintenance Challenges

In order to ensure continuous operation on a drilling structure in the Western Barents Sea (WBS) a plan for operational and maintenance is needed. Sudden and unplanned breakdown of essential systems can lead to expensive downtime, and in worst case be hazardous for HSE.

When *designing* for operations in hash and cold environment like in the WBS it is important to consider the physical environment. The most important factors that should be considered are darkness, low temperature, wind, and icing. Maintenance activities will for instance require proper lightning, and equipment has to be designed to tolerate high and sudden temperature changes (Markeset(b), 2008). As already mentioned, icing can make systems malfunction or make them unavailable. When considering which structural and technical solutions to use in the WBS region, an evaluation of existing systems can be used, and an analysis of the physical environment has to be done. Markeset ((b), 2008) have presented three issues that will affect drilling and production performance, and these factors must be checked in the design phase of systems. The factors are as follows:

"*Will the equipment be placed in such a way that it will be exposed to harsh and cold environment?*
Will the delivery time for the spare parts be affected due to location, infrastructure or weather?
Will the system need to be modified due to environmental requirements?" (Markeset(b), 2008, p.6).

Design for operation, maintenance, and support in harsh and cold environment like in the WBS, requires a good understanding of the interactions between the physical environment, geographical location, components, systems, and humans.

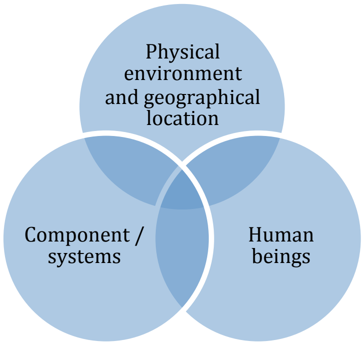


Figure 30: Design for operation, maintenance, and support (Markeset(c), 2011, p.35).

Maintenance is carried out to prevent system failure or to restore system functions when failure has occurred. The goal of maintenance is to maintain or improve system reliability and operation regularity. Unwanted factors like unreliability, poor quality, human errors, etc. influence the design and development of operational support and the maintenance concept (Larsen, 2007). Maintenance is often divided into three sections: improvement, planned maintenance, or unplanned maintenance. *Improvement* is upgrading of already existing systems and can for instance be small modification, modernization, redesign, etc. *Planned maintenance* is used to limit the downtime due to repairs. When using data from for instance OREDA (Offshore reliability data) for planning maintenance, the data has to be modified for use in the Arctic (Markeset(d), 2008).

Figure 31 shows scheduling point for maintenance and three different failure points: A, B, and C. By adjusting the data using various models, it is possible to get situations where equipment is put under more stress than assumed, and a failure can occur before maintenance is scheduled (failure in A). To avoid downtime it is normal to be conservative and schedule maintenance frequently and before it is needed (failure in C). This may lead to increased cost on spare part and personnel, and in addition loss of income because of more downtime. *Unplanned maintenance* is correction as a result of failures (Markeset(d), 2008).

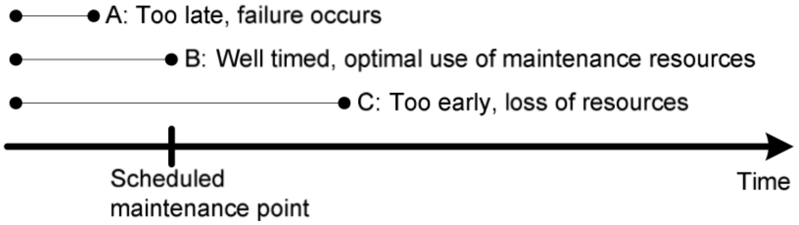


Figure 31: Scheduling of maintenance (Markeset(d), 2008, p.4).

In the WBS region the infrastructure is not well developed and special attention should be given to this when planning for maintenance. The remote location in the WBS may lead to longer delivery times of spares and personnel, and it may be necessary to keep more spare parts on site than normal. In addition, when starting up new operations in new and harsh environment, more corrective maintenance in a break-in phase must be expected. Even though the systems have been designed for the local conditions and taken all influencing factors into consideration, the equipment may never have been used in the actual conditions. Another factor that is of importance for maintenance is that by performing repairs one also increases the chance of failures after the repair. These failures are caused by the break-in of new components or spare parts, or failures induced when the maintenance was performed (Markeset(d), 2008).

When *scheduling for maintenance* it is common to use historical and statistical data of how often equipment have to be maintained or replaced. In cold climate, such as in the WBS, there is lack of available data because of the limited experience for such operations (Barabady, 2011). The frequency of maintenance intervals may be different from warmer environments. The expected types of challenges and the frequency of maintenance intervals can be changed. Figure 32 shows how different environmental factors may affect the failure rate of a system over time. Z_1, Z_2, Z_3, and Z_4 present different environmental factors affecting the same system. The figure shows that factor Z_4 leads to a higher probability of failure than Z_1 (Larsen, 2007).

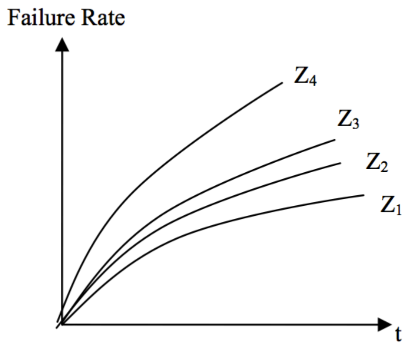


Figure 32: Failure rate of the same system but with different influences from environmental factors (Larsen, 2007, p.7).

A specific case study of gas production in the Arctic, performed by Gao, Barabady, and Markeset (2010), showed that the reliability of a system will decrease significantly faster compared to operation in non-Arctic (normal) condition. Figure 33 shows the result of the study. The decrease in reliability because of the physical environmental impact in the Arctic is significant. In normal condition the reliability is close to 1 (100 %) in the beginning whilst the Arctic condition has approximately 0.7 (70 %). After 19,000 hours the reliability in normal condition is close to 0.8 whilst the Arctic condition has reliability close to 0.1. However, these numbers are only used as an exemplification and illustration in this thesis, and information about how harsh the condition in the Arctic was is not presented. The actual reduction of reliability will vary with the influencing factors and exposed systems.

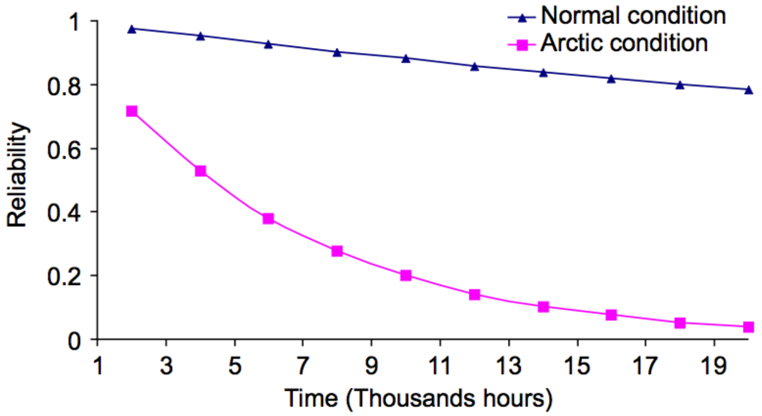


Figure 33: Reliability of a specific gas production system in the Arctic and normal condition (Gao et al., 2010).

Low reliability, like shown in the above figure, leads to increased uncertainty and influences the maintenance planning. In order to achieve effective maintenance management, the physical environment in the WBS has to be mapped and described in detail. After the mapping, the working environment must be designed (Barabady et al., 2009). In order to achieve low downtime, good system availability is essential (Markeset(b), 2008). It is important to have high system performance to keep systems stable and prevent corrective maintenance for critical components. *Corrective maintenance* is maintenance after failure of system/equipment. Unwanted corrective maintenance will in many cases lead to increased downtime, loss of income, and can potentially create dangerous situations for HSE and cost related issues (Markeset(d), 2008). However, to improve the reliability performance: sensitivity analysis, importance measures and risk analysis can be used (Gao & Markeset, 2007).

5.2 Working Environment

Human labour is important on a drilling structure. The industry is completely dependent on their staff and that they perform their intended tasks, at the intended time, and for the intended period of time. This section will introduce briefly how low temperatures and low visibility can affect human performance.

The calculated wind chill index (WCI) presented earlier (3.1.2 Calculation of environmental factors and loads) indicates that the low temperatures and wind in the Western Barents Sea (WBS) will set limitations for personnel operating on a drilling structure, if no shielding or other protection barriers are used. Achieving good work performance during winters is more demanding and challenging compared to summers. Low air temperatures reduce physical performance. Wind, snowfall, and darkness in combination with low air temperatures will significantly reduce the operational effectiveness for personnel (Larsen, 2007). Kumar, Barabady, and Markeset (2009) have presented a shortened list that emphasises that working in cold temperatures has adverse affect on the human performance. Cold environment may lead to:

- "*Reduced manual skills, dexterity, coordination and accuracy with impact on productivity and safety*
- *Increased risk of musculoskeletal injuries from stiffness of muscles and joints and reduced peripheral circulation.*
- *Increased risk of accidents from reduced alertness, manual dexterity and coordination.*
- *Discomfort from cold stiff hands and feet, runny nose and shivering*
- *Impaired ability to perceive cold, cut, pain and heat*
- *Reduced decision making ability*" (Kumar et al., 2009, p.4).

Poor visibility from fog or polar nights can also affect the working environment for personnel. Polar night usually causes lower visibility than fog. The darkness is constant and do not change as a result of increased wind speed, as it is for fog. Poor visibility may affect and slow down operations if it is lack of proper light to conduct specific tasks. Reduced visibility also increases the hazard for personnel injuries and misactions. To live and work in a place where it is dark over longer periods may also affect the mental state for a human in a negative direction. Sleep patterns and mood can change. The darkness can also reduce the cognitive and physical performance further (Thelma, 2010).

An additional challenge with the physical environment is that maintenance activities can be difficult to *perform for personnel*. Icing and snow deposits may be a serious problem. Icing can prevent access to or inhibit functions, and will pose a hazard for operation and HSE. Falling ice, slippery surfaces, and clogged systems can lead to severe damages. Heavy clothing like boiler suits, boots, and mittens can also lead to ergonomically and dexterity challenges of the maintenance performance (Thelma, 2010).

5.3 Operational Support

The remoteness of the Western Barents Sea (WBS) region and the limited infrastructure will pose a critical factor for operations and maintenance. The great distances to the majority of the suppliers and venders will cause greater lead-time, and an unplanned breakdown may lead to serious reduction of performance. This will put greater pressure on the spare part and maintenance program. The weather situation with occurrence of polar lows in combination with poor infrastructure and distance may increase lead-time further. Helicopters have flight limitations due to weather conditions. Wind speed and cloud coverage/visibility can in some cases lead to that helicopters cannot operate for hours, even days. These factors do not only apply to spare parts, but also for transportation of personnel and other equipment (Markeset(b), 2008).

6 RISK ASSESSMENT FOR DRILLING OPERATION IN THE WESTERN BARENTS SEA

The uncertainty related to drilling activity in the Western Barents Sea (WBS) region is significant. The vulnerable environment, remoteness, and possible outcomes of an accident are of great concern. The society, the regulatory authority, and affected industries such as fishery, expect and demand that the risk shall be within an acceptable limit.

This chapter will present a risk analysis and evaluation of the current situation in the WBS. The thesis will evaluate three different solutions; year round drilling operations with a standard structure, seasonal drilling, and year round drilling operations with a winterized drilling structure.

6.1 Risk Analysis of Todays Situation

This section contains a risk evaluation based on the presented data in this thesis. The challenges related to the risk assessment and vulnerable areas with existing technology will be presented. After, a risk analysis for year-round drilling operations for a standard structure in the Western Barents Sea (WBS) region will be given. Risk analysis of optimized (seasonal drilling and winterized structure) drilling operations in the region will also be given.

6.1.1 Challenges related to risk assessment

Since there is limited competence and experience related to drilling operations in this WBS region, the knowledge about possible site specific effects are to some extent unknown. Lack of experience also makes it challenging to express the risk. However, when the experience is limited it is possible to use information about related activities, like the situations looked into in this thesis.

There is also another uncertainty factor that should be considered when evaluating the risk. That is the “unknown unknown”. This is events and outcomes that have not been foreseen or expected by the operators. These factors can be unknown because they have never been experienced before. There is a slight chance of such an event to occur. However, to foresee all the possible outcomes is impossible, but it is important to remember that not all possible events can have been predicted and surprises can occur.

The risk influencing factors (RIF´s) can also have a negative synergic effect on systems and components. This means that the factors together will introduce more damage or hazard than they would have introduced individually. Factors like wind chill index is a combination of both cold air temperature and wind speed. Temperature and wind together makes operations more challenging than just low air temperature or wind alone. There is a possibility that not all the synergic effects on systems or components have been foreseen because of the limited experience. This will increase the uncertainty related to the activity. However, over time this uncertainty will be reduced as a result of more experience and knowledge will be gained.

6.1.2 Vulnerable areas with existing technology and equipment

In order to evaluate the risk, it is important to map vulnerable areas about existing technology and how much the RIF´s will affect the safety. Table 20 presents exposed and vulnerable areas on a drilling structure when operating in the WBS region. The table is based on information presented in Ryerson ((b), 2008 and (a), 2012) and the presented experience data. The possible outcomes from the different snow and ice types on the different vulnerable areas are shown to the right.

Today some of the vulnerable areas like antennas, fire fighting equipment, evacuation systems, and helicopter landing pads have requirements to have barriers like anti-icing when structures are used in regions where icing can be a problem.

Table 20: Exposed and vulnerable areas on a drilling structure operating in harsh and cold environment.

Vulnerable Areas	Snow/Ice Types	Outcome
Open derricks	Rime, glaze, snow, and icicles	Ice can fall when temperature increases, and present a hazard to and personnel and equipment
Antennas	Rime, glaze, saline ice, and wet ice	Blocking of signals on communication antennas and radar antennas
Flare booms	Rime, glaze, and sea spray icing	Clogging of ice in nozzles may cause an explosion, fire, or development of toxic gases
Handles, valves	Rime, glaze, and sea spray icing	Reduced safety for the structure personnel
Air intakes/vents	Atmospheric and sea spray icing	Potential for combustible gases to accumulate inside the facility
Window	Rime, glaze, and snow	Loss of visibility for personnel working in enclosed control stations such as for crane operators
Hatches	Rime, glaze, and snow	Can be hard to open due to increased weight or if it is clogged by ice/snow
Fire fighting equipment, life rafts, lifeboats, rescue capsules	Atmospheric and sea spray icing	Reduced safety and ability to escape and evacuate
Helicopter landing pad	Rime, glaze, snow, and sleet	Limited ability and increased risk for helicopter landing
Decks, stairs, railings, and catwalks	Snow, freezing rain, sleet, icicles, and sea spray icing	Slippery surfaces (especially if oil is spilled on top), loss of drainage, and natural ventilation
Moon pool	Icing from wave splash	Loss of safety due to ice accretion critical equipment. Accretion of ice on small diameter objects
Cellar deck	Sea spray icing	Ice accretion on small diameter objects
Crane	Rime, glaze, snow, and icicles	Hazardous if the ice falls off. The height often extends 100 m above sea surface
Legs and branching	Sea spray icing	Icing builds on columns, bracing, blowout preventer, mooring chains, marine riser, and flexible kill and choke lines in the splash zone 5–7 m above sea level in drilling mode. In moderate sea, most ice accumulates on platform legs above the water line and may not affect the centre of structure gravity seriously. In severe weather, spray ice may accumulate above deck levels (40 m above sea surface) and cause stability to deteriorate.

6.1.3 Risk analysis for year round drilling operations for standard structure (Solution 1)

This section will through a risk analysis show weather or not year round drilling operations with a standard structure (Solution 1), with no winterization, can be achieved safely in the WBS region. The analysis is performed by the author based on the data presented in the previous sections and chapters in the thesis.

The annual probability and consequences for snow and icing on different systems on a drilling structure is presented in Table 21. The probability and consequence is categorized in different levels from 1 to 5. Where 5 indicate a high probability and will most likely occur several times in one year, and 1 indicates low probability and will most likely not occur throughout a year. Consequences in category 5 have a potential to become a major accident if the amount of accreted ice is significant, several fatalities and harm to the environment can be expected. Consequences 3 - 4 can be critical due to damage on personnel, components and systems. Consequences 2 can lead to challenges for personnel to perform their work, injuries of personnel, or small damages on components and systems. Consequence category 1 will give marginal outcomes. These ranking categories will also be used later for the optimized solutions (Section 6.1.4 Optimization of the risk level). Guidelines for the risk analysis are described in detail in Appendix C.

As a result of the generally cold air temperature in the WBS region the probability of occurrence is high, and many of the environmental factors have the potential to occur several times throughout a year.

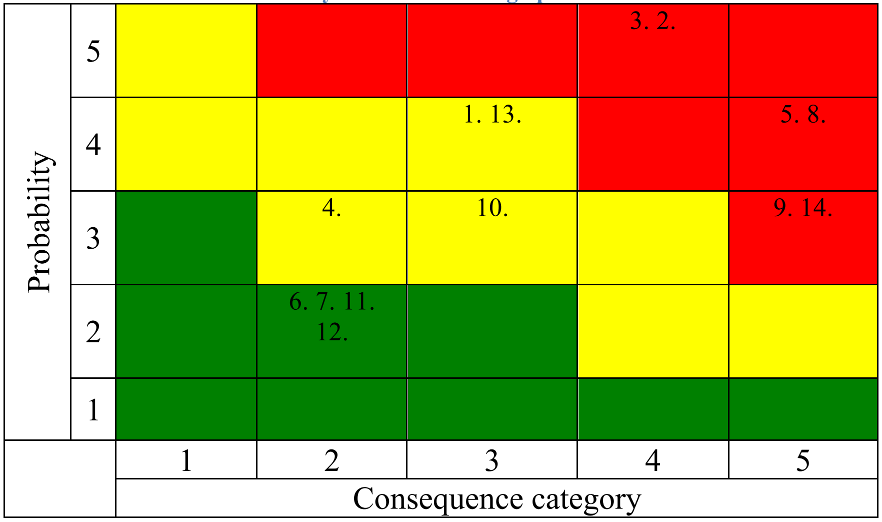
Table 21: Annual probability and consequence from environmental factors on different structure systems.

Solution 1 Year round drilling with standard structure					
ID.	Systems	Probability		Consequence	
1.	Derricks	Should be expected during winter months and in some summers	4.	Ice can fall presenting a hazard to personnel and equipment	3.
2.	Antennas	If not equipped with heat tracing it will most likely be iced in most parts of the year	5.	Blocking of signals on communication antennas and radar antennas. Damages can also occur	4.
3.	Flare booms	A standard flare boom has many small diameter surfaces for ice to attach and should be expected	4.	Clogging of ice in nozzles may cause an explosion, fire, or development of toxic gases	5.
4.	Handles, valves	Not exposed areas but may be expected in low temperatures	3.	Reduced safety for personnel	2.
5.	Air intakes/vents	If not protected from the environment it should be expected in most of the months throughout a year	3.	Potential for combustible gases to accumulate inside the structure	5.
6.	Window	Should be expected in most of the months throughout a year	2.	Loss of visibility for personnel working in enclosed control stations such as crane operators	2.
7.	Hatches	Should be expected in most of the months throughout a year	2.	Can be hard to open due to increased weight or if it is clogged by ice	2.
8.	Fire fighting equipment, life rafts, lifeboats, and rescue capsules	Should be expected in most of the months throughout a year. High number since it is placed on the outer boundaries of structures and is exposed	4.	Reduced safety and ability to escape and evacuate	5.

Solution 1 Year round drilling with standard structure					
ID.	Systems	Probability		Consequence	
9.	Helicopter landing pad	Should be expected in most of the months throughout a year	3.	Limited ability and increased risk for helicopter landing	5.
10.	Decks, stairs, railings, and catwalks	Should be expected from September to June	3.	Slippery surfaces (especially if oil is spilled on top), loss of drainage, and natural ventilation	3.
11.	Moon pool	Should be expected in most of the months throughout a year	2.	Loss of safety due to ice accretion critical equipment. Accretion of ice on small diameter objects	2.
12.	Cellar deck	In harsh weather it can be expected from October to June	2.	Accretion on small diameter objects and increased the total weight of the structure	2.
13.	Crane	Many small diameter surfaces for ice to attach and increases the likelihood for ice to accumulate	4.	Hazardous if the ice falls off. The height often extends 100 m above sea surface	3.
14.	Legs and branching	In harsh weather it can be expected from October to June	3.	In severe weather, spray ice may accumulate above deck levels (40 m above sea surface) and cause stability to deteriorate.	5.

The result of the probability and consequence ranking is placed in the risk matrix below. The identification number from the table above is used. Both the likelihood and consequences of its occurrence is high for many of the situations. The table shows that the icing on antennas, flare booms, air intakes, and fire fighting and evacuation systems, introduces the highest risk for drilling operations in the WBS.

Table 22: Standard risk matrix for year round drilling operations in the Western Barents Sea.



Probability						
	5	🟨	🟥	🟥	🟥 3. 2.	🟥
	4	🟨	🟨	🟨 1. 13.	🟥	🟥 5. 8.
	3	🟩	🟨 4.	🟨 10.	🟨	🟥 9. 14.
	2	🟩	🟩 6. 7. 11. 12.	🟩	🟨	🟨
	1	🟩	🟩	🟩	🟩	🟩
		1	2	3	4	5
		Consequence category				

Based on the scores given above, the average probability of occurrence for the systems and components is 3.14, and the average consequence is 3.4. Figure 34 shows the average risk of a year round drilling operation in the WBS region. The presented risk is as already mentioned, based on the presented data about environmental condition (RIF´s) and the existing information about barriers and technology. The risk is marked in a large area of the figure since the risk is varying because of changing weather conditions in the region and the physical influence on systems varies. Some systems are more vulnerable than others.

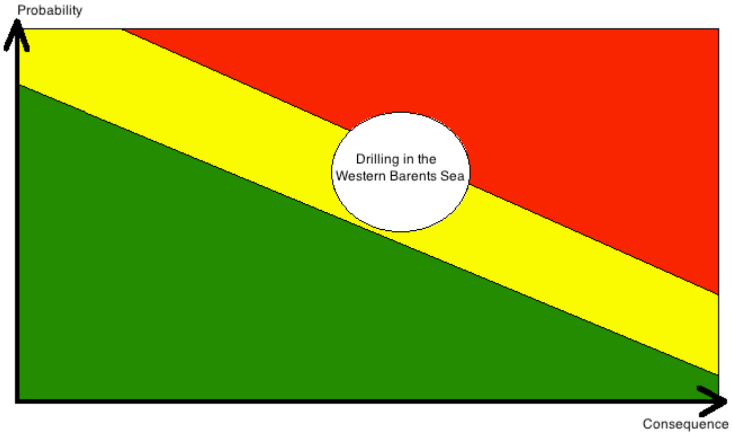


Figure 34: Risk level for a year-round drilling operation for a *standard structure* in the Western Barents Sea.

6.1.4 Optimization of the risk level (Solution 2 and Solution 3)

Today one of the most effective ways to optimize the risk level for drilling operations in the WBS is to narrow the drilling season to the summer months (Solution 2) or to enclose and winterize structures (Solution 3). It is more difficult to reduce the overall consequences if accidents occur, and the consequences can be of so high extent that the best solution is to reduce the probability of unwanted events to occur. If a major accident occurs damages to personnel, environment, and financials can be difficult to avoid independent from the environmental condition. However, the physical environment will influence the severity of the damages.

If the drilling season is narrowed to summers the influence from the physical environment will be less harsh. As already indicated, the environment in the WBS during the summer has similarities to the physical environment in the North Sea in the winter months, and it is possible that the same challenges can be experienced in the two regions.

Like in the previous section, this section will also present risk analyses. The analyses are performed by the author based on the data presented in the previous sections in the thesis. Table 23 is approximately the same as Table 21 presented in the previous section; however, this table is narrowed to seasonal drilling (Solution 2) with lower probability of ice occurrence. The ranking of probability and consequences is the same as for the previous section where the highest is 5 and lowest is 1. Guidelines for the risk analysis are described in detail in Appendix C.

The overall probability for Solution 2 will be lower compared to Solution 1. The expected amount of accumulated ice is lower compared to Solution 1, and therefore the corresponding consequences are also lower.

Table 23: The annual probability and consequence of environmental impact for seasonal drilling in the summer months.

Solution 2 Seasonal drilling					
ID.	Systems	Probability		Consequence	
1.	Derricks	Can occur if the air temperature is negative	2.	Ice can fall presenting a hazard to personnel and equipment	2.
2.	Antennas	Can occur if the air temperature is negative	3.	Blocking of signals on communication antennas and radar antennas. Damages can also occur	4.
3.	Flare booms	Many small diameter surfaces for ice to attach, can occur	2.	Clogging of ice in nozzles may cause an explosion, fire, or development of toxic gases	5.
4.	Handles, valves	Can occur if the air temperature is negative	2.	Reduced safety for personnel	1.
5.	Air intakes/vents	If not protected from the environment it can be expected	2.	Potential for combustible gases to accumulate inside the structure	5.
6.	Window	Can occur if the air temperature is negative	1.	Loss of visibility for personnel working in enclosed control stations such as crane operators	2.
7.	Hatches	Can occur if the air temperature is negative	1.	Can be hard to open due to increased weight or if it is clogged by ice	2.
8.	Fire fighting equipment, life rafts, lifeboats, and rescue capsules	Should be expected since they are placed on exposed areas	3.	Reduced safety and ability to escape and evacuate	4.
9.	Helicopter landing pad	Can occur if the air temperature is negative	1.	Increased risk and limited ability for helicopter landing	4.
10.	Decks, stairs, railings, and catwalks	Can occur if the air temperature is negative	2.	Slippery surfaces (especially if oil is spilled on top), loss of drainage, and natural ventilation	2.
11.	Moon pool	Slightly exposed area	1.	Loss of safety due to ice accretion critical equipment. Accretion of ice on small diameter objects	1.
12.	Cellar deck	Slightly exposed area	1.	Accretion on small diameter objects and increased the total weight of the structure	1.
13.	Crane	The amount of small diameter surfaces makes a good foundation for ice to accumulate	2.	Hazardous if the ice falls off. The height often extends 100 m above sea surface	2.
14.	Legs and branching	In most parts of the WBS the water depth is high	2.	In severe weather, spray ice may accumulate above deck	4.

Solution 2 Seasonal drilling					
ID.	Systems	Probability		Consequence	
		and the most feasible solution is a floating structure. A floating structure do not have so many small diameter surfaces for the ice to attach		levels (40 m above sea surface) and cause stability to deteriorate.	

The last solution is to enclose and winterize structures (Solution 3). This is to ensure that physical environment does not have the chance to entrain and affect systems or component. If a structure is enclosed it might be possible to have year round drilling operations in the WBS region. Table 24 is approximately the same as Table 21; however, this table is for year round drilling operations for winterized drilling structure (Solution 3). The ranking of probability and consequences is the same as for the previous tables where the highest is 5 and lowest is 1. Guidelines for the risk analysis are described in detail in Appendix C.

The overall probability for Solution 3 will be lower compared to Solution 1. But if the ice gets to accumulate on the structure is expected that the consequences will be in the same order as Solution 1. This is due to the expected amount of accumulated ice or snow, and the physical environment in the region throughout a year.

Table 24: The annual probability and consequence of environmental impact for year round drilling with a winterized structure.

Solution 3 Winterized structure					
ID.	Systems	Probability		Consequence	
1-1.	Derricks	The derrick will be enclosed and therefore not pose any hazard	1.	Ice can fall presenting a hazard to personnel and equipment	3.
1-2.	Antennas	Will be equipped with anti-icing and will in most cases not freeze	2.	Blocking of signals on communication antennas and radar antennas. Damages can also occur	4.
1-3.	Flare booms	Will be partly enclosed but some icing can occur around openings	2.	Clogging of ice in nozzles may cause an explosion, fire, or development of toxic gases	5.
1-4.	Handles, valves	The structure will be enclosed and will seldom experience icing	1.	Reduced safety for personnel	2.
1-5.	Air intakes/vents	Protection of air intakes/vents is important but some icing can occur	2.	Potential for combustible gases to accumulate inside the structure	5.
1-6.	Window	Equipped with anti-icing measures	1.	Loss of visibility for personnel working in enclosed control stations	2.

Solution 3
Winterized structure

ID.	Systems	Probability		Consequence	
				such as crane operators	
1-7.	Hatches	Protection from physical environment, but some icing can occur if temperature inside structure is low	2.	Can be hard to open due to increased weight or if it is clogged by ice	2.
1-8.	Fire fighting equipment, life rafts, lifeboats, and rescue capsules	Protected from the physical environment, but the locks or hatches may freeze	2.	Reduced safety and ability to escape and evacuate	5.
1-9.	Helicopter landing pad	Winterized but can in periods get ice formations	2.	Increased risk and limited ability for helicopter landing	5.
1-10.	Decks, stairs, railings, and catwalks	Will be enclosed but some icing can be expected if the temperature inside structure is low	2.	Slippery surfaces (especially if oil is spilled on top), loss of drainage, and natural ventilation	3.
1-11.	Moon pool	Equipped with anti-icing and enclosed	1.	Loss of safety due to ice accretion critical equipment. Accretion of ice on small diameter objects	2.
1-12.	Cellar deck	Enclosed area	1.	Accretion on small diameter objects and increased the total weight of the structure	2.
1-13.	Crane	Icing can be expected due to small diameter surfaces. Reduction of small diameter surfaces is desirable	4.	Hazardous if the ice falls off. The height often extends 100 m above sea surface	3.
1-14.	Legs and branching	In most parts of the WBS the water depth is high and the most feasible solution is a floating structure. A floating structure do not have so many small diameter surfaces for the ice to attach	2.	In severe weather, spray ice may accumulate above deck levels (40 m above sea surface) and cause stability to deteriorate.	5.

The results of both of the rankings (Solution 2 and Solution 3) are placed in the risk matrix below. The identification numbers from the tables above are used. Table 25 shows that the risk is in general lower for all the systems and components if it is compared to the year round drilling operation for standard structures (Solution 1, Table 22).

Table 25: Standard risk matrix for optimization of drilling operations in the Western Barents Sea.

Probability	5					
	4			1-13.		
	3				2. 8.	
	2	4.	1. 10. 13. 1-7.	1-10.	14. 1-2.	3. 5. 1-3. 1-5. 1-8. 1-9. 1-14.
	1	11. 12.	6. 7. 1-4. 1-6. 1-11. 1-12.	1-1.	9.	
		1	2	3	4	5
		Consequence category				

Based on the scores given, the average probability of occurrence for the systems and components is 1.79 for both seasonal drilling (Solution 2) and winterized structure (Solution 3). The average consequence is 2.8 for seasonal drilling operations, and 3.4 for use of winterized structures. Seasonal drilling gives a lower consequence because of the warmer and less harsh environment. Figure 35 shows how much the overall risk is reduced due to the optimization. The original risk (faded in the illustrations) is the risk presented for Solution 1, year round drilling operation for standard structure. To the left Solution 2 is placed and to the right Solution 3 is placed. The risk is marked in a large area of the figure since the risk is varying because of changing weather conditions in the region and the physical influence on systems varies. Some systems are more vulnerable than others.

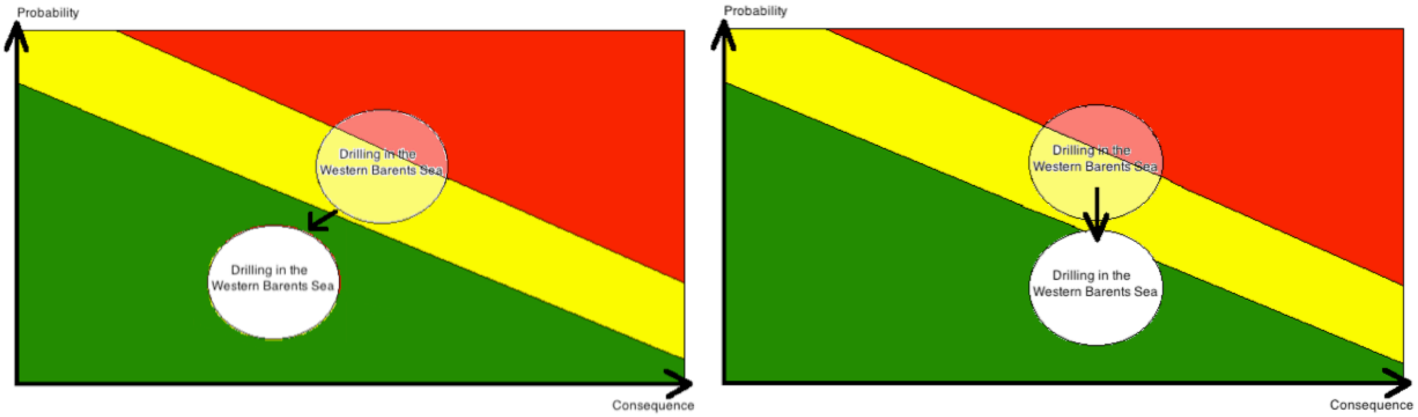


Figure 35: Risk level of seasonal-based drilling (Solution 2) operations in the Western Barents Sea (To the left), and year round drilling operations with winterized structure (Solution 3) in the Western Barents Sea (To the right).

6.2 Evaluation of the Risk Level

This section will discuss the acceptance of the current risk situation for drilling operations in the Western Barents Sea (WBS) region. Based on the risk analysis, and the existing acts and regulations a discussion will be presented. If the risk is in the ALARP zone or in the high-risk zone it is not acceptable and has to be reduced.

6.2.1 Solution 1, year round drilling operation with standard structure

For a year round drilling operation with a standard drilling structure with no winterization the risk is in the ALARP zone. According to Norwegian regulations, operators shall choose the technical and operational solutions that give the best results regarding risk level reduction, and for this case the solution has to be improved. The risk analysis accomplished in this thesis shows that a year round drilling operation in the WBS can be challenging because of the physical environmental condition. The probability is listed high as a result of the environmental condition in the region and the technology used. The consequences of an accident can be major if the stability is changed due to the amount of accreted ice, or if of systems and components to stop function or malfunction.

A structure that is not winterized often has several small diameter surfaces for the ice to attach. Heavy ice and snow loads can lead to changes in the stability and centre of gravity for a drilling structure. Snow and ice accumulations can also clog, damage, and block signals on antennas. Snow and ice accumulations can make hatches unavailable, and clog fire fighting equipment.

Lack of barriers to protect vulnerable systems or the working environment can, as already mentioned, cause problems for operational and maintenance processes. The environmental risk influencing factors (RIF´s) can affect the availability and reliability of components, systems, and equipment if they are not protected or made of such materials that they tolerate loads from RIF´s. Limitations regarding working environment for personnel can also affect operations and maintenance processes. Psychological and physical challenges for personnel working in cold and dark environment can lead to limitations on their performance and increase the risk for misactions and inaccuracy.

When drilling in harsh and cold environment there are some winterization measures that are required to be implemented. This is to ensure safe operations. This means that a standard drilling structure may has to install anti-icing and de-icing measures on for instance antennas, fire fighting systems, and evacuation systems to be allowed to operate during the winter months. In addition, the years with present of sea ice may have requirements for ice management.

As already mentioned, the remoteness in the WBS region is significant. Harsh and cold weather with low visibility in the region, will set limitations for helicopters ability to fly and can lead to delays for personnel and spare part transportation, and for search and rescue (SAR) operations. Personnel and spare part transportation are important for operations, and delays can lead to extra costs and loss of operation time. Delays in SAR operations are critical since every minute is of severe importance. The chance of having a successful SAR operation is higher if the response time and rescue time are low. SAR operations and oil spill clean ups will be more challenging during the winters compared to the summers. Harsh and cold weather in combination with darkness will make such operations difficult.

The risk connected to the drilling operations varies over a year due to the changing environmental condition. The risk during the summer months will be lower compared to the winter months. The environmental loads are generally lower and the occurrence of environmental RIF´s are lower during the summer months. Operational and maintenance tasks, transportations, SAR operations, and oil spill clean ups will be easier to handle.

6.2.2 Solution 2, seasonal drilling operation

Seasonal drilling in the WBS region will reduce the risk related to the activity. According to the risk analysis the risk will be within an acceptable limit. The climatic condition in the region is less harsh during the summer months and some of the RIF´s are not more challenging than they are in the North Sea during the winters. In addition, not all of the RIF´s will be present during the summer months and will therefore not contribute to an increased operational risk.

Seasonal drilling during the summer months will give 100 % daylight every day and no sea ice will be present. If an unwanted event should occur the SAR and evacuation will in most cases be easier to perform compared to a year round operation. If an oil spill occurs it will most likely be less challenging to clean up. On the other hand, the remoteness in the region is constant, and the response distance from shore will not be shorter when drilling seasonal. But better environmental conditions will increase the operating time for helicopters. The seasonal drilling will only limit the delays caused by the RIF´s.

Solution 2 will not require ice management or advanced technology to physical shielding from the RIF´s. However, annually variation should be expected and in some years negative air temperatures can occur in short time periods. Negative air temperatures can lead to icing and snowfall, and can lead to restriction of working time for exposed personnel. These factors can lead to operational and maintenance challenges.

This solution will reduce the operation time to approximately 1/3 or 1/2 of a year round drilling operation; this will off course vary with the annually variation of the environmental condition. Limitation to seasonal drilling operations will reduce the overall efficiency and possible lead to loss of income for operators.

6.2.3 Solution 3, year round drilling operation with winterized structure

A fully winterized drilling structure will have the possibility to operate in the WBS region in most of the weather conditions that can occur in the region throughout a year. A winterized structure will be partly or fully enclosed and be prepared for the physical environmental conditions in the region. Additional barriers like those presented in this thesis will be used. These implemented winterization factors will give a better working environment for personnel and protection of technical systems, components, and equipment.

The winterization actions will reduce the uncertainty related to the activity. The improved working environment will be advantageous for utilizing the working time for personnel. The personnel reliability is generally higher when the physical environment warm. Enclosure and winterizing of structures will also reduce the probability of icing on vulnerable systems, components, and equipment. This will make the operation and management tasks easier to perform for personnel and damages on systems due to loads from RIF´s will be reduced. However, if heating inside modules is not used, changes in reliability and failure rates of components as a result of low air temperatures can lead to more and unexpected down time where maintenance is needed.

Drawbacks with fully winterized structures are that they are more expensive, can be heavier, and can be more energy consuming than standard structures. Anti-icing and de-icing measures will for instance require energy, especially if heat is involved. This can pose new challenges since limited energy supply is the case for most structures. Another drawback with winterized structures is the enclosure of modules, which can lead to accumulations of combustible gases if leakages occur. This will increase the explosion risk.

The winter months have the highest number of RIF´s. Not all the interactions and synergic effects from the RIF´s are known or foreseen. This means that some challenges and surprises should be expected. To avoid unexpected incidents, testing of the systems or simulations can be used.

In harsh and cold weather with low visibility helicopters will have limited ability to fly and can lead to delays for personnel and spare part transportation, and for SAR operations. If unwanted events occur where evacuation or oil spill clean up is needed it will be more challenging in the winters. Harsh and cold weather in combination with darkness will make such operations rough and be at the same level as for Solution 1.

In comparison with seasonal drilling, year round drilling operations will have the possibility to lead to better economical potentials for operators since they will operate the whole year.

7 CONCLUSION AND RECOMMENDATIONS

Based on the presented information, analysis, and evaluation a conclusion on the formulation of the problem is addressed. This chapter will also give recommendations for further work with improvement of the safety and reduction of the risk.

7.1 Final conclusion

In this thesis the environmental risk influencing factors (RIF´s) related to drilling activity in the Western Barents Sea (WBS) region have been stated. Evaluations of acceptance of the risk level in the region have also been performed based on existing acts and regulations, the physical environment, and information regarding existing technology and experience.

The physical environment in the WBS is generally harsh and cold. The analysis in the thesis indicates that there are several RIF´s that may influence drilling activity, and that their interaction is complex and can in many situations have a negative synergy effect on systems, components, equipment, and working environment. The different RIF´s are listed below; the arrangement is not in accordance to their importance.

Sea ice
Sea spray icing
Icebergs
Fog
Snow
Atmospheric icing
Polar night
Icicles
Polar lows
Negative air temperature
Negative sea temperature
Wind

Based on the risk evaluation performed in this thesis the risk level for drilling operations in the WBS region will be acceptable if it is optimized. It is possible to reduce the risk to an acceptable limit if the drilling season is narrowed to summers (Solution 2) or if winterized structures (Solution 3) are in use. These solutions are prepared for the expected environmental conditions in the region and will therefore most likely not face too many unexpected operational and maintenance challenges. Seasonal drilling (Solution 2) during the summer months will give generally warmer climate compared to winters, but annual variation should be expected and negative air temperatures can occur in short time periods. Solution 3 will give a better working environment for personnel and protection of technical systems. However, changes in reliability and failure rates of components due to low air temperatures can occur. Harsh weather can make helicopter transportation, SAR operations, and clean up of oil spills challenging.

When designing drilling structures for operations in the WBS region: ice management, anti-icing, and de-icing are important barriers that will limit loads from the RIF´s and are highly recommended to implement and use, and are in some cases required by the authority.

7.2 Recommendations

Based on the analysis performed and knowledge gained throughout the work with the thesis, some points regarding further improvements and recommendations for further work will be stated. The information will only be given in bullet points.

- Human factors have not been describen in depth in this thesis. However, the limitation of human working in harsh and cold climate is significant and should be analysed further. The topic is elaborated in more detail in Thelma (2010). The report can be found here: *http://www.ptil.no/getfile.php/PDF/Kalde%20utfordringer%20-%20helse%20og%20arbeidsmilj%C3%B8%20p%C3%A5%20innretning%20i%20Nordomr%C3%A5dene_Thelma%20juni%202010.pdf*
- The Badger Explorer can be a good solution for exploration drilling in harsh and cold environment like in the Arctic. The drilling do not form any waste or transport cuttings to a drilling structure, and it transferes data to the surface. The drilling tool penetrates formations by using mechanical drill bits driven by electrical motors. Crushed formation is transported through the device and deposited in the void behind the tool. The tool carries an electrical cable, which is coiled inside the unit, connected to the surface and powers the electrical motors. The same cable is used for continous transfer of data back to the surface (Badger Explorer ASA, 2007). A demonstration of the tool is shown in a video here: *http://www.bxpl.com/*
- Exxon Mobil have found a new and faster way to drill a well. Shortening of drilling time will make the drilling more efficient and more optimal due to the periodicly harsh weather in the Arctic. Faster drilling rates and reduced downtime are the result of the fast drill borehole management (FDBM) process technology. This technology is used on the Sakhalin-1 wells, these wells are one of the world's longest wells and also some of the world's fastest-drilled extended-reach wells (Exxon Mobil, n.d.). A brouchure of the technology can be found here: *http://www.exxonmobil.com/Corporate/files/news_pub_poc_arctic.pdf*
- Training of employees for emergency sirtuations is important, especially in harsh and cold envirionment. Most of the equipment and systems on a drilling structure are manual (compared to a production platform where most shutdown functions required in an emergency is automatic) it is important that the crew are well trained to make the right decision in emergency situations. It is therefore important to focus on inspections training and education in relation to crisis management (SINTEF, 2011).
- Instead of designing for extreme loads from ice actions on drilling strutures, it is a solution to use DP and disconnect from riser if there is a high risk for extreme loads. Figure 36 is adapted from Løset (2011) and shows how this principle works. In the graph to the left the ice are presented, and in the graph to the right the proposed design level and ice management are presented.

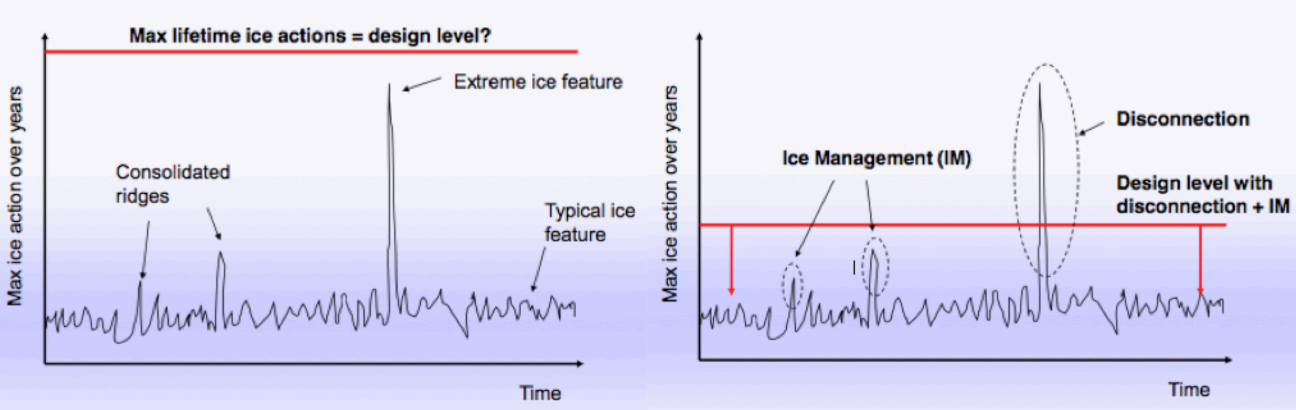


Figure 36: Ice management and decision of disconnection due to ice loads (Løset(a), 2011, p.5).

8 REFERENCES

Abramov, V., 1996. Atlas of Arctic Icebergs. *AARI, Arctic and Antarctic Research Centre*.

Arctic Council, 2009. Arctic Marine Shipping Assessment 2009 Report. p.194.

Arctic Council, 2011. *Arctic council history*. [Online] Available at: http://www.arctic-council.org/index.php/en/about-us/arctic-council/history [Accessed 30 May 2013].

Aune, A., 2000. *Kvalitetsdrevet ledelse - kvalitetsstyrte bedrifter 3. utg.* Gyldendal akademisk.

Aven(a), T., 2011. *Quantitative Risk Assessment*. Cambridge: Cambridge University Press.

Aven(b), T., 2008. *Risk Analysis - Assessing Uncertainties Beyond Expected Values and Probabilities*. West Sussex: John Wiley & Sons Ltd.

Aven, T. et al., 2011. *Samfunnssikkerhet*. Oslo: Universitetsforlaget.

Aven, T., Røed, W. & Wiencke, H.S., 2008. *Risikoanalyse - prinsipper og metoder, med anvendelser*. Oslo: Universitetsforlaget.

Aven, T. & Vinnem, J.E., 2007. *Risk Management*. London: Springer.

Badger Explorer ASA, 2007. *A Revolutionary Exploration Method*. [Online] Available at: http://www.bxpl.com/?id=1150 [Accessed 18 April 2013].

Barabady, A., 2011. Production Performance Analysis - Reliability, Maintainability and Operational Conditions. *Doctorial Thesis (PhD)*.

Barabady, A., Barabady, J. & Markeset, T., 2009. MANAGEMENT OF PRODUCTION ASSURANCE IN HARSH, REMOTE, AND SENSITIVE ENVIRONMENT. p.12.

Barents 2020, 2012. Assessment of international standards for safe exploration, production and transportation of oil and gas in the Barents Sea. *Harmonisation of Health, Safety, and Environmental Protection Standards for The Barents Sea*, p.300.

Berg, J., 2006. *St. meld. nr. 8 (2005-2006) Helhetlig forvaltning av det marine miljø i Barentshavet og havområdene utenfor Lofoten (forvaltningsplan)*. [Online] Available at: http://www.regjeringen.no/nb/dep/md/dok/regpubl/stmeld/20052006/stmeld-nr-8-2005-2006-/3/1/2.html?id=331454 [Accessed 15 February 2013].

Blumberg et al., 2011. *Business Research Methods*. Berkshire: McGraw-Hill Education.

Bonnemaire, B. et al., 2007. Challenges related to station-keeping in ice. *Oil and Gas Developments in Arctic and Cold Regions*, p.24.

Climatemps, 2012. *Climatemps.com*. [Online] Available at: http://www.bear-island.climatemps.com/ [Accessed 13 February 2013].

Cullen, D., 1990. *The public inquiry into the Piper Alpha disaster - Vol.1*. London: Department of Engergy.

Dagg, J. et al., 2011. Comparing the Offshore Drilling Regulatory Regimes of the Canadian Arctic, the U.S., the U.K., Greenland and Norway. p.179.

DNV Summer Project, 2012. Oil spill contingency in the Arctic - The process, equipment and systems. p.196.

DNV, 2008. *TEKNISK RAPPORT - STATOILHYDRO ASA - BEREDSKAPSANALYSE FOR LETEBRØNN ARENARIA*. Høvik: Det Norske Veritas DNV Energy.

Exxon Mobil, n.d. *Brouchure: Arctic Leadership*. [Online] Available at: http://www.exxonmobil.com/Corporate/files/news_pub_poc_arctic.pdf [Accessed 18 April 2013].

Faltinsen, O.M., 1990. *Sea Loads On Ship and Offshore Structures*. Cambridge: Cambridge University Press.

Freitag, D.R. & McFadden, T.T., 1997. *Introduction to Cold Regions Engineering*. ASCE - Armer Society of Civil Engineering.

Fugro, 2005. Regional Reference: Barents Sea. p.4.

Gao, X., Barabady, J. & Markeset, T., 2010. An approach for prediction of petroleum production facility performance considering Arctic influence factors. *Reliability Engineering and System Safety*, p.10.

Gao, X. & Markeset, T., 2007. Design for production assurance considering influence factors. *Design for Production Assurance Considering Influence Factors, In: The Proceedings of the European Safety and Reliability Conference (ESREL2007)*, p.7.

Google Earth, 2013. *Google Earth*. [Online] Available at: http://www.google.com/earth/index.html [Accessed 2013].

Gudmestad(a), O.T., 2009. Risks in Arctic offshore field developments. *The 4th Norway – Russia Arctic Offshore Workshop. Joint research and innovation for the petroleum industry working in the Arctic*, p.25.

Gudmestad(b), O.T., 2010. Vessel Winterization for Cold Climate Operations. In *Joint Research and Innovation for the Petroleum industry working in the Arctic*. Murmansk, 16 June 2010.

Gudmestad(c), O.T., 2013. Personal conversation with Tina Sætrum (author). 22 March.

Gudmestad, O.T. et al., 2007. *ENGINEERING ASPECTS RELATED TO ARCTIC OFFSHORE DEVELOPMENTS*. St. Petersburg, Russia: LAN Publisher.

Gudmestad, O. & Løset, S., 2004. Key considerations in the design of offshore production facilities for Arctic offshore conditions. *17th International Symposium on Ice*.

Gudmestad, O.T. & Quale, C., 2011. Technology and Operational Challenges for the High North. *International Research Institute of Stavanger*.

Hasle, J.R., Kjellén, U. & Haugerud, O., 2009. Decision on oil and gas exploration in an Arctic area: Case study from the Norwegian Barents Sea. *Safety Science*.

Haugen, J., Imsland, L., Løset, S. & Skjetne, R., n.d. Ice Management Supported by Models Using Unmanned Aerial Vehicles. p.8.

Hovland, M., 2001. The High-Arctic Drilling Challenge. *Final Report of the Arctic's Role in Global Change Program Planning Group (APPG)*, p.49.

IMO, 2002. GUIDELINES FOR SHIPS OPERATING IN ARCTIC ICE-COVERED WATERS. *International Maritime Organization*, p.32.

IMVPA, 2008. Arctic Offshore Technology Assessment of Exploration and Production Options for Cold Regions of the US Outer Continental Shelf Arctic Offshore Technology Assessment of Exploration and Production Options for Cold Regions of the US Outer Continental Shelf. *Project No. C-0605-15*, p.365.

International Standard, 2009. ISO 31000:2009. *Risk management — Principles and guidelines* , p.34.

International Standards, 2010. *Petroleum and natural gas industries - Arctic offshore structures ISO 19906:2010(E)*. Geneva: The international Organization for Standardization.

Jacobsen, D.I., 2005. *Hvordan gjennomføre undersøkelser?* Kristiansand: Høyskoleforlaget.

Jacobsen, S., 2012. Evacuation and Rescue in the Barents Sea, Critical issues for safe petroleum activity. *Master Thesis*.

Kjerstad, N., 2011. *Ice Navigation*. Trondheim, Norway: Tapir Academic Press.

Kolstad, E., 2005. A new technology of favourable conditions for reverse-shear polar lows. *Blackwell Munksgaard*, p.11.

Kumar, R., Barabady, J. & Markeset, T., 2009. IMPROVEMENT OF PERFORMANCE OF OIL AND GAS PRODUCTION FACILITY IN ARCTIC REGION BY APPLING HUMAN FACTORS/ERCONOMIC PRINCIPLES AT THE DESIGN PHASE. p.12.

Kvamstad, B. & Berg, T.E., 2012. Safety at Sea in Norwegian Arctic Waters – the Barents Sea. *Marintek, Arctic Frontier Conference 2012*, p.17.

Larsen, A.C., 2007. Production facility design for operation, maintenance and support in cold regions. *Papers from The University of Stavanger No. 19, Unpublished*, p.45.

Løset(a), S., 2011. ARCTIC OFFSHORE FIELD DEVELOPMENTS IN DEEPER EURASIAN WATERS. p.10.

Løset(b), S., 2012. Origin, drift and deterioration of icebergs. *UNIS, AT327 Lecture Material, Unpublished*.

Løset(c), S., 2012. Ice cover. *UNIS, AT327 Lecture Material, Unpublished*.

Løset, S. & Høyland, K., 1998. *Compendium AT327- Ice Physics and Mechanics*. Trondheim: NTNU.

Løset, S., Shkhinek, K.N., Gudmestad, O.T. & Høyland, K.V., 2006. *Actions from ice on Arctic offshore and costal structures*. St. Petersburg: LAN.

Lovdata, 1996. *Lovdata*. [Online] Available at: http://lovdata.no/all/hl-19961129-072.html [Accessed 24 January 2013].

Lovdata, 2005. *Lovdata*. [Online] Available at: http://www.lovdata.no/all/hl-20050617-062.html [Accessed 24 January 2013].

Markeset(a), T., 2011. MOM460 - Operations and maintenance management. *Unpublished lecture material*, p.390.

Markeset(b), T., 2008. Design for High Performance Assurance for Offshore Production Facilities in Remote Harsh and Sensitive Environment. *Quarterly Journal of the Operational Research Society of India Vol.45*, pp.189-208.

Markeset(c), T., 2011. Operation & Maintenance in the Arctic. *UiT, Unpublished lecture material*.

Markeset(d), T., 2008. Design for Petroleum Production Performance in Arctic Locations Considering Maintenance and Support Services. *Proceedings of the Mine Planning and Equipment Selection Conference (MPES2008), October 20-22nd, Beijing, China*.

met.no, n.d. *The Norwegian Meteorological Institute, eKlima*. [Online] Available at: http://sharki.oslo.dnmi.no/portal/page?_pageid=73,39035,73_39049&_dad=portal&_schema=PORTAL [Accessed 15 February 2013].

Njå, O. & Gudmestad, O.T., 2012. Disasters in Arctic Areas. p.4.

NOFO(a), 2007. *Regionalt Planverk mot Akutt Forurensning*. [Online] Available at: http://planverk.nofo.no/vanntemperaturer.htm [Accessed 26 February 2013].

NOFO(b), 2007. *Regional planverk mot akutt forerensning*. [Online] Available at: http://planverk.nofo.no/web_AP3E.asp?NAVN=Gullfaks+C&Month=Desember.

Norsk olje og gass, 2010. *Norsk olje&gass*. [Online] Available at: http://www.norskoljeoggass.no/no/Faktasider/Oljehistorie/ [Accessed 24 oktober 2012].

Odland, J., 2012. Offshore feltutvikling, Mod8. *Lecture material*.

Petroleum Safety Authority Norway, n.d. *Petroleumstilsynet*. [Online] Available at: http://www.ptil.no/about-us/category89.html [Accessed 24 January 2013].

Petroleumstilsynet, 2012. *Vår organisasjon*. [Online] Available at: http://www.ptil.no/vaar-organisasjon/category128.html [Accessed 8 november 2012].

Pilie, R.J. et al., 1979. The formation of Marine Fog and the Development of Fog-Status Systems along the California Coast. *American Meteorological Society*.

PolarView, n.d. *Polar View*. [Online] Available at: http://polarview.met.no/ [Accessed 26 February 2013].

PSA, n.d. *Petroleum Safety Authorety Norway*. [Online] Available at: http://www.ptil.no/acts/category214.html?lang=en_US [Accessed 24 January 2013].

Ptil, 2013. *Petroleumstilsynet*. [Online] Available at: http://www.ptil.no/major-accidents/focus-major-accidents-article9146-144.html [Accessed 26 March 2013].

Rausand, M. & Utne, I.B., 2009. *Risikoanalyse - teori og metoder*. Trondheim: Tapir akademisk forlag.

Reason, J., 1997. *Managing the Risks of Organizational Accidents*. Manchester: Ashgate.

Ryerson(a), C.C., 2010. Ice protection of offshore platforms. *Cold Regions Science and Technology*, p.14.

Ryerson(b), C.C., 2008. Assessment of Superstructure Ice Protection as Applied to Offshore Oil Operations Safety. *Cold Regions Research and Engineering Laboratory*.

Sørstrøm, S.E. et al., 2010. Joint industry program on oil spill contingency for Arctic and ice-covered waters. *Summary report*, p.40.

Sætrum, T., Herdlevær, U.E. & Olsen, A.J., 2011. *Bachelor Thesis: Weather shielding on facilities in harsh and cold environment*. Tromsø: UiT University of Tromsø.

SINTEF, 2011. Deepwater Horizon-ulykken: Årsaker, lærepunkter og forbedrings- tiltak for norsk sokkel. *SINTEF A19148*, p.228.

Skaugen, E., 2012. DRILLING – INTRODUCTION. *GEO-3129 Unpublished lecure material*, p.62.

Sklet, S., 2005. Safety Barriers on Oil and Gas Platforms - Means to Prevent Hydrocarbon Released. *Doctoral thesis for the degree of doktor ingeniør*, December.

Standards Norway, 2004. NORSOK D-010. *Rev. 3, Well integrity in drilling and well operations*, p.162.

Standards Norway, 2004. NORSOK S-002 Working Environment 4:2004.

Standards Norway, 2007. NORSOK N-003 Actions and action effects. *NORSOK STANDARD*, p.60.

Standards Norway, 2010. NORSOK Z-013. *Edition 3, Risk and emergency preparedness assessment*, p.107.

Sundsbø(a), P.A., 2011. The characteristics of drifting snow and snowdrift - Application to onshore/land and offshore winterization. *UiT Lecture Material, Unpublished*.

Sundsbø(b), P.A., 2011. Wind Chill and Wind Chill Measures - Application to onshore/land and offshore petroleum industry. *UiT Lecure Material, Unpublished*.

Sundsbø(c), P.A., 2011. Wind related to Snow Engineering. *UiT Lecture Material, Unpublished*.

The Joint Rescue Coordination Centres, n.d. *Hovedreningssentralene Sør-Norge og Nord-Norge*. [Online] Available at: http://www.hovedredningssentralen.no/ [Accessed 11 March 2013].

The Norwegian Coastal Administration, 2012. *Exel file: Skipsulykker 1981-2012 - uttrekk per 2012 03 02*. Admission by Trond Langemyr, Senior Adviser.

Thelma, 2010. Kalde utfordringer - helse og arbeidsmiljø på innretning i Nordområdene. *Rapport nr. 10-31, ISBN 978-82-8032-024-7*.

TU, 2012. *Teknisk ukeblad*. [Online] Available at: http://www.tu.no/olje-gass/2012/05/03/goliat-kan-bli-utsatt [Accessed 26 March 2013].

TU, 2012. *Teknisk Ukeblad*. [Online] Available at: http://www.tu.no/motor/2012/12/10/svalbard-far-nye-redningshelikoptre [Accessed 24 May 2013].

Vefsenmo, S., Mathisen, M. & Løvås, S.M., 1990. IDAP 90 - Statistical analysis of sea ice data. *Extrem Southern Limit Analysis*.

Vinnem, J.E., 2007. *Offshore risk assessment- Principles, modelling & applications of QRA studies*. London: Springer series in reliability engineering.

Wangsfjord, T., 2013. *E-mail: Hovedreningssentralen Nord-Norge*. [Online] Available at: Tore.Wangsfjord@jrcc-bodoe.no [Accessed 12 March 2013].

Woodson, W.E., 1992. Human Facors Design Handbook. *(First Published July 1981)*, p.815.

WWF-Norge, 2003. The Barents Sea - A sea of opportunities..and threats. *Petroleum activities and fragil nature, EXECUTIVE SUMMARY*, p.8.

Xue, L., Fan, J., Rausand, M. & Zhang, L., 2013. A safety barrier-based accident model for offshore drilling blowouts. *Journal of Loss Prevention in the Process Industries*, pp.164-71.

Yue, Q., n.d. OFFSHORE STRUCTURES IN ICE-INFESTED WATERS. *Cold Regions Science and Marine Technology*, p.9.

APPENDICES

APPENDIX A – Oktas Calculation for Bjørnøya in 2010 and 2012

The table below shows the oktas data for Bjørnøya in 2010 and 2012. The data is listed to the left, and as can be seen, there were tree measures of cloud coverage each day. ”Aver.” is an abbreviation for average and is the average cloud cover for each day. Places with missing data are marked with “.”.

2010																				
Date	January				Aver.	February				Aver.	March				Aver.	April				Aver.
1	7	7	3	2	4,75	5	7	7	3	5,5	6	6	7	5	6	7	7	6	6	6,5
2	7	8	8	8	7,75	2	4	.	3	2,25	7	5	4	2	4,5	8	7	8	8	7,75
3	8	8	6	8	7,5	5	8	8	8	7,25	2	7	6	7	5,5	8	8	7	4	6,75
4	8	8	7	6	7,25	8	8	7	8	7,75	5	6	7	8	6,5	7	.	6	6	4,75
5	5	5	7	6	5,75	6	.	7	7	5	8	7	6	7	7	7	7	.	.	3,5
6	8	2	1	0	2,75	8	8	7	8	7,75	2	4	5	8	4,75	7	6	6	7	6,5
7	2	2	8	8	5	8	8	5	2	5,75	8	8	6	7	7,25	7	7	6	7	6,75
8	8	7	4	4	5,75	3	2	2	4	2,75	7	5	7	7	6,5	7	6	7	8	7
9	8	8	8	8	8	6	7	6	2	5,25	.	7	7	8	5,5	4	7	5	7	5,75
10	8	8	8	.	6	3	5	8	8	6	6	6	7	8	6,75	4	7	7	6	6
11	3	8	4	4	4,75	8	7	4	6	6,25	3	8	6	7	6	7	8	8	8	7,75
12	8	7	7	7	7,25	8	8	7	7	7,5	5	7	7	7	6,5	8	7	8	8	7,75
13	8	7	6	7	7	8	6	2	1	4,25	7	3	7	8	6,25	7	8	7	2	6
14	8	6	2	7	5,75	2	8	8	8	6,5	8	8	7	7	7,5	7	.	7	7	5,25
15	6	8	3	6	5,75	8	8	8	7	7,75	5	8	2	6	5,25	8	8	8	8	8
16	3	3	7	3	4	3	4	6	3	4	3	4	2	4	3,25	.	3	8	8	4,75
17	8	8	8	8	8	5	2	4	5	4	3	5	4	7	4,75	6	8	8	8	7,5
18	6	8	8	7	7,25	3	7	6	7	5,75	3	7	5	5	5	.	8	8	8	6
19	3	8	7	3	5,25	7	7	7	8	7,25	3	8	3	.	3,5	8	8	8	8	8
20	8	7	8	8	7,75	8	6	7	6	6,75	7	1	5	4	4,25	8	6	8	8	7,5
21	8	8	7	7	7,5	6	6	8	7	6,75	3	8	7	8	6,5	8	.	6	8	5,5
22	4	8	5	3	5	7	6	6	7	6,5	6	7	8	8	7,25	8	8	8	6	7,5
23	4	7	6	4	5,25	6	7	8	8	7,25	6	8	4	2	5	6	3	4	4	4,25
24	5	8	7	7	6,75	.	8	.	7	3,75	3	4	3	3	3,25	3	1	1	1	1,5
25	8	8	7	7	7,5	7	6	5	4	5,5	3	7	2	3	3,75	1	1	3	3	2
26	8	8	8	8	8	6	4	5	6	5,25	5	7	6	7	6,25	.	2	7	8	4,25
27	7	4	7	8	6,5	4	6	6	4	5	8	8	8	6	7,5	5	8	7	7	6,75

28	8	8	8	6	7,5	6	5	5	4	5	4	7	5	6	5,5	4	8	8	8	7
29	4	6	8	5	5,75						8	8	8	7	7,75	8	8	8	8	8
30	7	4	8	3	5,5						3	4	8	.	3,75	7	4	5	6	5,5
31	3	4	6	3	4						3	8	8	8	6,75					
	Aver.jan.10				6,2	Aver.feb.10				5,7	Aver.mars.10				5,66	Aver.apr.10				6,066

Date	May				Aver.	June				Aver.	July				Aver.	August				Aver.
1	2	4	6	4	4	6	5	3	6	5	7	8	7	8	7,5	8	8	8	7	7,75
2	6	8	8	8	7,5	7	8	8	8	7,75	8	7	6	6	6,75	7	8	8	8	7,75
3	8	8	8	8	8	8	8	8	.	6	7	6	4	2	4,75	.	8	.	.	2
4	8	8	8	8	8	.	8	8	8	6	8	7	8	8	7,75	.	8	7	7	5,5
5	8	8	8	8	8	8	7	7	7	7,25	8	.	.	.	2	.	.	8	7	3,75
6	8	8	8	7	7,75	8	8	8	8	8	.	.	.	8	2	7	8	7	8	7,5
7	8	7	5	8	7	8	8	7	7	7,5	.	8	7	8	5,75	8	7	8	8	7,75
8	7	8	8	7	7,5	7	7	7	7	7	7	8	8	7	7,5	.	7	8	8	5,75
9	4	6	6	8	6	7	5	5	3	5	6	.	8	8	5,5	7	8	7	8	7,5
10	8	.	8	8	6	8	8	8	8	8	.	8	6	8	5,5	8	8	7	8	7,75
11	7	2	4	8	5,25	8	8	8	8	8	8	7	8	8	7,75	8	8	7	5	7
12	8	8	2	5	5,75	8	8	8	7	7,75	8	8	8	8	8	4	6	6	7	5,75
13	8	7	4	7	6,5	8	8	8	6	7,5	.	8	.	8	4	8	7	8	7	7,5
14	2	2	2	1	1,75	8	8	7	8	7,75	8	7	8	8	7,75	8	6	8	8	7,5
15	2	.	8	8	4,5	8	8	8	8	8	8	8	6	8	7,5		7	4	4	3,75
16	8	8	5	3	6	8	8	8	8	8	8	6	7	8	7,25	6	6	6	6	6
17	.	.	.	.	0	8	8	8	7	7,75	6	8	6	1	5,25	8	6	7	7	7
18	.	2	7	7	4	7	6	7	7	6,75	8	8	8	7	7,75	7	7	7	8	7,25
19	8	8	7	7	7,5	8	8	7	8	7,75	.	.	8	8	4	8	8	8	8	8
20	8	.	7	6	5,25	8	8	8	.	6	.	.	8	8	4	8	8	8	8	8
21	7	7	8	8	7,5	8	.	.	7	3,75	8	8	8	6	7,5	8	8	8	2	6,5
22	8	8	8	7	7,75	7	7	7	8	7,25	8	7	7	7	7,25	8	8	8	8	8
23	8	7	7	7	7,25	8	7	8	8	7,75	8	8	6	7	7,25	8	8	4	7	6,75
24	8	8	8	8	8	7	.	8	8	5,75	8	7	8	8	7,75	8	8	.	.	4
25	8	8	8	8	8	8	7	8	8	7,75	8	.	8	8	6	8	7	6	7	7
26	8	8	8	8	8	8	8	8	8	8	8	.	.	8	4	8	7	8	8	7,75
27	8	8	8	7	7,75	8	8	8	8	8	8	8	8	8	8	8	7	8	8	7,75
28	8	8	8	8	8	8	8	8	6	7,5	.	8	7	8	5,75	8	8	7	7	7,5
29	8	8	6	7	7,25	7	8	8	8	7,75	8	7	7	8	7,5	8	8	8	7	7,75
30	7	7	8	7	7,25	7	8	6	7	7	8	8	8	8	8	7	7	7	8	7,25
31	8	7	7	7	7,25					853	7	8	8	8	7,75	.	.	.	8	2
	AverMai.10				6,45	Aver.juni.10				7,1	Aver.juli.10				6,2	Aver.aug.10				6,5

Date	September				Aver.	October				Aver.	November				Aver.	December				Aver.
1	7	7	5	8	6,75	8	7	.	4	4,75	1	8	.	.	2,25	7	7	8	7	7,25

2	8	8	8	8	8	8	8	8	.	6	.	8	7	7	5,5	8	5	8	6	6,75
3	8	8	8	8	8	.	8	8	8	6	.	7	2	4	3,25	6	6	8	8	7
4	8	7	8	7	7,5	8	7	8	8	7,75	2	1	4	4	2,75	8	8	8	8	8
5	5	7	7	8	6,75	8	8	7	.	5,75	7	5	7	7	6,5	.	8	8	8	6
6	8	8	8	7	7,75	8	8	8	8	8	3	8	.	8	4,75	8	8	8	8	8
7	8	8	7	7	7,5	.	.	8	8	4	8	8	8	8	8	8	8	8	8	8
8	6	7	7	7	6,75	8	8	8	8	8	4	5	6	3	4,5	8	2	5	5	5
9	8	8	8	8	8	8	8	7	8	7,75	8	8	2	2	5	8	5	4	3	5
10	8	8	7	8	7,75	8	8	8	6	7,5	8	4	7	8	6,75	3	2	6	8	4,75
11	8	7	8	8	7,75	7	8	7	7	7,25	8	1	8	7	6	6	8	4	6	6
12	8	.	.	8	4	8	8	8	8	8	8	8	8	8	8	4	3	6	7	5
13	8	8	.	8	6	4	6	6	3	4,75	8	8	8	5	7,25	4	8	6	4	5,5
14	8	8	.	.	4	1	8	8	7	6	5	8	7	7	6,75	1	1	7	8	4,25
15	8	8	7	7	7,5	8	8	7	8	7,75	2	8	1	6	4,25	8	.	.	.	2
16	8	.	7	8	5,75	8	8	6	8	7,5	7	8	8	8	7,75	7	7	8	.	5,5
17	.	.	.	8	2	8	7	5	7	6,75	7	8	8	8	7,75	3	3	7	7	5
18	8	8	8	8	8	8	.	8	8	6	.	8	6	3	4,25	8	3	2	2	3,75
19	8	8	8	.	6	8	7	3	8	6,5	1	8	5	7	5,25	6	7	8	8	7,25
20	.	.	.	.	0	3	3	7	8	5,25	8	7	8	7	7,5	8	.	.	8	4
21	.	.	8	.	2	8	8	8	8	8	5	7	7	7	6,5	6	8	8	.	5,5
22	.	.	8	.	2	8	8	8	8	8	7	7	8	7	7,25	6	8	2	1	4,25
23	8	8	8	7	7,75	8	8	8	8	8	7	8	8	8	7,75	7	8	4	5	6
24	8	8	8	8	8	8	8	8	8	8	4	7	8	8	6,75	6	7	7	8	7
25	8	8	7	8	7,75	8	8	7	8	7,75	.	4	7	8	4,75	7	7	8	7	7,25
26	8	7	7	6	7	8	4	5	6	5,75	6	7	8	7	7	8	8	8	8	8
27	8	8	5	8	7,25	6	7	7	5	6,25	7	8	3	8	6,5	8	3	8	8	6,75
28	8	7	8	8	7,75	4	8	6	8	6,5	5	2	6	6	4,75	8	8	8	8	8
29	8	8	7	8	7,75	8	6	4	2	5	3	7	7	7	6	6	6	8	8	7
30	2	7	8	8	6,25	2	5	3	2	3	3	6	7	4	5	8	7	3	4	5,5
31						3	7	7	8	6,25						.	.	8	.	2
	Aversep.10				6,3	Aver.okt.10				6,5	Aver.nov.10				5,8	Aver.des.10				5,8
2012																				
	January				Aver.	February				Aver.	March				Aver.	April				Aver.
1	7	4	8	6	6,25	8	6	8	8	7,5	4	5	6	7	5,5	7	7	6	8	7
2	8	8	7	8	7,75	8	8	6	8	7,5	8	8	6	6	7	8	7	2	3	5
3	8	8	8	8	8	6	6	6	8	6,5	8	6	8	8	7,5	2	8	5	8	5,75
4	8	8	8	4	7	7	3	6	8	6	8	6	7	1	5,5	8	7	8	7	7,5
5	4	1	4	2	2,75	7	5	5	7	6	3	7	7	6	5,75	8	8	7	6	7,25
6	2	7	5	4	4,5	7	3	2	6	4,5	1	7	7	6	5,25	7	8	8	8	7,75
7	6	6	5	3	5	7	7	8	8	7,5	7	7	6	7	6,75	8	7	7	7	7,25
8	4	7	7	2	5	7	8	8	8	7,75	8	8	7	7	7,5	8	6	7	7	7

9	2	1	1	1	1,25	8	7	3	3	5,25	8	8	6	8	7,5	7	6	6	8	6,75
10	2	5	2	6	3,75	.	7	6	8	5,25	4	4	7	7	5,5	8	8	8	8	8
11	6	7	7	7	6,75	8	7	4	.	4,75	.	7	6	6	4,75	8	7	8	8	7,75
12	6	7	7	0	5	8	5	6	3	5,5	1	7	5	6	4,75	8	8	7	7	7,5
13	3	3	2	0	2	3	6	8	7	6	1	3	2	3	2,25	7	7	7	8	7,25
14	7	7	7	8	7,25	2	3	6	3	3,5	8	7	6	7	7	8	5	6	5	6
15	8	8	8	3	6,75	8	7	7	8	7,5	3	6	8	8	6,25	6	4	4	3	4,25
16	8	2	5	8	5,75	0	7	8	5	5	7	.	7	8	5,5	6	6	2	3	4,25
17	4	8	7	8	6,75	2	7	3	3	3,75	8	8	8	8	8	8	3	7	4	5,5
18	8	8	8	8	8	3	3	6	5	4,25	8	7	7	6	7	7	6	6	2	5,25
19	8	8	7	8	7,75	4	8	8	7	6,75	7	7	7	7	7	3	7	8	6	6
20	8	8	7	8	7,75	2	6	8	8	6	1	1	6	4	3	8	7	1	1	4,25
21	8	8	5	7	7	1	2	7	4	3,5	7	7	6	6	6,5	1	1	1	3	1,5
22	1	2	4	0	1,75	6	4	5	.	3,75	3	6	5	7	5,25	1	2	1	1	1,25
23	1	1	3	7	3	2	3	7	6	4,5	6	6	2	7	5,25	7	7	4	3	5,25
24	8	3	8	8	6,75	3	3	7	5	4,5	8	7	6	7	7	6	7	7	6	6,5
25	3	2	3	2	2,5	6	7	4	4	5,25	7	6	5	6	6	6	.	.	8	3,5
26	7	8	7	6	7	8	3	7	8	6,5	2	3	6	8	4,75	8	.	8	8	6
27	8	8	7	8	7,75	6	7	8	8	7,25	8	8	8	8	8	7	7	8	8	7,5
28	8	8	3	3	5,5	8	8	8	8	8	8	8	6	1	5,75	8	.	7	7	5,5
29	4	6	2	3	3,75	.	7	8	8	5,75	5	7	7	5	6	8	8	6	7	7,25
30	6	4	6	5	5,25						5	5	6	6	5,5	8	8	8	.	6
31	7	5	7	7	6,5						6	5	6	8	6,25					
	Aver.jan.12				5,5	Aver.feb.12				5,71	Aver.mars.12				5,9	Aver.apr.12				5,91
	May				Aver.	June				Aver.	July				Aver.	August				Aver.
1	8	8	8	7	7,75	7	7	8	7	7,25	8	.	8	8	6	7	8	8	7	7,5
2	5	6	7	8	6,5	8	7	8	7	7,5	.	8	8	8	6	8	8	8	.	6
3	7	7	5	4	5,75	7	8	7	8	7,5	.	8	8	8	6	.	8	8	7	5,75
4	1	7	8	2	4,5	.	8	8	7	5,75	8	8	8	8	8	8	8	8	8	8
5	6	6	1	6	4,75	7	6	7	4	6	8	7	7	7	7,25	8	7	8	6	7,25
6	8	8	8	8	8	7	8	7	8	7,5	8	8	7	8	7,75	6	4	6	5	5,25
7	8	7	6	6	6,75	8	8	8	7	7,75	7	8	7	7	7,25	7	6	8	2	5,75
8	8	8	7	8	7,75	7	8	8	7	7,5	8	7	8	7	7,5	7	4	4	7	5,5
9	8	8	1	1	4,5	8	8	7	8	7,75	8	7	8	8	7,75	8	7	8	8	7,75
10	2	3	6	7	4,5	8	8	8	8	8	8	7	7	1	5,75	8	8	.	.	4
11	6	7	7	7	6,75	7	7	7	7	7	0	1	6	7	3,5	8	8	8	7	7,75
12	3	3	4	7	4,25	7	7	8	8	7,5	8	7	7	8	7,5	8	.	8	.	4
13	5	7	8	8	7	8	.	8	8	6	8	8	8	.	6	7	7	.	8	5,5
14	8	7	7	7	7,25	8	.	8	8	6	.	.	.	2	0,5	8	8	7	8	7,75
15	7	8	8	8	7,75	8	8	8	8	8	5				1,25	8	8	8	7	7,75
16	8	.	8	8	6	7	8	8	.	5,75				8	2	8	7	.	8	5,75

17	8	7	8	8	7,75	.	8	7	8	5,75	8	8	7	3	6,5	8	8	8	8	8
18	8	8	8	8	8	8	8	8	.	6	7	7	7	7	7	8	7	7	7	7,25
19	8	8	7	5	7	.	.	6	8	3,5	6	7	7	7	6,75	1	7	8	8	6
20	5	.	8	8	5,25	8	8	8	.	6	8	7	8	8	7,75	8	8	7	1	6
21	8	8	8	5	7,25	.	8	8	8	6	8	8	8	.	6	1	6	7	7	5,25
22	7	8	8	8	7,75	8	8	7	8	7,75	.	.	.	8	2	8	5	7	7	6,75
23	8	7	8	7	7,5	8	8	8	8	8	8	8	8	3	6,75	8	6	6	7	6,75
24	7	7	.	8	5,5	8	8	8	7	7,75	8	8	8	8	8	8	8	7	7	7,5
25	8	.	7	7	5,5	8	8	7	8	7,75	8	8	.	7	5,75	8	8	6	8	7,5
26	8	8	8	8	8	8	7	4	5	6	8	8	8	7	7,75	8	8	8	7	7,75
27	8	8	7	8	7,75	7	5	2	7	5,25	8	8	8	8	8	7	7	7	7	7
28	8	7	7	8	7,5	6	7	6	7	6,5	8	7	5	7	6,75	5	1	7	8	5,25
29	7	7	7	7	7	6	7	7	7	6,75	5	8	8	4	6,25	8	7	8	8	7,75
30	3	7	6	6	5,5	7	5	3	7	5,5	8	8	8	8	8	6	6	2	4	4,5
31	7	7	7	7	7						8	8	8	7	7,75	3	5	8	7	5,75
	Aver.mai.12				6,58	Aver.juni.12				6,7	Aver.juli.12				6,471	Aver.aug.12				6,4
	September				Aver.	October				Aver.	November				Aver.	December				Aver.
1	6	7	6	7	6,5	7	7	.	5	4,75	7	8	8	3	6,5	3	8	3	4	4,5
2	8	8	8	7	7,75	.	7	8	8	5,75	2	1	6	8	4,25	7	7	2	1	4,25
3	7	7	7	8	7,25	8	8	7	8	7,75	7	8	8	8	7,75	1	3	3	3	2,5
4	8	8	6	8	7,5	7	6	7	8	7	8	8	8	4	7	4	6	7	2	4,75
5	.	8	8	.	4	6	7	7	8	7	6	8	7	8	7,25	4	2	4	1	2,75
6	8	8	8	8	8	8	7	7	7	7,25	8	3	8	8	6,75	1	5	7	2	3,75
7	7	8	8	8	7,75	6	8	6	7	6,75	6	7	5	8	6,5	1	2	2	1	1,5
8	7	.	8	.	3,75	8	8	7	7	7,5	7	8	8	8	7,75	8	2	7	8	6,25
9	8	8	7	7	7,5	7	6	7	8	7	6	6	7	7	6,5	8	7	6	3	6
10	7	5	7	7	6,5	7	7	7	.	5,25	2	6	5	1	3,5	8	8	7	7	7,5
11	4	8	7	8	6,75	8	8	3	1	5					0	6	3	3	2	3,5
12	8	8	8	8	8	8	8	7	8	7,75	8	4	8	8	7	6	1	2	2	2,75
13	8	6	8	8	7,5	8	7	7	1	5,75	8	8	6	8	7,5	7	3	2	1	3,25
14	.	.	7	7	3,5	2	8	7	8	6,25	8	8	7	7	7,5	1	6	8	3	4,5
15	6	8	6	8	7	3	0	0	0	0,75	8	4	7	8	6,75	1	2	6	3	3
16	8	7	8	8	7,75	0	8	8	8	6	8	8	8	6	7,5	3	2	1	8	3,5
17	8	7	7	7	7,25	8	7	5	3	5,75	8	8	8	8	8	7	5	6	4	5,5
18	8	.	8	8	6	8	7	8	5	7	8	7	8	8	7,75	4	2	2	3	2,75
19	8	8	8	7	7,75	4	8	4	.	4	6	8	.	6	5	3	7	7	7	6
20	8	8	8	8	8	8	7	6	6	6,75	5	2	7	8	5,5	7	3	7	4	5,25
21	8	8	6	7	7,25	8	7	7	8	7,5	8	6	7	6	6,75	8	8	8	8	8
22	4	7	7	8	6,5	7	7	7	8	7,25	8	8	5	3	6	6	7	8	8	7,25
23	8	7	7	8	7,5	8	7	3	6	6	1	1	7	5	3,5	7	8	7	6	7
24	4	7	8	8	6,75	8	8	7	7	7,5	4	8	8	8	7	4	4	7	6	5,25

25	8	7	8	7	7,5	7	8	8	8	7,75	8	8	8	8	8	7	8	8	7	7,5
26	5	5	6	5	5,25	6	7	7	6	6,5	8	8	8	8	8	5	6	6	6	5,75
27	3	2	3	2	2,5	8	3	2	1	3,5	.	8	8	8	6	4	4	5	7	5
28	7	7	6	3	5,75	1	2	7	4	3,5	8	7	3	6	6	8	8	.	5	5,25
29	1	1	1	2	1,25	7	2	4	4	4,25	3	7	2	2	3,5	5	8	4	6	5,75
30	2	3	6	7	4,5	1	1	3	7	3	.	.	7	3	2,5	5	8	8	.	5,25
31						6	8	8	7	7,25						8	8	4	6	6,5
	Aver.sep.12				6,35	Aver.okt.12				5,9	Aver.nov.12				6,3	Aver.des.12				4,9

APPENDIX B – Environmental Calculations for Bjørnøya

This appendix shows how the different formulas are used for calculation.

SEA SPRAY ICING

$$PR = \frac{U_A(T_F - T_A)}{\left(1 + 0{,}4\,(T_W - T_F)\right)}$$

Where	PR	Accretion prediction [m°C/s]
	U_A	Wind speed [m/s]
	T_F	Freezing temperature of sea water with salinity 34 ppt (- 1.9°C) [°C]
	T_A	Air temperature [°C]
	T_W	Sea water temperature [°C]

	Air Temperature Average	Air Temperature Minimum	Sea Water Temperature	Average Wind speed	Strongest wind speed
January	-8,1	-22,6	-1,5	8,3	19,6
February	-7,7	-22,7	-1,65	7,3	20,3
March	-7,6	-20	-1,55	7,9	18
April	-5,4	-16,7	-1,2	6,6	20,1
May	-1,4	-10,1	-0,2	6,4	17
June	1,8	-3,1	1,8	6	14
July	4,4	1	3,15	6	16,3
August	4,4	0,9	3,6	5,7	14
September	2,6	-1,9	3,25	7,8	17,2
October	-0,5	-7,1	1,85	7,4	18,6
November	-3,7	-10,9	0,1	6,4	15,3
December	-7,1	-19,1	-1	7,9	18,6

	PR Average	PR Maximum
January	44,36	349,76
February	38,49	383,85
March	39,50	285,79
April	18,05	232,41
May	-1,90	82,98
June	-8,95	6,77
July	-12,52	-15,65
August	-11,22	-12,25
September	-11,47	0,00
October	-4,14	38,69
November	6,40	76,50
December	30,21	235,24

Example that shows how the formula is used		
	PR (m°C/s) Average	**PR (m°C/s) Maximum**
January	(8,3*(-1,9-(-8,3))/(1+0,4*(-1,5-(1,9)) = 44,36	(19,6*((-1,9)-(-22,6)))/(1+0,4*((-1,65)-(-1,9))) = 349,76

WEIGHT OF SNOW AND ICE LOAD

$$m = (V * \rho) * 10$$

Where	m	Mass [kg]
	V	Volume of snow/ice [m^3]
	ρ	Density [kg/m^3]
	10	Areal of snow/ice

How the formula is used			
	Density kg/m^3	**Accreation (cm)**	**kg on 10m^2**
Sea spray icing	926	5	(1*1*0,05)*926*10 = 463
Snow	400	4,8	(1*1*0,048)*400*10 = 192

ICEBERG DRIFTING

$$t = \frac{\left(\frac{x}{v}\right)}{60}$$

Where	t	Time [minutes]
	x	Distance [m]
	v	Velocity [m/s]
	60	From seconds to minutes

How the formula is used						
Horizontal view		**Drift speed**		**Time**		
800	m	0,25	m/s	(800/0,25)/60 = 53	min	average
		1,13	m/s	(800/1,13)/60 = 12	min	for 31 hours
		1,38	m/s	(800/1,38)/60 = 10	min	maximum

WIND CHILL INDEX

$$WCI = \left(10 * \sqrt{U} - U + 10.5\right) * (33 - T)$$

Where WCI Accretion prediction [W/m^2]
U Wind speed [m/s]
T Ambient air temperature [°C]

Wind chill index		
	WCI (W/m^2) Average	WCI (W/m^2) Maximum
January	1274	1956
February	1230	1964
March	1247	1851
April	1136	1751
May	1011	1497
June	905	1224
July	829	1106
August	820	1089
September	931	1214
October	1015	1405
November	1079	1506
December	1231	1825

Example that shows how the formula is used		
	WCI (W/m^2) Average	WCI (W/m^2) Maximum
January	((10*(8,3^0,5)-8,3+10,5)*(33-(-8,1))) = 1274	((10*(19,6^0,5)-19,6+10,5)*(33-(-22,6))) = 1956

APPENDIX C – Guidelines for the Risk Analysis

This appendix will introduce the framework used in for the risk analysis in the thesis. Both the probability and the consequence are divided in 5 categories depending on their likelihood and severity. The tables below describe the meaning behind the categorisation. Below the tables a short list of guidelines to the ranking is presented.

Probability category	
1	Rare probability and will most likely not occur throughout a year
2	Unlikely probability. Event/hazard/incident/ice accumulation is possible, but unlikely
3	Likely probability and can occur during a year
4	Expected a few times in one year
5	Certain with high probability of occurrence and will most likely occur several times in one year

Consequence category	
1	Minor consequences
2	Moderate and can lead to challenges for personnel to perform their work, injuries of personnel, or small damages on components and systems
3	Serious category and can be critical due to damage on personnel, components and systems
4	Major consequences and can lead to fatalities for involved personnel and severe damages on systems
5	Catastrophic and have a potential to become a major accident if the amount of accreted ice is significant. Several fatalities and harm to the environment can be expected

Guidelines to the risk analysis	
Probability	Consequence
High probability if the given system is exposed to the physical environment	High consequence if the weather condition is harsh
High probability if the weather condition is harsh	High consequence if there is a possibility that personnel can be harmed
High probability if no shielding or protection from physical loads	High consequence if there is a possibility that the environment can be damaged by pollution
High probability if no proactive barriers are used	High consequence if there is a possibility that a major accident can occur
	High consequences if essential systems for the operation can be damaged
	High consequences if there is a possibility that communication systems will be damaged
	High consequences if there is a possibility that safety functions is damaged

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