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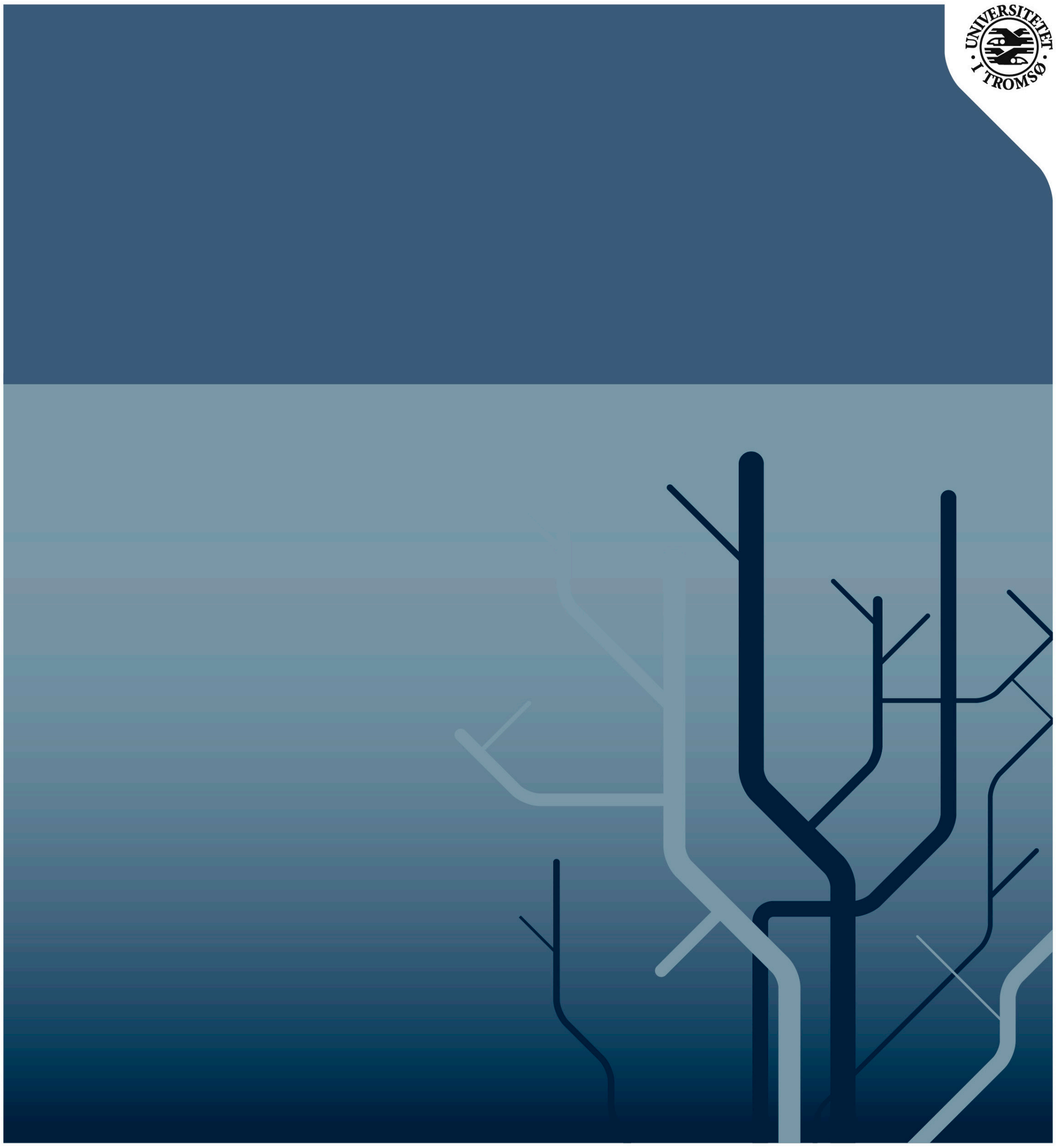

**Faculty of Science and Technology**

**Department of Engineering and Safety**

# MASTER'S THESIS

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| Title of Thesis:<br><br>**Drilling Waste Minimization in The Barents Sea** |
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# DRILLING WASTE MINIMIZATION IN THE BARENTS SEA

Master Thesis by

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UiT / THE ARCTIC UNIVERSITY OF NORWAY

**Faculty of Science and Technology**

**Department of Engineering and Safety**

**2014**

# Preface and Acknowledgements

This thesis is submitted as a fulfilment of the requirements for completion of the master degree in Technology and Safety in the High North at the University of Tromsø, Norway. The work is carried out in the time period between January 2014 and January 2015.

I would like to express my sincere thanks to my supervisor Assoc. Prof. Abbas Barabadi for his thoughtful supervision, guidance, and inspiration and for showing faith in my capability to carry out this research.

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Finally I am very grateful to my wife Rozhin for always supporting me, her patience and encouraging, and to my father for always pushing me forward in life.

Rezgar Zaki

Tromsø, January 2015

# Abstract


With the increasing demand for energy over recent decades, the Arctic region has become an interesting area for future oil and gas exploration and development. The Barents Sea has the most western position among the Arctic seas surrounding the coast of Western Russia and Northern Norway. In the recent years several oil and gas discoveries done in this area and the number of wells is steadily increasing.

During oil and gas drilling operations various types of waste are generated and waste minimization has major benefits for oil and gas companies by reducing costs used for waste management and disposal. Often oil and gas operators have not enough experience related to the waste handling in the Arctic environments. Moreover there are restrictions about selection of suitable drilling waste management options due to environment condition, regulatory requirements and poorly developed waste treatment facilities in the area. The Barents Sea has a harsh and sensitive environment at a remote location, hence, effective handling and management of drilling waste is becoming essential to ensure fulfillment of health, safety, environmental, and quality requirements. For this purpose, in this master thesis qualitative assessment of drilling waste handling options is conducted and suggests suitable methods for minimization of generated well drilling wastes. To achieve that, the work presented in this study addresses the potential impact of operation condition in the Barents Sea. The results obtained in this master thesis contribute to the goal of improving the assessment of drilling waste management.

Physical environment can affect any oil and gas activities in the Barents Sea. Less developed infrastructure may create several challenges such as limitations to the logistics of supplies, material and personnel required for the operation and maintenance activities. Operation condition in the Barents Sea has significant effects on systems and equipment in various ways, including repair time and failure rate. Moreover, it can increase the power losses, life cycle costs and safety hazards.

In Norway a production assurance concept was developed in the 1980s for the oil and gas industry. The production assurance concept is built on reliability, maintainability and supportability. However the concept of sustainability and safety is not considered in this definition. In the Barents Sea with the strict regulations and requirements for safety and environment, it can be challenging to fulfilling these requirements without considering these terms.

To address this problem in this master thesis the concept of performability with its elements (reliability, maintainability, quality, safety and sustainability) is presented and the effects of operation condition on the perfomability of equipment and systems will be studied and analyzed. Moreover considering the operation conditions and variety of the effects on different equipment performability, a standard factor, performability risk index is developed in order to assess and estimate the effects.



***Keywords:*** *The Barents Sea, Sensitive Environment, Waste minimization, Harsh Climate Condition, Performability, Performability risk index,*

# List of Appended Papers

**Paper I**

Zaki, R. & Barabadi, A. (2014), "Application of de-icing techniques for Arctic offshore production facilities": Critical review, presented at the international conference: Ocean, Offshore and Arctic Engineering, OMAE2014 in San Francisco USA.

**Paper II**

Zaki, R. & Barabadi, A. (2014), "Drilling waste management in the Barents Sea": Critical review, presented at the international conference: Industrial Engineering and Engineering management, IEEM 2014 in Kuala Lumpur, Malaysia.

**Paper III**

Zaki, R. & Barabadi, A. (2014), "Icing and Performance of Offshore Production Facilities in Cold Climate Region", presented at the international conference: Industrial Engineering and Engineering management, IEEM 2014 in Kuala Lumpur, Malaysia.

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# PART I

# DRILLING WASTE MINIMIZATION IN THE BARENTS SEA

# CHAPTER 1

# INTRODUCTION

# Introduction

*In this chapter you will find an introduction in order to introduce the reader to the research problem. Further the objectives, goals and limitations of the thesis will be described.*

## 1.1. Background and problem statement

Energy is a key element for driving modern industries and people's quality of life. World demand for oil and gas leads the industry to harvest energy in more distant and sensitive areas such as the Arctic region. The studies shows the world demand for oil is set to increase 37% by 2030 and over 28% of the world's undiscovered oil and gas petroleum reserves are expected to be in the Arctic region where the share of the offshore is approximately 84% (Kayrbekova et al., 2011). Oil and gas activities already occur in the Arctic region and given the large undiscovered petroleum resources increased activity could be expected with reduced sea-ice. However energy consumption is inseparably linked with environmental impact issues. The Arctic has great resources of different fish species, planktonic organisms and bird habitats, which makes the area vulnerable (Brantley et al., 2013).

During oil and gas drilling operations various types of wastes are generated. For each well the volume of drilling wastes range from 1000 to 5000 $m^3$, avoiding waste generation, minimizes the problems associated with waste management. Hence, waste minimization is given the highest priority in the waste management hierarchy (Eirik et al., 2013). Moreover, waste volume reduction will expand the choice of waste treatment options, reduce waste management costs, energy consumption, regulatory compliance concerns and enhance public perception of the company and the industry as a whole.

Oil and gas operators have not enough experience related to the waste handling in harsh and sensitive Arctic environments (Elnozahy et al., 2012). Drilling waste handling has to perform in such way that ensures fulfilment of health, safety, environmental, and quality (HSEQ) requirements.

The Barents Sea has harsh climatic conditions due to low temperatures, sea ice, polar low pressures, poor visibility and seasonal darkness, etc., that can affect any oil and gas activities in this area. Less developed infrastructure may create several challenges such as limitations to the logistics of supplies, material and personnel required for the operation and maintenance activities (Gudmestad and Løset, 2004, Barabadi et al., 2013). Furthermore often systems are designed, built, and tested in an environment with a normal condition. However operations in the Barents Sea can increase failure rate and reduce the performability of the system significantly and may cause downtime in process (Barabadi et al., 2011). An industry with a high level of investment, such as offshore oil and gas, the costs of the production losses due to a long downtime are substantial which can affect business performance. Thus, considering the unique and challenging Arctic operational conditions, the designed system must be performable. Misra (Misra, 2008b) defined perfrmability as the entire engineering effort that goes into improving the performance of a system that not only ensures high quality, reliability, maintainability and safety but also is sustainable. Improved performance should necessarily imply less environmental pollution, less material and energy requirements, waste minimization, and finally conservation and efficient utilization of available resources, which in turn result in minimum life-cycle costs.

## 1.2. Aims and Objectives

The main aims of this master thesis is to determine suitable methods for minimization of generate well drilling wastes in the Barents Sea and analysis the effect of operation condition in the Barents Sea on the perfomability of equipment and systems. More specifically, the objectives of this master thesis are:

- To define and review critical factors for operation and maintenance in the Barents Sea.
- To determine suitable methods for minimization of generate well drilling wastes in the Barents Sea
- To assess and analysis how operation condition in the Barents Sea can affect the performability of a system.
- To develop a performability risk index in order to estimate the effects of operation condition in the Barents Sea on performability of systems and equipment.

These objectives contribute to the goal of improving the assessment of waste management in the Barents Sea and effect of operation conditions on performability of systems and equipment.

## 1.3. Research Questions

The following research questions are posed to achieve the research objectives:

RQ1. What are the main critical factors for operational and maintenance in the Barents Sea.
RQ2. What are the available technologies contribute to minimization of well drilling waste in the Barents Sea.
RQ3. How operation conditions in the Barents Sea can affect the performability of a system.
RQ4. How can develop a performability risk index in order to estimate the effects of operation condition in the Barents Sea on performability of systems and equipment.

### 1.4. Outline of the master thesis

This master thesis contain of two parts. Part 1 consist of five chapters:

*CHAPTER 1. Introduction*

In this chapter you will find an introduction in order to introduce the reader to the need for research. Further the objectives, goals and research questions that are posed to achieve the research objectives will be described.

*CHAPTER 2.The Barents Sea*

Aim of this chapter is to increase understanding about physical environment, and appropriate and sufficient infrastructure in the Barents Sea. These factors may influence drilling waste management and performability of systems on offshore petroleum facilities. An overview of main critical factors will be provided.

*CHAPTER 3. Drilling waste minimization*

In this chapter you will find definition of main types of waste generated during oil and gas drilling operations and three available options regards to waste disposal and treatment in the Barents Sea reviewed and discussed. Moreover most preferred methods, systems and strategies, which contribute to minimization of drilling wastes will be discussed and presents.

*CHAPTER 4.The Effects of operation condition on performability of systems in the Barents Sea.*

In this chapter you will find a brief description of the concept of performability and study the effect of operation condition like remote, harsh, and sensitive environment in the Barents Sea on the different elements of performability.

*CHAPTER 5. performability Risk Index*

The aim of this chapter is to develop a performability risk index in order to estimate the effects of operation condition in the Barents Sea on performability of systems and equipment.

Part 2 contains three appended papers, which have written based on the theoretical and mathematical engineering of the thesis. Relation between the appended papers and research questions and chapters in part 1 is shown in table 1.

**Table 1: Relation between research questions, chapters and depended papers.**

| Research questions and Chapters | Paper I | Paper II | Paper III |
|---|---|---|---|
| RQ1 (Chapter 2) | ✓ | ✓ | ✓ |
| RQ2 (Chapter 3) | ✓ | | |
| RQ3 (Chapter 4) | | ✓ | |
| RQ4 (Chapter 5) | | ✓ | |

## 1.5. Limitation

The master thesis mainly focuses on the offshore oil and gas activities in the southwestern Barents Sea, north of Norway.

# CHAPTER 2

# THE BARENTS SEA

# The Barents Sea

*Aim of this chapter is to increase understanding about physical environment, and appropriate and sufficient infrastructure in the Barents Sea. These factors may influence drilling waste management and performability of systems on offshore petroleum facilities. An overview of main critical factors will be provided.*

The Barents Sea is located between 70° and 80° N on the North European continental shelf with an average depth of 222 m. It has its greatest depth up to 600 m in the Franz Josef Land and in the central part, and a vast shelf with depths of less than 100 m predominating in the southeast and near the coast of the Svalbard Archipelago. The Barents Sea has the most western position among the Arctic seas surrounding the coast of Western Russia and Northern Norway. The climate of the sea is polar, but compared to all other Arctic seas the climate of the Barents Sea is characterized by high air temperatures, mild winters and high rainfall. Through the Barents Sea the greater part of the warm North Atlantic cyclones take their course, coming to the east and northeast of the Barents Sea (figure 1 Left). In the Barents Sea, environmental conditions vary substantially from north to south and east to west. Unlike other Arctic seas almost 3/4 of its surface is covered by ice but never freezes completely even in the winter, and about 1/4 of its area remain in average free of ice, due to enter of warm surface ocean currents from the Atlantic water, preventing the cooling of the surface layer to the freezing point. Norwegian discovery and fields such as Johan Castberg, Snøhvit and Goliat have taken place in this environmental region, which is generally ice free during the whole year (Bulakh et al., 2011).

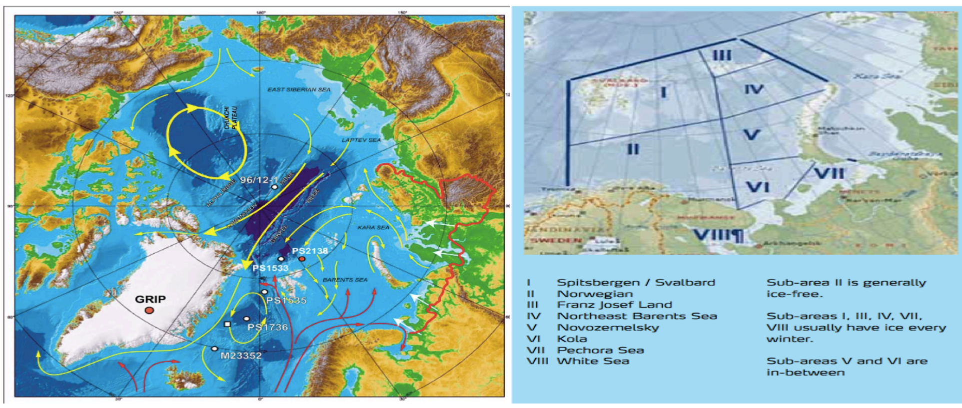


Figure 1: Left: Warm surface ocean currents from Atlantic water are marked by red and cold Arctic water is marked by yellow arrows (Knies and Vogt, 2003). Right: Dividing the Barents Sea in the eight different environment regions (Saebo and Cammaert, 2011).

The Barents Sea 2020 (Saebo and Cammaert, 2011) has divided the Barents Sea in eight different environmental regions: I) Spitsbergen; II) Norwegian; III Franz Josef Land; IV Kara; V Novozemelsky; VI Kola; VII Pechora; VIII White Sea. This division takes into account the general physical-geographical features of the Barents Sea (seabed relief, atmospheric process, system of currents, ice edge position, etc.). This report is limited to the Norwegian Barents Sea, western region of the Barents Sea and south of Bjørnøya including area I and II (figure 1 Right).

## 2.1. Petroleum activity in The Barents Sea

*Snøhvit;* In 1984, the Snøhvit-field was discovered in the Barents Sea. Snøhvit is the world's northernmost field in production and the well stream is the longest in the world with multiphase flow, which started its production in 2007. The development concept involves a construction of subsea installation at 250-345 m depths remotely controlled from shore (figure 2). The gas is transported from the field in a 143 km long multiphase pipeline to the LNG facility at Melkøya. The recoverable resources in the Snøhvit field are estimated at 193 billion m3 of natural gas, LPG and condensate (light oil). With the LNG production plans on Melkøya it is estimated that 5.67 billion cubic meters of LNG will be produced per year, and the resources will stretch to a delivery of 25-30 years. Produced quantity of LNG will be shipped with 70 shiploads per year in purpose-built LNG carrier where the gas is kept cooled down. In addition, 15 to 20 shipments of LPG and 15-20 with condensate in other vessels. Operator and the largest owner of the Snøhvit project is Statoil ASA (Eikeland et al., 2002).

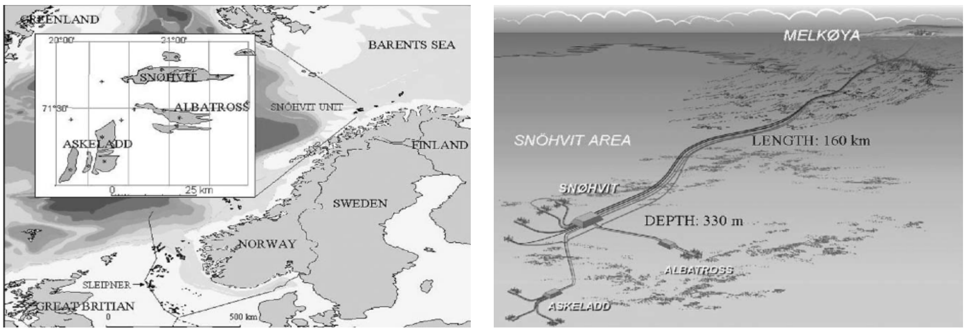


Figure 2: Snøhvit location and its subsea field development (Maldal and Tappel, 2004).

*Goliat;* Goliat is the first oil field developed in the Norwegian part of the Barents Sea and was discovered in year 2000. It is located in the south-western part of the Barents Sea, about 85 km northwest of Hammerfest and about 50 km south of the Snøhvit field (figure 3). The water depth at Goliat is between 320 m and 420 m. Goliat contains two main oil bearing reservoirs (Realgrunnen and Kobbe) with 28 million $Sm^3$ of recoverable oil reservoirs, which are basis for the planned development. In addition, the field contains 8.8 billion $Sm^3$ of gas. Goliat is developed by subsea wells drilled from templates linked to circular floating production, storage and offloading (FPSO) facilities. The well stream will be processed on the FPSO and the oil exported to the market using tankers, and during the first phase-produced gas will be re-injected to provide pressure drive. Planned production start is at the third quarter of 2014. Production on the Goliat field is expected to last at least 15 years. If there is any more gas and oil in second, nearby fields, these can be connected to

Goliat platform, so that production is extended. Goliat license is owned by Eni Norway (65%) and Statoil (35%) and Eni Norway is the operator (Bjornbom et al., 2012, John Erik et al., 2012b).

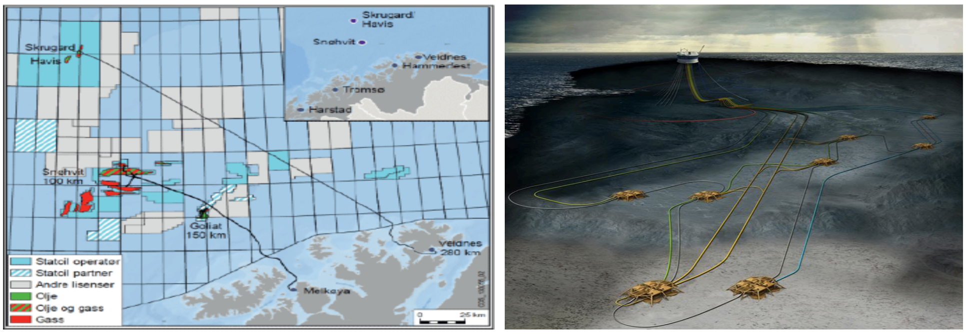


Figure 3: Left: Overview of fields and pipelines in the Barents Sea (Bjornbom et al., 2012) . Right: Goliat subsea arrangement with 8 templates (Bjornbom et al., 2012).

*Johan Castberg;* Johan Castberg is a new discovery that started drilling in 2012 in the Norwegian Barents Sea and consists of Skrugard and Havis. They are located 7 km from each other with 40.93 million $Sm^3$ of recoverable oil reservoirs. Johan Castberg is located at a distance of about 200 km from the nearest land which is Ingøya in Måsøy in Finnmark, 210 km from Bjørneøya, 100 km north of the Snøhvit-field and about 150 km north-west of Golia at the water depths of 360-390 m. The field will be developed with a semi- submersible platform. Using a 280 km long pipeline the oil will be sent to a terminal at Veidnes in Northern Norway. Johan Castberg licence is owned by Statoil Petroleum AS  (50%), Petoro (20%) and Eni Norway (30) % (Andrade, 2011).

## 2. Main critical factors that may influence drilling waste management and performability of systems in the Barents Sea

In this sub section a brief overview of main meteorological features and infrastructure and resources in the Barents Sea will be provided.

### 2.1.1. Low temperature

The maximum average air temperature in the Norwegian part of the Barents Sea is +4,4 °C with the annual range between +2,0 to +7,0. The maximum air temperature that can be expected in the southwest, near Goliat and Snøhvit, is in the range of 20°C to 25°C. Towards the north and east, the maximum temperature decreases to the range of 15°C to 20°C (Figure 4). The minimum average air temperature is -7,7 °C with an annual range between -6,0 to -9,0. The minimum air temperatures that can be expected in the southwest are in the range of -15°C to -20°C. Towards the north and east, the temperatures decrease to a range of -20°C to -30°C (Jacobsen and Gudmestad, 2012).

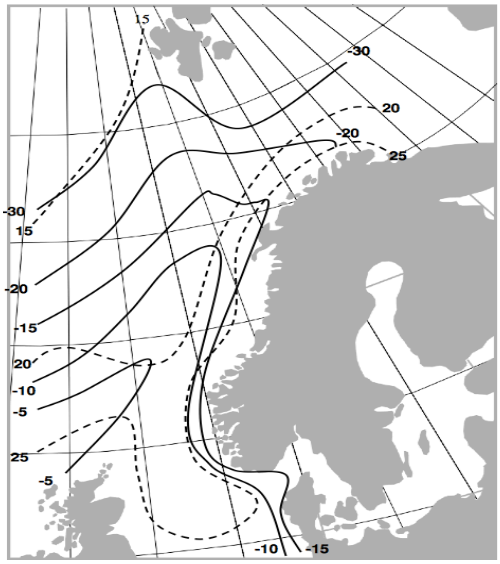

Figure 4: Highest and lowest air temperatures in the winter (solid line) and in the summer (dotted line) in the Barents Sea with an annual probability of $10^{-2}$, the temperature is given in ° C (NORSOK, 2007).

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The maximum average sea temperature in the Norwegian part of the Barents Sea is +7,0 °C with the annual range between +5,0 to +9,0. The maximum sea temperatures that can be expected in the southwest are in the range of 10°C to 12,5°C. Moving towards the north and east, the maximum temperatures decrease to the range of 5°C to 10°C. The minimum sea temperature that can be expected in the southwest is in the range of +2°C to +4°C. Towards the north and east, temperatures decrease to the range of +2°C to -2°C. Figure 5 indicate the average of surface sea temperature in the summer and winter periods in the Barents Sea. Both air and sea surface temperatures tend to decrease from south to north and from west to east reflecting not just atmospheric, but also oceanic factors (Jacobsen and Gudmestad, 2012).

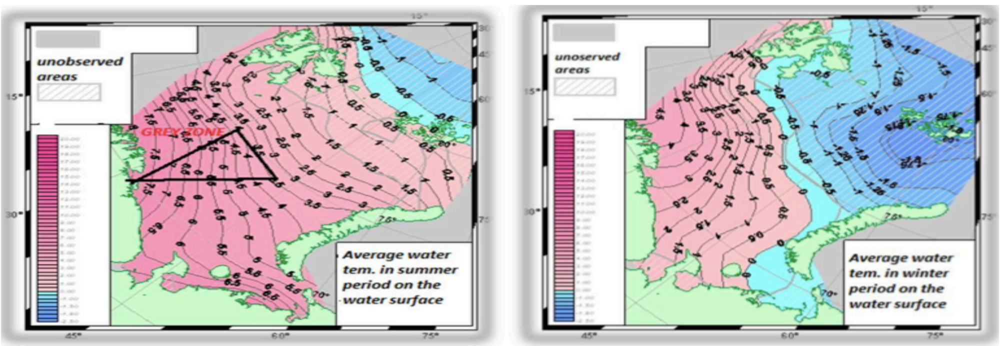



Figure 5: Left: Average water temperature in the summer (Bulakh et al., 2011). Right: Average water temperature in winter periods in the Barents Sea (Bulakh et al., 2011).

### 2.1.2. Polar low

Polar lows are small but intense maritime cyclones which most is commonly found in the areas around Svalbard, the Norwegian Sea and in the Barents Sea when a packet of cold Arctic air moves across relatively warmer water such as the North Atlantic as it sweeps into the Barents Sea. They usually provide small storms, and approximately 30% of cases are full storms around parts of the center. Polar lows normally disappear when they move over land because the driving force, the warm sea, no longer provides energy to sustain the wind system. A polar low forms during the period of September to early summer with a frequency of 2 to 4 per month. Typically 10 to 20 fully developed polar lows are seen in the Norwegian and Barents Seas during the season. Figures 6 shows monthly distribution of polar lows in the Norwegian Sea and the Barents Sea as recorded at the Meteorological Institute from 2000 to 2012 (Jacobsen and Gudmestad, 2012, Sørland, 2009).


Figure 6: Monthly distribution of polar lows in the Norwegian Sea and the Barents Sea as recorded at Meteorological Institute from 2000 to 2012(Meteorologisk, 2005).

The polar lows develop in a short space of time, they can increase from air to storm in just a few minutes and have short lifespan typically from 6h to 2 days.

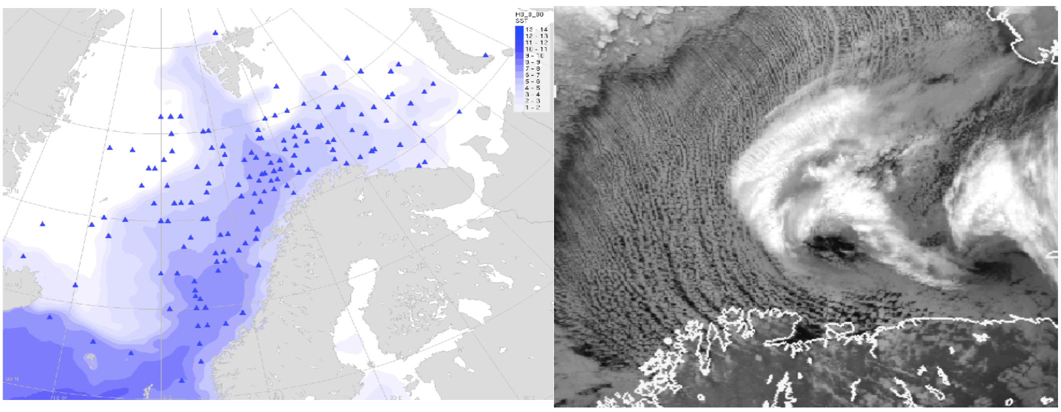


Figure 7: Left; Polar low formation point is indicated by a blue triangle and ocean temperature is indicate by blue shading (Meteorologisk, 2005). Right; Polar low pressure northeast of Varanger 3 April 2005 (Meteorologisk, 2005).

They are difficult to forecast and its typical diameter is 100–500 km. However, a rapid change of the wind direction, an increase of the wind strength, increase waves by up to 5m in under an hour, decrease in air temperature (until to -30), icing and heavy precipitation can be a warning of the approach of a polar low. 35-50% of the polar lows have storm force winds of 50 knots or more, and the strongest ever recorded in modern times was northeast of Varanger 3 April 2005 (see figure 7 right). This low pressure gave 70knop air over a 12-hour period. The formation ranges of polar lows from 2000 to 2012, a total of 166 cases shown in figure (7 Left) (Gudmestad and Karunakaran, 2012, Meteorologisk, 2005).

### 2.1.3. Wind

Strong winds form in the North Atlantic Ocean and lead into the central part of the Barents Sea. The dominant wind direction during the summer is from the west and during the winter from the northeast. The average wind speeds in the northern and central Barents Sea ranges from 8.0-9.0 m/s, and 6.0-10.0 m/s, respectively.
The highest wind speed appears around Bjørnøya, which can exceed to 36 m/s and decreases towards east and north. Extreme wind speed can occur during polar low and polar front condition(Thelma, 2010).

### 2.1.4. Icing

Icing is a function of meteorological parameters such as air temperature, wind speed, cloud liquid water content, cloud droplet spectra, etc. Icing can be categorized in two main groups *i*) Atmospheric icing and *ii*) Sea spray icing or superstructure icing. Atmospheric icing occurs in combination of precipitation and in- cloud with low air temperature and can cause accumulation of snow, rime ice, sleet, glaze and frost. Based on the methods and characteristics of deposition the atmospheric icing can be categorized in *glaze* from precipitating freezing rain or freezing drizzle (water drops smaller than 0.5 mm in diameter), *wet snow*, *rime* resulting from super cooled cloud, sea smoke and fog droplets, *Sleet* resulting from raindrops which have been frizzed before hitting surfaces and *frost* resulting from the deposition of water vapour directly as ice crystals. Atmospheric icing will normally lead to less ice development on structures than sea spray ice accretion and occurs when the air temperature is between 0 and – 20 degrees Celsius and the wind speed is less than 10 m/s. Atmospheric icing can accrete any place in the world where there is snow, typically in arctic and subarctic areas such as the Barents Sea, and in places where the temperatures can fall drastically below 0°C (Ryerson, 2009, Ryerson, 2011).

Sea spray accumulation occurrence is very rapid when there are high winds, low air temperature and low sea temperature. Sea waves, volume of spray flux and salinity of seawater are other important factors that affect rate of sea spray. Sea spray ice has generally lower density than atmospheric ice due to the salinity. This type of icing is a dominant source of ice accumulation in the Barents Sea. According to the Meteorological Department, when the air temperature is colder than the freezing temperature of seawater, approximately –2°C and wind speed exceeds 11 m/s freezing spray occurs. According to this definition most part of the Barents Sea, which is not covered with ice and have open water with higher waves, offshore facilities are more exposed to sea spray icing and they are potential areas for icing from November until May (Jones and Andreas, 2012).

In the Barents Sea, and in coastal areas, sea spray can occur at low temperatures combined with strong winds from the south and southeast that brings with it cold air masses from the east. It can also cause problems for coastal infrastructure, especially in areas that are exposed to storms and sea spray (Figure 8). For example on 17 to 22 January 2006 the unexpected storm named Narve hit the Snøhvit LNG production facility on Melkøya in the northern part of Norway outside Hammerfest, and heavy ice accreted on the equipment. Moreover the voyage with K/V Nordkapp from Tromsø to Nordøya 25-26 Febrauary 1987. Estimated from drought about 110 tons of sea spray ice accreted on this vessel in a period of 17 hours during storm and air temperatures of -15 C (Løset et al., 1999).

Figure 8: Icing on Snøhvit LNG production facility (Meteorologisk, 2005)

Overland (Overland, 1990) has developed algorithms for predicting sea spray vessel icing as:

$$PPR = \frac{V_a(T_f - T_a)}{1 + 0.3(T_w - T_w)} \qquad (1)$$

Where
$PPR$ = Icing Predictor ($m^oCs^{-1}$)
$V_a$ = Wind Speed ($m\ s^{-1}$)
$T_f$= Freezing point of seawater (-1.7 $^o$C for North Pacific)
$T_a$ = Air Temperature ($^o$C)
$T_w$ = Sea Temperature ($^o$C)

In the northern Barents Sea icing problems could be extreme and at worst, spray can build up to four centimeters of ice per hour on the surface of a device and according to table 2 from Overland (Overland, 1990) it classifies as extreme icing rate.

Table 2: Expected icing class and rates for 25-75 meter vessels (Overland, 1990).

| | **Light** | **Moderate** | **Heavy** | **Extreme (proposed)** |
|---|---|---|---|---|
| **Icing rate (cm/hour)** | <0.7 | 0.7-2.0 | >2.0 | |
| **Predictor (PR*) (m°C $s^{-1}$)** | <20.6 | 20.6-45.2 | >45.2 | >70.0 |

### 2.1.5. Darkness

In the Barents Sea during the winter the sun is below the horizon for a given period and this results in polar nights, which means that the area is totally dark. There are limited periods of twilight during the day until the sun returns. The length of the daylight period decrease rapidly from the autumn equinox until the sun leaves. Similarly the daylight period increases rapidly from the return of the sun until the spring equinox (Jacobsen and Gudmestad, 2012). Table 3 shows darkness periods in some locations in the Barents Sea.

Table 3: Dates for the sun below the horizon (Jacobsen and Gudmestad, 2012).

| **Location** | **Sun leaves** | **Sun returns** |
|---|---|---|
| Vardø | 23. November | 19. January |
| Hammerfest | 22. November | 20. January |
| Nordkapp | 20. November | 22. January |
| Johan Castberg | 14 November | 28 January |
| Snøhvit Field | 17 November | 24 January |
| Goliat Field | 19 November | 23 January |
| Bjørnøya | 07. November | 04. February |
| Longyearbyen | 26. October | 16. February |
| North Pole | 25. September | 18. March |

### 2.1.6. Visibility

The parameter visibility is based on an assessment of an observer. It is therefore only manned stations that have data on visibility. The nearest weather stations for this area are stations on the coast of Finnmark, the station on Bjørneøya, Svalbard Airport, Ny Alesund and Hopen II. Table 4 shows conditions and the observations at these stations according to Meteorologist institute (Iden, 2012).

Table 4: Conditions observed in the stations in the Barents Sea area (Iden, 2012).

| **Visibility**<br><br>**Stations** | **Good (Sight more than 10 km)** | **Moderate (Sight between 4 - 10 km)** | **Low (Sight between 1 - 4 km)** |
|---|---|---|---|
| Bjørnøya and Hopen | 50 % in July & 60% Rest of the year | 12 – 19 % | 10 – 19 % |
| Svalbard Airport and Ny-Aalesund II | 80 % | 2 – 10 % | 1 – 6 % |
| Vardø Radio | 80-90 % | 5 – 8 % | 9 – 12% in December and January & 3 – 7 % Rest of the year |

Precipitation such as rain and snow can reduce visibility to less than 2 km and fog under 1 km. Typically there are 64 days per year with visibility below 2km due to snow and 76 days per year with visibility below 1km due to fog (Gudmestad and Karunakaran, 2012). Another reason for poor visibility is called “whiteout” and creates an all white vision due to falling heavily snow and can block the vision of operation employer (Freitag and McFadden, 1997).

### 2.1.7. Weather forecasting

Barents Sea has a harsh winter climate with quicker shifts in weather conditions than the south along the Norwegian coast and the North Sea. The rapid changes represent a greater risk to maritime transport and oil activity in the area than further south. The weather stations are sparse, and the weather forecasts are in general more uncertain due to satellite constraints. Satellites are restricted in the northern regions as most satellites circumnavigates at lower latitudes. Currently polar orbit only brings the satellite over the area for a limited period each day (Sørland, 2009, Gudmestad and Karunakaran, 2012).
Meteorological Department has manned observation stations on Jan Mayen, Hopen and Bjørnøya. In addition, the institute observes weather at a number of stations on the mainland and Svalbard, and some observations from vessels at sea and in the air. Meteorological Institute's regional observation for Northern Norway in Tromsø is responsible for the operation of *ishavsstasjonene* and weather forecasting in the northern regions (Meteorologisk, 2005).
Polar lows are the greatest concern for weather forecasting in the Barents Sea. With the models used today the Norwegian Meteorological Institute estimate that most polar lows will be detected 6-12 hours before they are fully developed (Iden, 2012).

### 2.1.8. Appropriate and sufficient infrastructure

Activities in the Norwegian Barents Sea are currently supported from Finnmark in Northern Norway. Finnmark is different from the rest of Norway in relation to the large distances between regions and low population in these regions.
Infrastructure and logistics services, relevant to petroleum activities in Finnmark, which will be presented here, are: 1) transport infrastructure, 2) port, bases and base capacity, 3) waste disposal.

Activity directed towards the petroleum industry is currently taking place at the following locations:

Hammerfest: Snøhvit LNG plant at Melkøya, operated by Statoil. Polar Base provides service and supply services, maintenance and port operations. ENI is the operator for oil development in progress for the Goliat field, and also builds up the operating organization in Hammerfest. A helicopter base is located at Hammerfest Airport.
Several regional functions are located in Hammerfest such as hospital with acute medical ward, West Finnmark Customs and two major hotels, Rica and Thon.
Polar Base is located 8 km from Hammerfest Airport and 52 km from road E6. There are no restrictions on water depth when sailing from the north to Hammerfest to Melkøya and the Polar Base. The fjord is wide, which means few course changes, good stops and turn around opportunities. Polarbase is ownd by Ishavsolje AS (90%) and NorSea Group (10%). Table 5 show service offerings of the polarbase in Hammerfest (Karl et al., 2012)

Table 5: Polarbase in Hammerfest (Karl et al., 2012).

| **Offers** | **Specific information** |
|---|---|
| Quay 1 | Length 260m and 10 m depth |
| Quay 2 | Length 90m and 12 m depth |
| Quay 3 | Length 80m and 8 m depth |
| Floating Quays | Length 120m and 7 m depth |
| Crane | Crane capacity up to 200 tons |
| Storage | Outdoor area 220,000 m2 and indoor area of 8000 m2 |
| Bulk Construction | Cement, barite, bentonite, brine |
| Other services | • The port service: Loading and unloading of ships and automobiles, internal transport, crane and lift, assembly units, bulk handling and bunker deliveries.<br>• Terminal Services: Product Reviews, goods receipt, inspection, storage, customs clearance (by<br>• Bring Polar Base as), packing, securing cargo, consignments.<br>• Technical Services: Preservation, lifting gear control.<br>• Property: Rental of warehouses, offices and outdoor areas.<br>• Manning: management, materials management, warehousing, material coordinators for drilling and operating supply, project and logistics coordinator, helicopter coordinator.<br>• Private quay for well boat and OCTG pipe inspection hall.<br>• Bunker constructions |

Honningsvåg: Operators of oil spill preparedness. Oil-transfer in Sarnesfjord.
Alta: Head office of North Energy ASA, exploration and field development. Kirkenes: Oil-transfer is located in Bøkfjorden and Kirkenes hospital. Figure 9 shows existing and possible transportation in Finnmark; roads, airfields and use of airplanes and helicopters, train connections and transportation via vessels to ports.

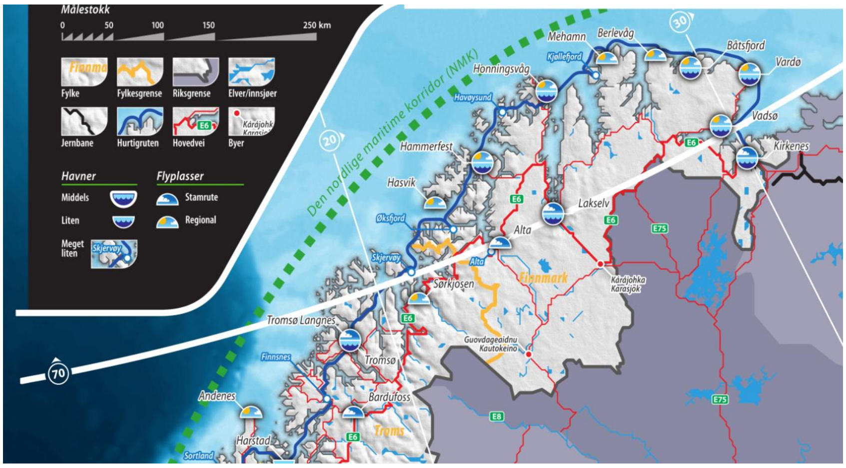



Figure 9: transportinfrastruktur i Finnmark (Karl et al., 2012)

There are eleven airports in Finnmark (figure 9). The biggest airports are Alta, Lakselv and Kirkenes. Presently, Alta and Hammerfest Airport mainly handle aircraft and helicopter traffic associated with land-based infrastructure that serves the offshore petroleum activities in the Barents Sea.
The operator Bristow Norway has 2-6 helicopters for transportation to and from petroleum installations in addition to a private helicopter for the petroleum industry based in Hammerfest. There are also a number of ambulance traffic and Sea King rescue helicopters from the Armed Forces 330 Squadron who use the airport in connection with the hospital in Hammerfest.
Route 94 through the city of Hammerfest, together with E6 through Alta is Finnmark´s busiest road (figure 9).
Kirkenes and Honningsvåg are currently ports used by offshore oil and gas industry in Finnmark and in addition polar bases in Hammerfest.
Sandnes Sea is the only place in Northern Norway that provide drilling waste management for other drilling wastes than water-based drill cuttings. Here you have the facility for final treatment of both slop and oil-based cuttings. In Finnmark there are currently only Hammerfest that is fully equipped for receiving waste from offshore drilling activities with larger scope. The only final treatment for drilling waste in Troms and Finnmark are two different options for disposal of water-based drill cuttings respectively in Balsfjord and Squamish(Karl et al., 2012)

# CHAPTER 3

# DRILLING WASTE MINIMIZATION

# Drilling waste minimization

*In this chapter you will find definition of main types of waste generated during oil and gas drilling operations and three available options regards to waste disposal and treatment in the Barents Sea reviewed and discussed. Moreover most preferred methods, systems and strategies, which contribute to minimization of drilling wastes will be discussed and presents.*

During oil and gas drilling operations various types of wastes are generated, which can be classified into three main categories:
*Drill cuttings:* The materials removed from the wellbore during a drilling operation, mostly solids, are drill cuttings, which are the largest source of drilling waste. In addition to formation solids, they contain formation fluid (e.g. oil) and small quantities of liquid and solid components of drilling fluid. Drill cuttings have an angular configuration and range in size from clay-sized particles (~ 2μm) to coarse gravel (> 30 mm)(Svensen and Taugbol, 2011, Neff, 2010a).

*Drilling fluid:* Dumped drilling fluid is another main source of drilling waste. Dumping of drilling fluids occurs in several situations, for instance when increase in the solids content of drilling fluid cannot be treated by adding fresh mud. It may also occur when drilling a new formation interval requires a drilling fluid with different properties. Therefore the previous mud needs to be dumped. Contamination of drilling mud with cements or other contaminants may also results in a fluid, which is usable no longer (Jensen et al., 2004).

*Slop and wastewater:* Drilling slop is a waste stream, which is generated when drilling or displacement fluid, melted snow, water rain runoff, and firewater become contaminated with drilling fluid components. Additionally, slop can be the wash water from routine cleaning operations such as cleaning of pits, drill floor, shaker room, pump room Accidental discharge of chemicals, or leakage of lubricants need to be cleaned up for personnel safety reasons. This also generates a considerable quantity of slop. Depending on geographic location, operational practices and rig configuration, the daily volume of drilling slop can vary from 100 to 500 barrel per day (Mueller et al., 2013).

Waste minimization is part of the concept of the Waste Management Hierarchy, which is a sequence of prioritized waste management options and guiding principle (Figure 10). The first, and most preferred option is source reduction. Source reduction is any activity that reduces or eliminates the generation of waste at the source. The next level is to reuse components as much as possible in their original state. The next option is recycling of components for other purposes than originally utilized. Recycling is the reclamation of the useful constituents of a waste for reuse, or the use or reuse of a waste as a substitute for a commercial feedstock or as a feedstock in an

industrial process. If possible, components need to be recovered from the waste stream and used further up the pyramid. Finally, the waste stream remaining that cannot be recovered, recycled, reused or reduced is the residue, need to be isolated and disposed of in a responsible manner (Olatubi et al., 2008, Eia et al., 2006).
Source reduction is given the highest priority in the waste management hierarchy and since for each well, the volume of drilling wastes range from 1000 to 5000 $m^3$ avoiding waste generation altogether minimizes the problems associated with waste management. Waste that is not generated does not need to be managed(Veloso and Dos Santos, 2013). This ensures that further waste treatment options deal with smaller quantities materials that need to be treated. Figure 10 shows that by avoid waste from arising, costs are typically reduced. It also illustrated how low cost and increased environmental benefits are linked. Volume reduction would expand the choice of treatment options available to deal with wastes, current audits show that increasing waste volumes due to higher subsurface reach are making uneconomical preferred waste treatment and or disposal options, even options deemed environmentally friendly. The most potential benefits for a company that implements a waste minimization program include: reduced costs, materials, waste management and disposal, energy consumption, reduced regulatory compliance concerns and enhanced public perception of the company and the industry as a whole.

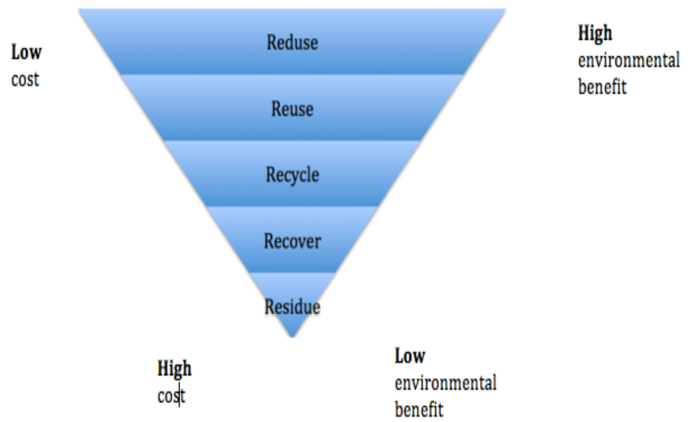



Figure 10: Waste management hierarchies with cost and environment evaluation (Eia et al., 2006).

## 3.1. Handling options for drilling waste in the Barents Sea

The Barents Sea is an environmentally sensitive area with harsh climatic conditions due to low temperatures, sea ice, polar low pressures, poor visibility and seasonal darkness, etc., that can affect any oil and gas operation in this area. Less developed infrastructure may create several challenges such as limitations to the logistics of supplies, material and personnel required for the operation and maintenance activities. Additionally, since the Barents Sea has great resources of different fish species, planktonic organisms and bird habitats, which makes the area vulnerable is under strict rules by the Norwegian environmental regulation to prevent the adverse effects of discharges of hazardous chemicals to sea from petroleum operation (Kayrbekova et al., 2011).

From to 2011 Norwegian government had zero discharge policy; a spatial requirement related to drill cutting, drilling mud and produced water in order to eliminating discharge of hazardous chemicals during offshore operations in the Barents Sea. However the Barents Sea now has the same general requirements for waste management as the rest of the Norwegian continental shelf. There are no longer any general requirements for the use of water-based drilling fluids; it will be assumed an increasing use of oil-based drilling fluids ahead, especially for the production wells.
With regards to waste disposal, there are three options available in the Barents Sea: i) re-injection into the subsurface formations, ii) discharge into sea; iii) transport to the shore for further treatment/disposal options (Peter, 2008).

### 3.1.1. Transport of waste to the shore

Waste shipped to shore to the drilling waste treatment facility (Figure 11) could be challenging for fulfilling the requirements for safety, logistics and environment due to remote and sensitive areas and harsh climate conditions in the Barents Sea. Moreover transport waste to shore for treatment has also a negative effect on the environment by increasing air pollution, energy consumption and also increasing the marine traffic.
In the Northern parts of Norway, waste treatment facilities are poorly developed. Hammerfest is the northernmost location where SAR has established drilling waste treatment facility, for disposal of water-based drill cuttings. However final treatment is still handled further south due to capacity and technical limitations. Moreover the only place that have completed treatment for other drilling waste than water-based drill cuttings and the facility for final treatment of both slop and oil-based cuttings in northern Norway is Sandnesjøen which is located long south from the Barents Sea.
A typical offshore well can generate in excess of 1000 tones of cuttings and require several hundred skips. All these skips have to be lifted onto a boat, transported to the rig, lifted up onto the rig, and lifted to the filling station on the rig. Once filled with cuttings, the skip is lifted away from the filling station, lifted down onto the boat, and finally lifted off the boat when it returns to the shore base. This means six or more crane lifts are required for each skip filled, and at 200 skips per well this amounts to 1200 individual crane lifts per well (Svensen and Taugbol, 2011, Morris et al., 2006). There are many HSE issues connected to it and the number of crane lifts makes these high-risk methods due to polar low and high wind in the area. The environmental effect causes a lack of concentration, and the reason for the human errors. Falling objects can be dangerous during operations; trapped fingers or bodies are also in danger. Nine out of ten fatal an accident on the Norwegian shelf is caused by human error during crane lifting activities. In addition, these skips can take up considerable deck space on a rig, many of which were never designed for these types of operations. In periods with high activity, one major problem is availability and turn-around of skips; this is because of the problems onshore. During the winters of 2009 and 2010 the NCS went through long lead-time because cutting were frozen in skips waiting onshore to get emptied (Ayele et al., 2013).

Figure11: Cuttings collection boxes installed on supply vessel (Eia et al., 2006)

### 3.1.2. Re-injection

The next drilling waste handling option is reinjection of drilling waste into underground formation. The injection pressure must be high enough to fracture the subsurface formation. In certain geological situations, formations may be able to accept waste slurries at an injection pressure below the pressure required to fracture the formation. Wastes are ground, slurried, and injected, but the injection pressures are considerably lower than in the case of slurry injection. As a first step, the solid or semi-solid drilling waste material is made into slurry that can be injected. The waste material is collected and screened to remove large particles that might cause plugging of pumps or well perforations. Liquid is added to the solids, and the slurry (or the oversize material) may be ground or otherwise processed to reduce particle size. Prior to injection, various additives may be blended into the slurry to improve the viscosity or other physical properties (Peter, 2008).

In 2009 it was found that there had been loss of integrity through the injection process in some injection wells on the Norwegian continental shelf (NCS), which causes fractures up waste to the seabed. These findings lead to closing of several cuttings injectors, and others were given limitations to the volumes and rates injected (Svensen and Taugbol, 2011). In Norway the share of cuttings and slop that was re-injected dropped from above 50 percent in 2006 to 40 percent in 2009, 20 percent in 2010 and below 8 percent in 2011 due to formation fractures causing leakages from disposal wells(Sigra, 2013). Some subsurface geological structures are not fit for waste reinjection (Figure 12); therefore evaluation of the geological conditions that favor the re-injection process is needed. Requirements and regulation for underground injection in the Barents Sea needs to be assessed, because governing authorities are strict as to approve reinjection, and they do this on a case-by-case basis. Another issue related to reinjection is to make the solid drilling waste material injectable, it must be transformed into slurry, during which the volume of the waste increases by the factor of 5-6 (Sigra, 2013, Peter, 2008).

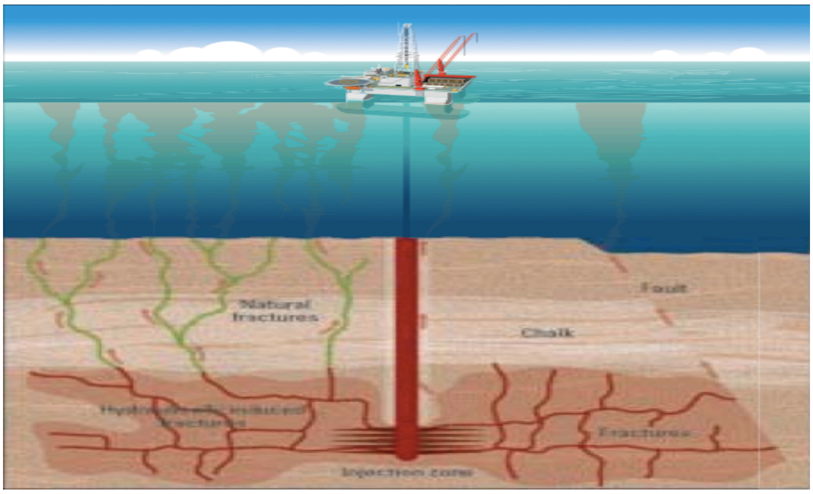



Figure 12: Poorly designed reinjection projects risk waste materials leaking back to the surface through natural fractures, along fault planes (Geehan et al., 2006)

### 3.1.3. Discharge into the Sea

In this option drill cuttings usually are treated to remove as much of the drilling mud as possible and are discharged to the ocean. Drilling muds containing cuttings are circulated through several separation devices on the rig to separate the drill cuttings particles from the drilling mud. Figure 13 illustrates dispersion and fates of WBM and cuttings following discharge to the ocean. The larger particles, representing about 90 % of the mass of the mud solids, form a plume that settles quickly to the sea floor.

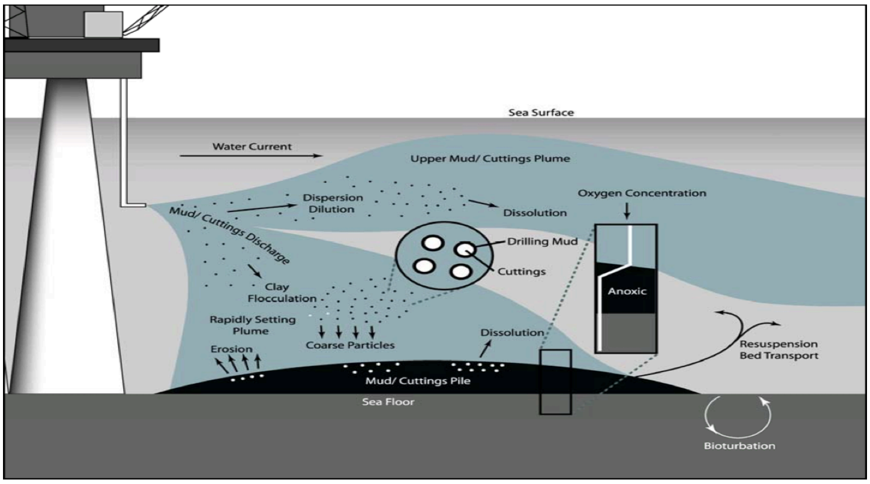



Figure 13: Dispersion of WBM and cuttings following discharge to the ocean (Neff, 2010a)

This lower plume is containing dense larger-grained particles, including cuttings, and flocculated clay/barite particles. About 10 % of the mass of the mud solids, consisting of fine-grained unflocculated clay-sized particles and a portion of the soluble components of the mud, form upper plume in the upper water column that drifts with prevailing currents away from the platform and is diluted rapidly in the receiving waters. The fine-grained solids in the upper plume settle slowly over a large area of the sea floor (Neff, 2010a)

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the OSPAR Convention) was presented to the former Oslo and Paris Commissions in Paris on September 22, 1992. The Convention entered into force on 25 March, 1998 and has been ratified by Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Sweden, Switzerland, and the United Kingdom and approved by the European Community and Spain. OSPAR developed environmental guidelines for offshore oil and gas operations in the OSPAR region. The OSPAR countries with offshore oil and gas resources (mainly Norway, the United Kingdom, and the Netherlands) independently apply these guidelines to the unique environmental and political conditions of the regions of the North Sea, Norwegian Sea, and Barents Sea under their jurisdiction (Neff, 2010a).

The Norwegian Pollution Control Authority (SFT) works with a color-code system figure 14 for chemicals and substances used and discharged offshore in the OSPAR area. They have divided relative hazard of chemicals used and discharged offshore into four categories: black, red, yellow, and green. The black and red categories include the most harmful or hazardous chemicals, while those in the yellow and green category pose no or little risk to the environment (PLONOR). According to (SFT) all chemicals intended for use and discharge offshore should be tested for the biodegradability, bioaccumulation and acute toxity unless the substance is on the PLONOR list (Knol, 2011).

| SFT Color Category | Chemical Characteristics |
|---|---|
| Green | Chemical on the PLONOR list |
| Yellow | Unclassified chemicals, not considered hazardous |
| Red | Chemicals recommended for substitution because:<br>Two of three categories: biodegradability < 60%; log $K_{ow} \geq 3$; Toxicity ($ED_{50}$ or $LC_{50}$) $\leq 10$ mg/L<br>Chemicals on the OSPAR taint list<br>Inorganic chemical toxicity ($EC_{50}$ or $LC_{50} \leq 1$ mg/L<br>Biodegradability < 20% |
| Black | Chemicals prioritized for substitution (White Paper No. 25, 2002-2003, Table 8.1), including:<br>Hormone disrupting chemicals<br>Biodegradation < 20%, log $K_{ow} > 5$<br>Biodegradation < 20%, toxicity ($EC_{50}$ or $LC_{50}$ < 10 mg/L |

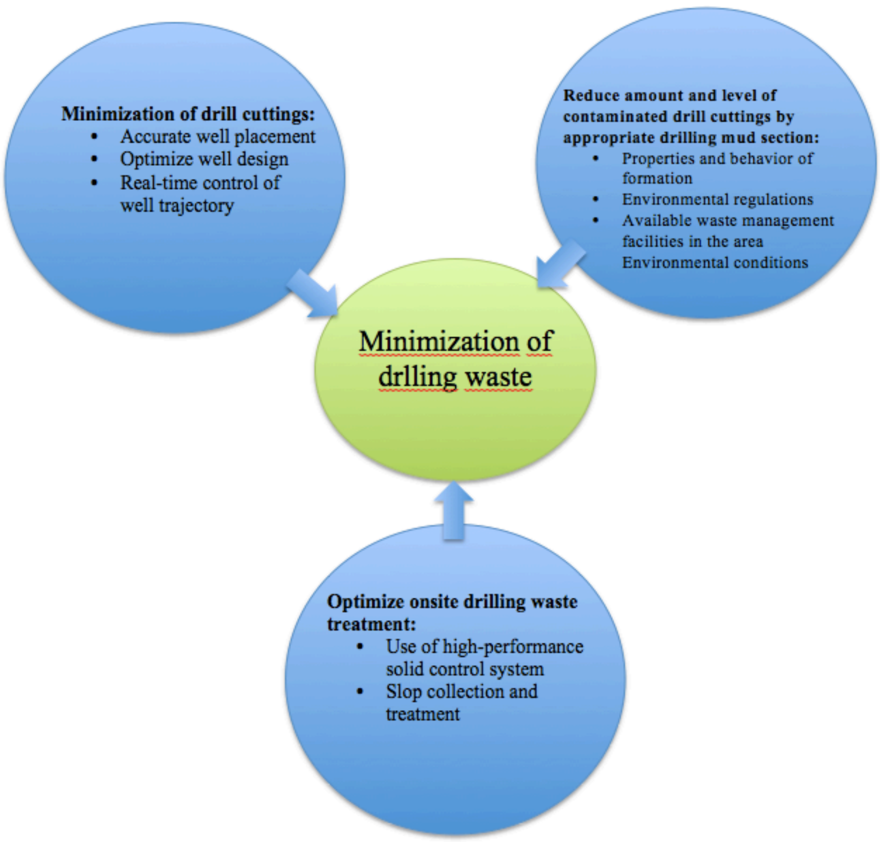
Figure 14: Color Scheme Used by the Norwegian Pollution Control Authority to Classify Relative Hazard of Chemicals (Neff, 2010a).

As a baseline requirement in the Norwegian part of the Barents Sea, in order to discharge cuttings to sea well should be drilled with water based drilling fluids only containing chemical selected from the Pose Little or No Risk to the Environment (PLONOR) list and hydrocarbon content of the cuttings are below1% (Neff, 2010a).

Compared to reinjection and transport waste to shore, discharge cutting into the Sea has low cost, low safety risk, energy consumption, CO2 emissions, and air pollution with no weather restrictions and is a simple process with little equipment needed. Moreover field observations have shown repeatedly that drilling mud disperses rapidly after discharge.

## 3.2. Minimization of drilling waste in the Barents Sea

Figure 15 shows three main categories that include implementation of the most preferred methods, systems and strategies, to minimize the drilling wastes, which need to be transfer to the onshore. The categories are i) reduce amount and level of contaminated drill cuttings by appropriate drilling mud selection ii) minimization of drill cuttings iii) Optimize onsite drilling waste treatment.




- Figure 15: A model for Minimization of drilling waste in the Barents Sea

### 3.2.1. Selection of drilling mud

The volume and level of contaminated drill cuttings waste generated from a drilling operation is highly dependent on the type of drilling fluid. Drilling-fluid selection in the Barents Sea requires evaluation and consideration of numerous factors, the most important are performance of drilling mud, formation properties and behavior, environmental regulations, available waste management facilities in the area, economics, environmental condition and absolute minimum waste for disposal onshore. Taking these one at a time, and in order, will in most cases lead to a proper choice of drilling fluid.

In the Barents Sea, the use of water-based drilling fluids had been completely dominant. A major reason has been the special requirements that have been in the Barents Sea, but that was repealed in 2011(Sigra, 2013). Component employed in WBMs have a lower chemical stability and are a safer option from the perspective of lowering risk of harmful exposure to the local marine environment. Basically, WBMs are designed for separation from cuttings on rig and a major part can be discharged to sea opposite to oil-based mud, which produce high drilling waste and all must be transported to shore for treatment. In exploration wells WBMs should be the preferred choice also for technical reasons (Brantley et al., 2013). In case of wells which have indicate more than 50 degree, are long, will be drilled by smaller diameter holes or in high reactive shale’s, WBMs may are not suitable selection. WBMs do not have the highly inhibitive quality so shale’s are prone to sloughing and swelling that can cause stuck pipe, and washouts whereas the latter can increase drilling waste (figure 16). However high performance water based mud (HPWBMs), which normally contain chemicals from yellow groups, are developed for shale dispersion inhibitor in reactive shale’s and provide wellbore stability in complex wells (Eia et al., 2006).

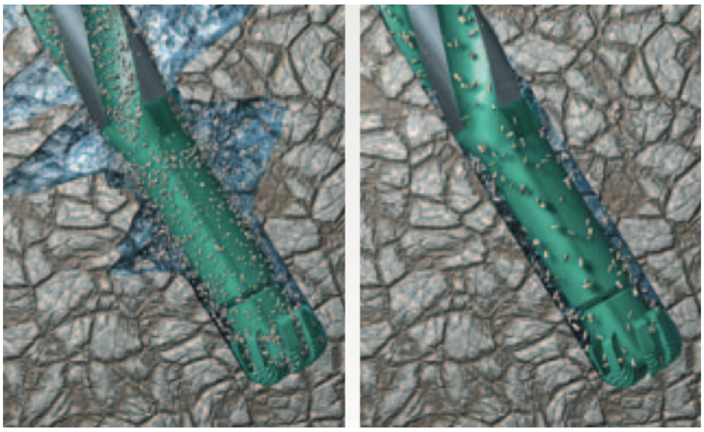


Figure 16: Minimize drilling waste by using HPWBMs, left picture demonstrate washout (Eia et al., 2006).

During drilling the top-hole sections, there is no way to return drilling mud or cuttings to the rig and all waste deposited to the seabed, therefore seawater is the best choice as drilling mud to use in top hole because does not contain hazardous substance. Seawater with viscous fluid pills are used to drilling the top-hole sections in almost all wells in the Norwegian Barents Sea. The viscous fluid pills consist of freshwater added bentonite and pumped in conjunction with drill hole cleaning.

For the next sections of drilling a HPWBM will be mostly used. Statoil has been using WBM contain KCl/Polymer/Glycol-systems in Johan Castberg field and want to use it in Ensis field for sections 17 ½, 12 ¼ and 8 ½ as the primary choice when inhibitive water based drilling fluids with relatively good technical performance is required (Eivind, 2013, Andrade, 2011). Eni Norge in Goliat has used KCl-Glydril, and EMS-3100 in Salina field and GDF SUEZ E&P NORGE AS want to use glydril in Byrkje. They are all environmentally categorized as yellow chemicals(John Erik et al., 2012a, John Erik et al., 2012b). They have been in use a while on the Norwegian continental shelf and have proved to be a good technical and environmental solution for the Barents Sea.

### 3.2.2. Minimization of drill cutting

Minimization of drill cuttings is a kind of reduction of drilling waste at the source that has high influence on minimization of drilling wastes. In order to reduce volume of produced drill cuttings some methods need to be implemented. Basically most of these methods developed for various purposes such as increasing the final hydrocarbon production rate, high recovery and reducing drilling cost. One of the other benefits of such methods is reducing the amount of generated drill cuttings, which itself benefits the overall waste management processes.

*Acquiring more data about the subsurface;* Some aspects of well planning such as avoiding drilling of dry wells, accurate well placement and planning the most optimized well trajectory are key factors in reducing the total amount of generated drill cuttings. For this aim detailed information about characteristic and behavior of subsurface formations is vital. This includes information about; composition and physical properties of the formations; accurate location of the reservoir; fluid migration and distribution; thickness of different formations; subsurface geological features (such as fault, fold, and salt domes)(Mueller et al., 2013, Rena, 2009).
There are different sources where such data can be acquired, such as previous drilled or abandoned wells (i.e. their well logs, well tests, and coring data), and 3D, and 4D seismic activities.
In addition Remote sensing surveys allow geologists and engineers to show a large area on the surface of the earth, map surface features, and locate potential oil and gas sources faster and effectively than conventional ground survey and improve exploration success rates. By use satellite and airborne images and geological interpretation can generate start models before to the 3D or 4D geophysical surveys, and where on the ground information collection is required, 3D seismic surveys is used. This led to more accurate placements of the drilling; reduce the number of drilled dry holes, as well as reducing the drilling waste generated (Rana, 2010, Elnozahy et al., 2012).
Acquiring more detailed data on the subsurface characteristics may improve the mud preparation and selection of its additive. It can also result in an optimized well plan such as cementing and completion operations. This finally results in a reduction in final drilling waste in terms of minimized drill cuttings, minimized drilling and completion fluid, cement, etc (Mueller et al., 2013, Rena, 2009).

*Drilling well design;* Reservoirs have different size, form, thickness and depth, and by using conventional drilling methods to recover these resources, several vertical wells are required. Recent advances in drilling technology have facilitated the drilling of more complex wells such as slimholes, extended reach and multilateral wells. These drilling methods eliminate the need for drilling multiple vertical wells and have high influence on volume of produced drill cuttings. In multilateral wells, only one main well is drilled and then other lateral wells, smaller in diameter, are drilled to reach the resources. This is of the particular interest, where subsurface formation consists of multiple small zones at different depths that need several vertical wells to achieve the designed recovery rate. In multilateral wells, they share the upper portion of the well and the upper portion of each well is larger in diameter than the lower portion of the same well and this reduce volume of drill cuttings (Peter, 2008, Mueller et al., 2013).
Some formations are thin and extends over a huge lateral area by using horizontal drilling expands over this area can recover more and avoids a number of unnecessary vertical drilling. Moreover directional and extend-reach drilling in different directions or to different depths from one main well requires fewer drilling facility and generate less drilling waste (Mueller et al., 2013, Rana, 2010).
In Goliat field 11 wells have drilled horizontal by semi-submersible drilling rig scarabeo8 with an average horizontal length of 10m. Seven of these are horizontal production wells in the Kobbe reservoir and four horizontal production wells in Realgrunnen and of the four wells drilled in Realgrunnen three are as multilateral wells (John Erik et al., 2012b).
Another method, which reduces the volume of drilling waste, is to drill slimholes. Slimhole refers to wells that have reservoir sections of 6 inches or smaller in diameter and at least 90% of the well has been drilled with a bit of six inches or smaller. It's generated less drilling wastes and is environmentally friendly method and has economic benefits by reduce amount of cementing, casing and fuel use in drilling operation. Deepening or sidetracking existing wells, and exploring of wells in remote areas and when reaching new reserves in mature fields by re-entering existing small-diameter wells are typical operations where ultra slimhole drilling is applied (Elnozahy et al., 2012).

*Real-time well trajectory control;* Fiber optic sensor technology and developments in computing gives present drillers great information about the on-going actions beneath the surface with high-speed data transmission which are much faster than mud pulse and other downhole telemetry in common use (Rana, 2010). Implement of measure while drilling (MWD) with small, lightweight fiber-optic systems for measuring and reporting subsurface characteristics, and equipment for steering of the drill bit mounted on the bottom hole assembly (BHA) give well operators the possibility to respond to changing conditions in real-time when a drill bit deviates from the desired location, and it reduces volume of drilling waste.

### 3.3.3. Optimizing onsite drilling waste treatment

Solid control system, vacuum collection system and waste and slop treatment system are main part of onsite waste treatment which have a major effect on maximize recovering and reusing of drilling mud. The process contributes to discharging of most part of drill cuttings into sea.

*Solid control system;* Solid control system is an essential portion to prepare a drilling rig according to regulations related to discharging of drill cuttings in the Barents Sea. Solid control system is to minimizing the loss of drill fluids and maximizes the recovery and reusing of the costly drilling fluids. The size and, type and amount of solids in the drilling muds will be controlled in solid control system. The solids-control equipment selected for a well drilling program depends on the drilling fluids used, formation characteristics and the specific cuttings disposal requirements (Charles et al., 2010)
On the drilling platform (Figure 17), the mixture of drilling fluid and cuttings returned from well are collected for treatment to control solids and recycle the drilling fluid back down the hole.

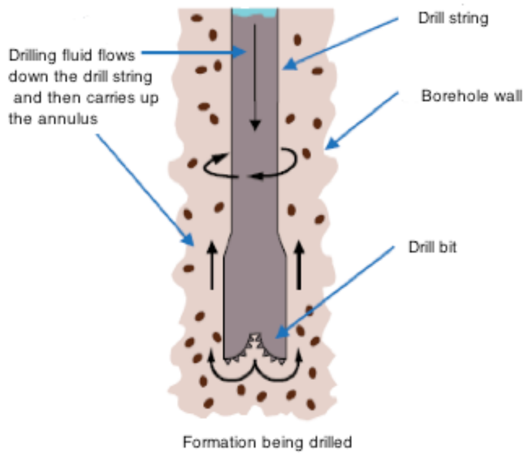
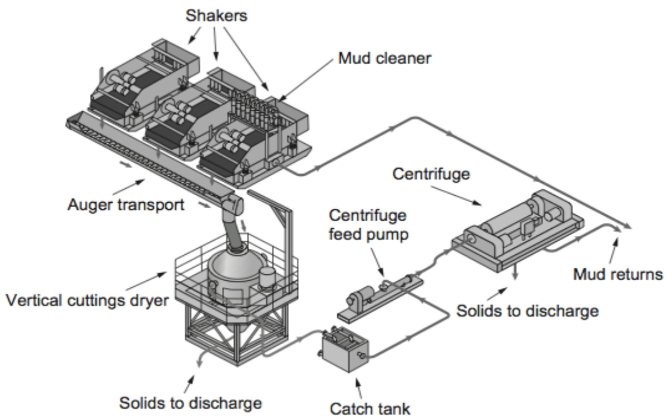



Figure 17: Circulation of drilling fluid during drilling and suspension and removal of drill cuttings(Charles et al., 2010).

Solids control can be carried out at three levels. First, when the mixture of the drilling fluid and drill cuttings returns from the wellbore they go to shale shakers, the shale shakers are the first step in separating solids from mud. Second, solids collected by the shale shakers are still coated with so much mud that they are unsuitable for the discharge. Therefore, further treatments are required to recover the remaining drilling fluid mixed with cuttings that can be done by cutting dryers. Finally, drilling fluid separated from cutting in shale shaker still have some quantities of solid which shale shaker cannot separate. Mud cleaners before reuse of the drilling fluid in the recirculating mud system will do this. Figure 18 shows a solid control system and the process for cleaning cuttings-laden drilling fluid from wells and reusing of drilling fluid.




18: Example of Solids-Control System (Stantec, 2009).

Bentonite or, barite or other density- adjustment materials are the typical solids added to a mud system to achieve desired properties. Drilled cuttings, on the other hands, are undesirable solids. It is important to understand how particle sizes in drilling muds are classified and the types of solids that fall into each category. Further, it is important to be aware of the effect solids have on the properties of a drilling mud system, as they are ground into finer and finer particles. A small fraction of the solids should be colloidal sized (<2μm) for needed viscosity. Too high a concentration of colloidal solids is problematic as it increases viscosity beyond the desired range (Neff, 2010b). In figure 19 you see different types of solids that usually are in drilling fluids, and their size. The figure also shows what type of equipment is used to separate the different solids.

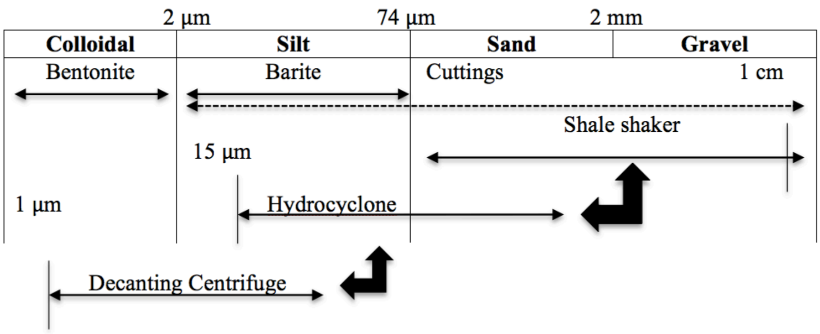



Figure 19: Solids-Control Equipment Optimum Particle Size Cut Points ((CAPP), 2001)

After separation of solids and fluid in the solid control system, solid will be tested and if the hydrocarbon content of the solid are within the limit set of the environmental agency, it can be discharged to sea, if not it must be sent to shore for more treatment. Fluid recovered from solid control system must be concentration and quality tested because solid control cannot remove ultra ultra-fine particles and they increase alter the physical and chemical properties of the viscose of the drilling fluid. , if it is possible, the mud most be diluted by adding liquid to the drilling fluid prior to reuse of the drilling fluid in the circulation system, and if dilution is not possible the drilling fluid must be transported to onshore for disposal (Charles et al., 2010).

#### *3.3.3.2. Vacuum collection system*

Vacuum Collection System (VCS) collects and moves drilled cuttings within a totally enclosed environment, minimizing spills and contamination. This system utilizes integrated shale conveyor technology, vacuum system, cuttings transport and real-time monitoring systems (Seaton and Morris, 2005, Eia et al., 2006).

#### *3.3.3.3. Waterwaste and slop treatment system*

Drilling slops and wastewater must be collected in a tank (slop water tank) and subjected to purification to meet the environmental discharge regulation. As the slop contains drilling fluid and some other hydrocarbon that leaked from machinery, the regulations and permits applied to the drilling fluid can be enforced (Figure 20). This includes the regulations regarding the chemical contents and also the level of hydrocarbon in the mixture. To minimize waste volume, it can be possible to recover useable drilling fluids from slop waste, recondition the fluid if needed, and recycle it back into the active system. Discharge of slop to sea is permitted if oil content is lower than 30mg/l (Bakke et al., 2013).

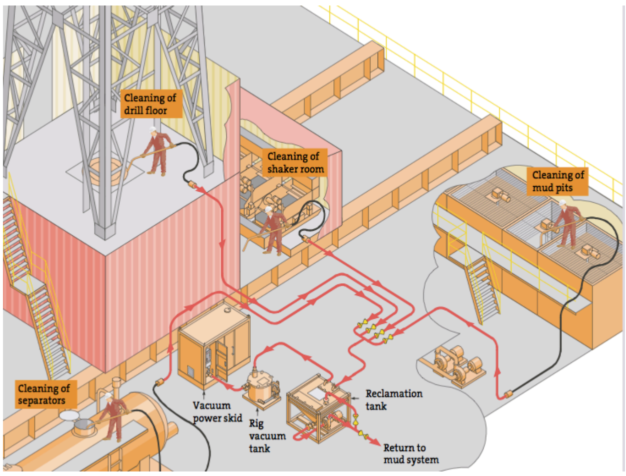



Figure 20: Rig- and tank-cleaning operations with Vacuum Collection System (VCS)(Stantec, 2009)

# CHAPTER 4

# THE EFFECT OF PERATION CONDITION ON PERFORMABILITY OF SYSTEMS IN THE BARENTS SEA

# Effect of operation conditions on performability of systems in the Barents Sea

*In this chapter you will find a brief description of the concept of performability and study the effect of operation conditions like remote, harsh, and sensitive environment in the Barents Sea on the performability of systems.*

Offshore oil and gas facilities are complex and integrated systems that include different component and subsystems such as motors, pumps, compressors, cables, hydraulic and pneumatic devise, pipes, separators, valves, tanks, automation and control components like sensors. To avoid environmental and human disasters and high life-cycle costs for such systems particularly in harsh, sensitive and remote area, they must to have an acceptable performability.

In Norway a production assurance concept was developed in the 1980s for the oil and gas industry. According to standard Norsok Z-016 the production assurance is defined as "*a term used to describe how a system is capable of meeting demand for deliveries or performance.* The production assurance concept is built on reliability, maintainability and supportability. However the concept of sustainability and safety is not considered in this definition. In harsh and sensitive area like the Barents Sea with strictly regulations and requirement for safety and environment be challenging for fulfilling these requirements without considering of these terms.

Misra (Misra, 2008b) defined perfrmability as the entire engineering effort that goes into improving the performance of a system that not only ensures high quality, reliability, maintainability and safety but also is sustainable. Improved performance should necessarily imply less environmental pollution, less material and energy requirements, waste minimization, and finally conservation and efficient utilization of available resources, which in turn result in minimum life-cycle costs. The relationships, of these concepts are illustrated in figure 21.

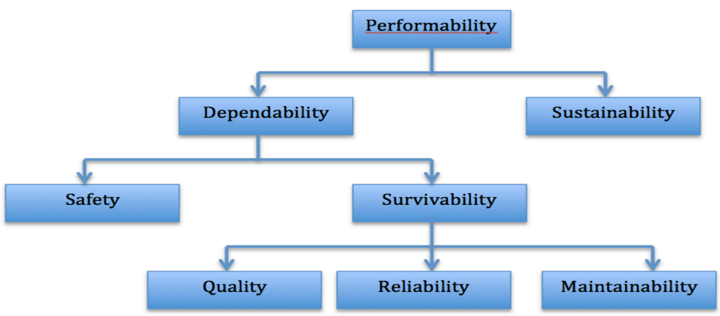



Figure 21: Implication of performability (Misra, 2008b)

## 4.1. Sustainability

The word "sustain" comes from the Latin sustenare meaning "to hold up" or to support, which has evolved to mean keeping something going or extending its duration (Sandborn and Myers, 2008). The sustainability principle requires that the products and systems use minimum material (dematerialization), and minimize the use of energy throughout their entire life cycle (extraction phase, manufacturing phase, use and disposal phase) and they should use non-hazardous materials and should be highly recyclable at the end of their life. Minimizing the use of matter minimizes the impact of the extraction phase and minimizes total material flows (Misra, 2008b). The objective of environmental sustainability is to increase energy and material efficiencies, preserve ecosystem integrity, and promote human health and happiness by merging design, economics, manufacturing and policy(Sandborn and Myers, 2008).

The effect of the icing and low temperature on the sustainability can be due increase of energy consumption, increasing the use of material and increasing the use of process and product that are used to ice protection and heating. The large power demand of offshore installations in the Arctic area is in most cases covered by their own gas, and greenhouse gas emissions from power production are high. De-icing technologies with high consumption of energy have negative impacts on the sensitive environment and wilderness in the Arctic. Moreover use of hazardous chemical ice protection cause degradation the environment quality; increase the produced waste and serious environmental consequences.

## 4.2. *Survivability*

To ensure that a system or product is dependable, we must ensure that its survivability is high and that it is safe during its operation and use. How well a product or a system meets its survivability requirements depends on its various characteristics, such as quality, reliability and maintainability. A product or a system having these attributes is usually expected to perform well over its lifetime incurring minimum life-cycle costs, which include design and development, manufacturing, and maintenance costs. Therefore, to ensure higher survivability of a product or a system, it is essential that all the above attributes be ensured, not just one of them (Misra, 2008a).

## 4.3. *Safety*

The general definition of safety is the condition of being protected against physical, social, spiritual, financial, political, emotional, occupational, psychological, educational or any other types of consequences arising from failure, damage, error, accidents, harm or any other event that could be considered undesirable. This can take

the form of being protected from an event or from exposure to something that can cause health or economical losses (Misra, 2008b).
Engineering products and systems can cause hazards during operation or maintenance and if they fail. Design, development, manufacture and maintenance of engineering products must obviously seek to minimize the possibility of hazards. However, there is a balance to be struck between the safety and the cost of achieving it (Misra, 2008b, O'Connor, 2008). Prevention of an accident requires excellence in performance, which leads to reduce the chances of failure and the associated risk.
Working in the cold climate such as the Barents Sea can be dangerous for personnel. Salt water ice on antennas bridges insulators, causing arcing and loss of communication. At very low temperature electrical insulation become to crack and exposed the conductors to the environment and this made a serious hazard for personal. Moreover Low temperature generates static electricity that destroys computer and making data unreliable. Icing on stairs, deck and other surfaces can cause slippery hazards that can result in accidents and the risk of falling are present. Structures and equipment can be damaged, access to equipment will be reduced and work can be prevented due to this. Snow and ice on burner booms on the platforms can lead to explosion, fire or accumulation of toxic gases if the snow and ice are over the burner booms load rating(Ryerson, 2009).

The majority of investigators agree that the greatest hazard to infrastructure safety is sea spray- created superstructure icing. High weight caused by sea spray accumulation is an issue for buoyancy and stability, and can cause platform sinking, in addition icing increases the wind resistance of the superstructure. Moreover sea spray icing (figure 22) can cover boats lifesaving apparatus, deck fire fighting equipment, which are vital and critical equipment (Ryerson, 2011).

Visibility is an important factor for equipment to carry out efficient and safe operations. The main challenge from low visibility and darkness are that tasks can only be performed slowly and that safety issues might arise (Freitag and McFadden, 1997).

Figure 22: Ice accretion on the lifeboat and davits (Bridges et al., 2012).

## 4.4.*Quality*

Quality of a product is a measure of the degree of conformance to applicable design specification and workmanship standards. If quality can be thought of as the excellence of a product at the time it is delivered to the customer, reliability is used in the engineering context to describe the ability of a product to work without failure during its expected time in use. A product's reliability therefore depends upon how well it is designed to withstand the conditions under which it will be used, the quality of manufacture, and, if appropriate, how well it is used and maintained (O'Connor, 2008). Quality can be classified into two types: design qualities and manufacturing qualities. In design quality by understanding the mechanisms and environments involved and the stresses that can be applied can prevent wear out failures and overstress failure. Materials that are common in more benign weather conditions require assessment early in the design process to confirm integrity under arctic or subarctic conditions over the full life cycle of the facility. Failure to recognize the possible variable results of material selection early in the project can lead to invalidation of conceptual developments and require rework. In the harsh condition area such as the Barents Sea, a stronger emphasis is required on material selection and performance aspects such as accuracies, efficiency, and operational energy requirements. On the other hand, manufacturing qualities pertain to the manufacturing processes used when producing products that incorporate desired design qualities. In the case of machine tools, such qualities would correspond to dimensional variances, surface roughness, processing accuracy. Variation of parameters and dimensions, leading to weakening, component mismatch, incorrect fits, vibration, etc (Yoshimura, 2008). These issues in the Barents Sea with long delivery time of spare parts due to remote area can make stop the projects particularly in installation phase or increase the first time failures.

## 4.5. Reliability

According to (IEV191-12-01) definition of reliability is "the ability of an item to perform a required function over specified time and under the specified conditions ". The main aim of system or equipment reliability is to prevent the failures that make stop and downtime or reduce adequate functionality performance of the system as far as possible and also to downgrade the consequences of the failures that cannot be removed. Reliability can be expressed in other ways, for example as the mean time between failures (MTBF) for a repairable system, or mean time to failure (MTTF) for a non-repairable item, or the inverse of these, the failure rate or hazard rate (Barabady, 2007).

Failures occur when the effect of the applied load (L) is greater than the resistance (R) of the component or material (L > R). The resistance R is primarily related to the materials, the design, and the in-service condition of the structure. The load L can be any type of load: functional, environmental or accidental. The reasons why (L > R) occurs are many, ranging from, e.g. poor design specification, design errors, and material defects, through to, e.g. fabrication errors, degradation in operation, and other unknown events (Veritas, 2002). The period of use, the environment of use and preventive maintenance are among the factors, which have an important influence on equipment reliability. In actual fact reliability is only a measurement of a statement of history (Barabady, 2007). Reliability of systems or equipment often degrades over time due to usage. Moreover the reliability of a product can be adversely affected by environmental conditions. This includes operational environments as well as preoperational environments, when stresses imposed on parts during manufacturing assembly, inspection, testing, shipping and installation may have a significant impact on equipment reliability. For example, equipment may be exposed to a combination such as temperature, humidity, altitude, shock, and vibration, while it is being transported. Very often more than one environmental factor may be acting on systems or equipment. These combined environments factors may be has more adversely effect on reliability than the effects of these single environments separately (Misra, 2008c).

To achieve equipment or system with high reliability, require identifying the critical and sensitive items, which have a major effect on system failure. It also require to consider the possible causes of failures and failure mechanisms during testing, assembly, installation and operation phase in design and manufacturing processes and explore the ways of reducing the likelihood or frequency of failures. In other words high reliability of a system require competence, cost and efficient organization.

In the Barents Sea, low temperature, icing and humidity are main concerns that can change in the properties of some material and fluids, increase the failure rate and reduce the equipment performance by decreasing theirs reliability. In this subsection some adverse effects due to low temperature, icing and humidity on reliability of materials and fluid will be discussed.

### 4.5.1. Low temperature

In the Norwegian part of the Barents Sea, the minimum air temperatures that can be expected is a range of -20°C to -30°C (Jacobsen and Gudmestad, 2012). However there are frequent changes in temperature that can make this area more detrimental to reliability of parts or equipment than the Arctic, which has a steady cold climate.

As the temperature falls, contraction of the material creates stresses that push the molecular bonds to the breaking point. Sometimes, sudden changes of temperature may also induce a large amount of internal mechanical stresses in structural elements, particularly, when dissimilar materials are involved.

In low temperature the yield strength ($\sigma_y$) of the materials increase until it is equal to the ultimate strength. Before to the yield strength, material will deform elastically and will return to its original shape when the applied stress or load is removed. However if the yield point is passed, the deformation will be permanent and non-reversible. In this point brittle materials rupture suddenly but for ductile materials, rupture is preceded by noticeable plastic deformation and the strength loss is not abrupt. In low temperature, ductility of the materials is converted into higher yield strength, and consequently the material becomes more brittle (Freitag and McFadden, 1997).

For example the yield strength of metals, which have a body cantered cubic (BCC) crystal structure, (e.g., iron, chromium, columbium, molybdenum, and tungsten) increases rapidly as temperature drops. In the other hand materials that have a face centered cubic (FCC) crystalline structure (e.g., aluminium, copper, and nickel) undergo little or no increase in yield strength as temperature drops (Freitag and McFadden, 1997, Misra, 2008c).

In low temperature the tensile strength of plastics increases. Polymers undergo a transition to brittle behaviour much the same as steel. For example a nylon material increase in tensile strength from 7400 psi at 21 °C to 13000 psi at – 57 °C, but its impact strength decreases from 16 ft-lbf at 21°C to 9 ft-lbf at – 40 °C. Serviceability of rubber components, e.g. tires, inner tubes, cable, hose, bushings and seals, is seriously affected by low temperature. At low temperature rubber behaves as a glass and as the temperature is raised, it become less brittle (Ward and Sweeney, 2012).

Low temperature generates static electricity that destroys computer and making data unreliable. Engines and equipment operating during cold weather are subject to higher wear and increased breakage. Several polyvinylchloride (PVC) insulations that are normally used as electrical insulation do not withstand repeated flexing at low temperatures and at temperature below -30°C they crakes and can cause a short circuit or develop grounding problems. Cracking of the insulation exposes the conductors to the environment and can create a serious hazard (Dutta, 1988).

Most organic hydrocarbon lubricants solidify and become unsuitable at very low temperature (≤ -29 °C) and eventually lead to friction, corrosion wear and increased energy usage due to metal-to-metal contact in the bearings and machinery. Routine operations such as steering, starting and braking will require increased energy usage due to insufficient lubrication performance. A hydraulic fluid with low viscosity will stop to perform when the environment temperature drops to a few degrees above the pour point. Moreover low temperature increase viscosity of drilling muds by effect on the water and hydrocarbon contain in the drilling muds and thereby affect adversely on mud pomp, drill string and well pressure (Darley and Gray, 1988).

### 4.5.2. Icing

The general impact of icing on structure and equipment reliability is the increased vertical loads on the iced equipment and structures and increased wind drag caused by the increased wind-exposed area that can lead to more severe wind loads than without icing. Main aspect of effect of icing on structure and equipment can categorize in *i)* Static ice loads *ii)* Wind action on iced structures and equipment*; iii)* Dynamic effects *and iv)* Damage caused by erosion and by falling ice. The load of accreted ice can easily deform or damage elements and damage also might occur if the ice has not fallen off before forces have grown too great. Moreover sagging of ice on equipment may be exposed to unexpected ice loads because the ice sags downwards and covers or presses on the elements (Fikke et al., 2006). Tension forces from ice accretion in some material such as steel and cables increase considerably. Cables experience significant icing problems and are a cause of system failure when iced too heavily, especially when water sources are wind-driven and cables are oriented at nearly right angles to the wind direction. It makes ice accumulation on only one side. The torsional weak cable then rotates down, or twists, because of the weight of the ice accumulating on the side, and more ice accumulates on the new exposed face. This process, if occurring for a long enough time, can cause cables to rotate multiple times with a spiral of ice enveloping them. Antennas and antenna structures can easily be overloaded by accreted ice. In particular, small fastening details are weak when increased load is added on top of other actions, because the ice may easily double the normal load (Ryerson, 2009). Icing on structures and equipment increase wind drag by changing of dimensions and weight, shapes and drag coefficients of accreted. Moreover icing on structures and equipment can change their natural frequencies, which is a significant factor influencing the dynamic behaviour and control of the systems. If a structure is heavily iced, its natural frequencies decrease to a great extends due to its increased reactive mass. Shedding and breaking of ice, which normally are due to increasing temperature, small deflections and vibrations from higher parts of structures have high potentially destruction on lower equipment. Moreover falling ice may cause important dynamic vibrations and stresses in the structures (Madugula et al., 1998).

In some cases humidity with a salty air environment or Ice and snow, combined with large temperature variance can be a major cause of degradation of equipment performance. They advance corrosion effects in metallic components and furthermore leading to the formation of surface films on non-metallic parts. Moisture absorption by insulating material can also induce conductivity and a dissipation factor of these materials (Misra, 2008c, Fikke et al., 2006).

## 4.6. Maintainability

The formal definition of maintainability according to IEV (191-02-06) is: "*the ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources*". Maintainability measures the ease and the time with which a system can be restored to an operational level after failure. Moreover maintaining component or system can not only help to increase the life of product and system but also ensure that it works smoothly without breakdown (Kumar et al., 2012, Barabady, 2007).

The main attributes of maintainability are: standardization, interchangeability, troubleshooting, mounting proof, ergonomics, removal/installation, ease of handling, accessibility, safety precautions and skill level (Kumar et al., 2012).In general, the operational conditions can contribute in changing the maintainability performance of an item by affecting i) Maintenance crew, ii) Components and maintenance tools and iii) Maintenance support.

The impact of environmental stresses on human performance efficiency leads human productivity to decrease; here stress refers to an external or environmental situation. The consequences of stresses are reduced sensory capacities, slower motor response, and reduced mental alertness, leading to increased maintenance-error probability. In addition maintenance procedures which are perceived as being difficult or complex, or a poor management and supervisory style, can lead to increased psychological demand, frustration and poor attitude towards the work (Kumar et al., 2012).

The working conditions are made more difficult by low temperature, the presence of ice, and the short period of daylight. The long periods of darkness during winter may cause human depression and reduces the efficiency of workers, the period of brightness during the summer may cause sleep problems. Visibility is reduced by when it is snowing, raining, foggy, or darkness. Strong wind in combination with precipitation in the form of snow or rain may reduce all kinds of maintenance operational activities.

Maintenance activities in the Barents Sea may increase time to access to failed component, inspection, testing, replacement and repair due to reduced physical mobility by slippery pathways and increases the measurement of body dimensions due to cold-protective clothing (Thelma, 2010). Lack of satisfactory access to the equipment requiring maintenance is the most common problem that mentioned by maintenance personnel.

Icing may change the accessibility of the failed item by changing their appearance and the shape. Improper accessibility can increase access, replace and removal time of failed component. Equipment labels are improving the maintainability. Labels should be accessible in visual limits and located in well-lighted places. Icing can fail or obscure the equipment labels over time and they need to be replaced in systematic manner. Under such conditions multi-unit plants in which both units are identical or highly similar in appearance offer special opportunities for maintenance errors. Ice conditions cause several problems for safe and quick passage of personnel and materials. Polar low and cloudiness may cause stoppages in the helicopter activities important for logistics of people and materials. Moreover, crane, lifting or hoisting provisions devices are the key elements in maintenance of equipment. Ice can adversely affect reliability and availability of this equipment.

The low temperatures may affect the performance of the a number of materials such as iron and steel, polymers and plastics used in maintenance tools and they experience embitterment at cold temperatures (Markeset, 2008).

Supply function also has a considerable effect on maintainability. The supply function is concerned with providing of the necessary personnel, material, parts and equipment to support operation in the field. Some of the most important factors that may influence support and logistics may be the remote geographical location and insufficient and inconvenient infrastructure (Barabadi, 2012, Gao and Markeset, 2007).

As is mentioned in chapter 2 the development of roads, airports and railroads in the Northern Norway is limited and most heavy transportation is carried out using ships and barges. Polar lows with high waves and wind can make challenges for transport operation. Oil and gas production facility development and construction requires competence with such technology and expertise. The population in this area is small and the local communities may not have the right competence, skills and experience to support the operation of advanced, complex and integrated production facility (Markeset, 2008). Effective communication is very important in maintainability. Usage of modern information and communication technology can to some degree, compensate for long distance. Ice on antennas can cause insufficient communications coverage impeded telephone conversations for example between the operator and repairperson.

# CHAPTER 5

# PERFORMABILITY RISK INDEX

# Performability Risk Index

*The aim of this chapter is to develop a performability risk index in order to estimate the effects of operation condition in the Barents Sea on performability of systems and equipment.*

Considering the operation conditions in the Barents Sea and variety of the effects on different equipment performability, selecting the appropriate statistical approach to predict these effects is important.

Most of the statistical approaches, which are used in reliability, maintainability analysis rely greatly on historical data and most of these methods consider the repair time and failure time as the only variables. However, suitable data from the actual operating environment in the Arctic area are often not available. Hence applicability of such methods may be limited. Moreover historical data have often been collected under different conditions, which in most cases are milder than Arctic operational conditions such as in the North Sea and Norwegian Sea. Therefore, using these historical data directly may lead to inaccurate results with a high level of uncertainty. Thus a statistical approach, which is not based on repair time and failure time, is required.

Performability has 5 principle elements (reliability, maintainability, quality, safety and sustainability) and 2 dependent elements (dependability and survivability) (Figure 21).

Considering the effect of the operation conditions in the Barents Sea on quality, reliability and maintainability, survivability risk index, *SI* can be developed as:

$$SI = \alpha_q I_q + \alpha_r I_r + \alpha_m I_m \qquad (4)$$

where, $I_q$, $I_r$, $I_m$ are the operation condition risk index for quality, reliability and maintainability of a specific item respectively, $\alpha_q$, $\alpha_r$ *and* $\alpha_m$ are shows the weight or importance of different element of survivability where $\alpha_q + \alpha_r + \alpha_m = 1$. The operation condition risk will be changed from 0 to 10, where 0 shows no risk on reliability, maintainability or quality and 10 shows very high effect on these elements. These values can estimate by a qualitative analysis. The effective methods to accurate estimation of these values can be using historic data or expert opinions. The criticality and required availability of an item will decide the weight of the different survivability elements. Moreover, considering operation risk index for safety, $I_s$, The operation condition dependability risk index, *DI*, of an item can be calculated as:

$$DI = \beta_{Sur}.SI + \beta_s I_s \qquad (5)$$

where $\beta_{Sur.}$ and $\beta_s$ show the weight or importance of survivability and safety on dependability and where $\beta_{Sur.}+\beta_s=1$. Finally the operation condition performability risk index can be calculated by:

$$PI = \gamma_{Dep.}DI + \gamma_{su.}I_{su.} \quad (6)$$

where, $I_{su}$, *is* the operation condition risk index for sustainability and $\gamma_{Dep.}$ and $\gamma_{su.}$ show the weight of survivability and dependability on performability where $\gamma_{Dep.} + \gamma_s = 1$.

Table 6 shows the numerical example for calculation performability risk index for shale shakers (consist of electrical parts, motor, rotating part and metal) on solid control system on offshore drilling platform located on the Barents Sea. Based on qualitative analysis in chapter 4, the effect of the operation condition such as low temperature, icing, darkness and low visibility and poor infrastructure on quality, reliability, maintainability, safety and sustainability of the shale shaker can estimate values for $I_q, I_r, I_m, I_s$ *and* $I_{su.}$(show in the blue cells). As you see in the table for example *Remote area & poor infrastructure* has max risk index on maintainability of the shale shaker with $I_m = 10$, due to supply function has a high effect on maintainability and *Remote area & poor infrastructure* can cause downtime of the solid control system. *Icing* and low temperature also have high risk index on safety

**Table 6: The numerical example for calculation performability risk index for shale shakers on solid control system on offshore drilling platform located on the Barents Sea.**

| Performability element | Low temperature | Icing | Darkness & low visibility | Remote area & poor infrastructure |
|---|---|---|---|---|
| **Quality** | 7 | 7 | 1 | 3 |
| **Reliability** | 9 | 9 | 1 | 3 |
| **Maintainability** | 8 | 9 | 7 | 10 |
| **Survivability** ($\alpha_q$= 0.33, $\alpha_r$= 0.33 $\alpha_m$= 0.33) $SI_. = \alpha_q I_q + \alpha_r I_r + \alpha_m I_m$ | 7.92 | 8.25 | 2.97 | 5.28 |
| **Safety** | 9 | 9 | 8 | 7 |
| **Dependability** ($\beta_{Sur.}$ = 0.5, $\beta_s$ =0.5) $DI = \beta_{Sur.}SI + \beta_s I_s$ | 8.46 | 8.62 | 5.48 | 6.1 |
| **Sustainability** | 7 | 8 | 5 | 7 |
| **Performability** ($\gamma_{Dep.}$ = 0.6, $\gamma_s$ = 0.4) $PI = \gamma_{Dep.}DI + \gamma_{su.}I_{su.}$ | 7.87 | 8.37 | 5.3 | 6.46 |

with $I_s = 9$ due to at very low temperature and icing electrical insulation on the shale shaker become to crack and exposed the conductors to the environment and this made a serious hazard for personal.

Even the importance of sustainability on performability, the weight or importance of sustainability is less than dependability ($\gamma_s = 0.4$ and $\gamma_{Dep.} = 0.6$), there is due to balance to be struck between the sustainability and requirement to dependability of the shale shaker in Solid control system.

As the table 6 shows *Icing* with PI =8.37 has highest effect on performability of the shale shaker and *Darkness & low visibility* has the minimum effect o with PI = 5.3.

# CHAPTER 6

# CONCLULISION

# Conclusion

Waste minimization has major benefits for oil and gas companies by reducing costs used for waste management and disposal, and enhance public perception of the company and the industry as a whole. Oil and gas operators have adapted new technologies and modified drilling processes to generate less drilling waste. The oil and gas industry has restrictions about selection of suitable drilling waste management options due to environment condition, regulatory requirements and poorly developed waste treatment facilities in the area. The use of water-based drilling fluids is a safer choice from the perspective of lowering risk of harmful exposure to the local marine environment and field observations have shown repeatedly that drilling mud disperses rapidly after discharge. Water-based drilling fluids are basically designed for separation from cuttings on rig and most part of drill cuttings can be discharged to sea. Discharge cutting into the Sea has low cost, safety risk, energy consumption, CO2 emissions, and air pollution with no weather restrictions and is a simple process with little equipment needed.

Design for performability is an effective way to meet the design goal for a complex operational condition such as the Barents Sea. Design for performability imply less environmental pollution, less material and energy requirements, waste minimization, and finally conservation and efficient utilization of available resources, which in turn result in minimum life-cycle costs. Operation conditions in the Barents Sea have significant effects on performability of equipment. To manage and minimize these effects on performability it is necessary to study the physical environment, and appropriate and sufficient infrastructure in this area. Moreover a methodical approach is thus required to quantitatively analyze this relation. This master thesis has reviewed the effect of operation condition on performability and then a concept of performability risk index was developed. Performability risk index can be used as index measure the effect of operation condition on performability of equipment. The implementation of performability risk index is simple to apply, valid for all types of impacts, inexpensive and not time-consuming.

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# PART II

# APPENDED PAPERS

# Paper I

# APPLICATION OF DE-ICING TECHNIQUES FOR ARCTIC OFFSHORE PRODUCTION FACILITIES

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# APPLICATION OF DE-ICING TECHNIQUES FOR ARCTIC OFFSHORE PRODUCTION FACILITIES

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## ABSTRACT

With increasing energy demand the oil and gas industry is pushing towards new unexplored remote Arctic area. More than 25% of undiscovered petroleum reserves are expected to be in the Arctic region. Moreover, it is estimated that approximately 84% of the undiscovered oil and gas occurs offshore. There are numerous challenges and environmental factors that must be overcome before one can conduct oil and gas exploration, and engage production activities in Arctic regions. Superstructure icing from sea spray, atmospheric icing, frost and sleet affect operation and maintenance of offshore production facility in various ways including repair time, failure rate of mechanical and electrical components, power losses, life cycle cost and safety hazard and cause downtime in the facilities. These problems are motivating designers, manufacturers and safety researchers to find better practical solutions for ice protection technologies. Many active and passive anti-icing and de-icing techniques have been used in different industries such as electric power. However, Arctic offshore operational conditions provide new challenges for application of these methods and they have limitation of usage due to harsh and sensitive environment and wilderness, lack of infrastructure as well as distance to the market. Hence, such conditions must be considered during design and operation phase for anti-icing and de-icing techniques. This paper discusses how operational conditions of Arctic region can affect the application of available anti-icing and de-icing techniques. Moreover, it will discuss different types of ice accretion and their hazard for the Arctic offshore production facilities.

## 1. INTRODUCTION

For Arctic offshore activities ice accretion is a challenging problem which can affect the operation and maintenance of production facilities as well as safety and health. For example it can provide slippery surface and increase the risk of falling or ice on burner booms can lead to explosion, fire or accumulation of toxic gases. Moreover, ice and snow accumulation on valves inhibits manual operation and the ability to see position indication. In addition the life cycle cost of material increases because of damage and degraded reliability[1, 2].

Considering the high optional risk and maintenance cost associated by icing the suitable method for ice protection or ice management must be identified in early design phase. Based on the location and the method of ice deposition, it may have different characteristics. For example the ice which is accreting on the window may have completely different density and strength compare to the ice on stairway[3, 4]. Hence, in order to find practical solutions for de-icing one must have a comprehensive knowledge about the different types of ice, how they form and where they appear. Moreover in design such technology the arctic operational conditions should be considered. Arctic provides unique challenges for any technology which is going to be used there among them are harsh operational condition, lack of infrastructure, distance to the market and sensitive environment and wilderness. Such condition need to be considered during the design process and selecting a technology. For example long distance to the market may provide support challenges if the technology need more often inspection and maintenance[5].
There are different types of technologies and a lot of fabrication methods that are utilized to prevent or remove icing [3, 6-9]. Most of these technologies are currently used principally in non-marine environments and offshore industries have no enough experience about the application of these methods. Hence it is important to see how these techniques will work under challenging arctic operational conditions. In this paper some of the available and under development methods will be

 

reviewed and the application of each method for the Arctic region will be discussed. Different types of ice that can occur on offshore platforms will be described in Section 2. Section 3 reviews different ice protection technologies. Application of ice protection technologies on offshore structures in the Arctic will be discussed in Section 4. Finally Section 5 provides conclusions.

## 2. TYPES OF ICE ACCRETION ON OFFSHORE FACILITIES

The process of ice build-up on the surface of an object is described as accretion[10]. This accretion is a function of meteorological parameters such as air temperature, wind speed, cloud liquid water content, cloud droplet spectra, etc.[11]. In general ice accretion on offshore production facilities can be categorized in two main groups *i*) Atmospheric icing and *ii*) Sea spray icing or superstructure icing[7, 12]. Atmospheric icing includes the processes where falling or drifting raindrops, refrozen wet snow, snow, slush, rain or drizzle forms accretions on an object that is exposed to the weather. Atmospheric icing can cause accumulation of snow, rime ice, sleet, glaze and frost on ring surface[13]. The most common ice type on Arctic production facilities are described below briefly.

- Wet snow accretion occurs in general wherever snow occurs, but mostly it is found in places where high precipitation rates are near the freezing point[12] . The air temperature interval is probably between 0.5-2°C. Snow accretion on structures is also affected by air humidity[14].

- ***Rime*** form when the droplets in fog, sea smoke or cloud drops hit a surface below 0°C and freeze. There are two types of rime, soft rime and hard rime. Hard rime has a high dense structure, and is more difficult to remove; in some cases the rime resembles the structure of glaze. In soft rime accretion the super cooled droplets has pockets in between and there is little attachment to surfaces. The momentum is small and the density is low[15, 16]. Rime ice is a big contributor to icing on tall stationary sea structure, for example rigs. Rime can affect both personnel and equipment such as: antennas, railings, cables, booms and derricks. Melting rime can cause pieces to fall down and create hazard for personnel. Rime on stairs, deck and other surfaces can cause slippery hazards that can result in accidents.

- ***Glaze*** form when a portion of the droplet does not freeze upon impact, but runs back on the surface and freezes later. The resulting ice density and adhesion are strong. It is often associated with precipitation. Glaze can disable wrenches and cranes, and locking cables are common results. Glaze also coats antennas, windows, radomes, hatches, rescue and firefighting equipment and valves[3, 8].

- ***Sleet,*** also called ice pellets, are less than 5000 μm, but can gather up and create accumulations of 1.3 cm in diameters. Sleet is made by raindrops that freeze before hitting the surface, and therefore does not stick or freeze to surfaces [17]. Sleet is mostly formed in the same conditions as freezing rain or glaze. Sleet accumulation occurs on horizontal surfaces such as stairs, decks, hatches, cables and helicopter landing pads and produces a slipping hazard[3, 13, 14].

- ***Frost*** is formed from water vapor onto surfaces due to air sublimation below 0°C when a solid surface holds a temperature below the freezing point of water. Frost appears as a thin layer that consists of needles oriented away from the surface. The density of frost is less than 100 kg/m3. There is little danger of ice loads due to frost, which is a small amount of ice on rigs because there are limitations by the size of the liquid water content in the air. Frost causes slippery conditions and can be dangerous. All horizontal surfaces can frost, including windows where visibility can be impaired[3, 16].

- ***Sea spray*** accumulation occurrence is very rapid when there are high winds, low air temperature and low sea temperature. This type of icing is a dominant source of ice accumulation on offshore platforms and can be quite dangerous. The sea spray droplets are carried by the wind and hit objects in their way. When the air temperature is colder than the freezing temperature of seawater, approximately –2°C, freezing spray occurs. The majority of investigators agree that the greatest hazard to drill rig safety is sea spray. High weight caused by sea spray accumulation is an issue for buoyancy and stability, and icing increases the wind resistance of the superstructure. Sea spray icing can cover winches windlasses, boats lifesaving apparatus, deck firefighting equipment, and valves, which are vital and critical equipment. Sea sprays containing brine and has a low density and therefore is not as strong as the glaze and rime[6, 13, 17].

## 3. ICE PROTECTION TECHNOLOGIES

Ice protection methods can be categorized into two main groups, active systems, which require power supply to operate and passive systems, which are based on natural forces and operate without power supply.

### 3.1. Active ice protection systems

 

Offshore processes are associated with significant energy consumption and large $CO_2$ emissions. The oil and gas industry is itself, a major consumer as well as a producer of energy and reducing energy consumption is one of the most important design aspects. Hence in using the active ice protection systems this subject should be considered.

#### 3.1.1. Thermal methods

Thermal methods are based on melting the ice. There are several ways to use heat as an ice protection technology; some popular heating methods are discussed below.

***Electrothermal heating***: Electrothermal materials convert electric energy into heat. In commercial electrothermal, electricity conducted through wires, which are nichrome or kanthal, results in occurrence of heat. As in this method the heat has to go through the surface first the required heat for removing the ice is really high. Moreover, Thermal rise is slow, and much energy is being used. However, in new electrothermal systems give the possibility to place heaters directly on the icing surface, which can be an applicable method for complex operational condition such as offshore Arctic[1, 18]. An example of electrothermal deicing is the heating elements bonded to the interior of the windows. Resistance of the wires to current causes heating, which is locally conducted to the glass.

***Carbon fiber heating wires (***CFHWs)***:*** Electrothermal systems use carbon fiber heating wires with light weight, high tensile strength and large flexibility. CFHWs have better electric-thermal properties, lower resistivity and double maximum heating temperature. The costs of Carbon fiber heating wires are about one-tenth of the metallic wires de-icing. The concrete deicing system with CFHWs can readily be applied to accident-prone locations, such as bridge overpasses, exit ramps, airport runways, street intersections, sidewalks, and driveways, which will greatly improve winter road clearance and travel safety and reduce the economic losses caused by snow storms[19].

***Pulse electro-thermal de-ices (PETD***): PETD uses a thin, electrically conductive film applied to the surface of any object in need of ice protection. The film is then heated with a milliseconds-long pulse of electricity. Pulse electro-thermal ice protection heats only a thin layer of interfacial ice and leaves the environments temperature unchanged. A short heating pulse is used- about 1ms to 5s long, to heat a minimal layer of interfacial ice. Use of PETD on ice-structures just above the melting point causes the ice to slide of and melt The heat losses in conventional electro thermal de-icing are not present with the use of PETD and the energy required is reduced to a factor of one hundred. PETD was successfully tested for a variety of applications including the de-icing of airplanes, car windshields, bridge over-structures, glass roofs, commercial and residential icemakers, and windmill rotors[18].

#### 3.1.2. Infrared de-icing technology

Infrared technology delivers heat to an object from a gas-fired or electrically emitter. Infrared energy is not placed directly at the surface, but transmitted through the atmosphere from an emitter. The energy is absorbed by ice, and causes melting, or it can heat up surfaces and prevent icing. Its radiation is part of the electromagnetic spectrum, with wavelengths from about 0.75 $\mu m$ to over 1000 $\mu m$. Infrared energy used in de-icing technologies has wavelengths between about 3 and 15 $\mu m$. Ice seems to be an effective absorber of radiant energy in the infrared spectrum, when wavelengths are longer than 3μm. The temperature and distance of the emitter can control how much energy is being absorbed by an ice-covered surface; it is also possible to do this by controlling the surfaces absorptivity. Objects should be coated with material with high absorption in the infrared wavelengths, if they are meant to be warm [3, 13, 20].

#### 3.1.3. High-Velocity Water, Air and Steam

Air, water and steam, are high-velocity fluids that are efficient for ice and snow removal from structures. The main job for high-velocity water is to cut large ice accretions into smaller pieces, which makes them easier to remove by mechanical de-icing technologies. High velocity water and steam can also provide thermal energy and melt ice and remove soft, new superstructure ice [3, 13, 20].

### 3.2. Passive de-icing methods systems

#### 3.2.1 Chemical de-icing

Chemical de-icers and anti-ices melt snow and ice by depressing the freezing point of water to below 0°C. The main performance properties of chemical method are deicers; melting, penetration, undercutting and disbanding[21]. The eutectic and effective temperatures of the chemical de-icer are two factors that determine the ability to perform these functions. Eutectic number gives the lowest temperature at which the chemical can depress the freezing point of water, and all eutectic points have a corresponding concentration percentage. The effective temperature is also used to describe performance and efficiency of a de-icer for melting snow and ice. It is an empirical value that describes the lowest temperature for practical use in relation to ice melting, anti-icing ability, type of precipitation and application rates. A number of chemical de-icing products with different characteristics are available. Table 1 summarizes some available method, their benefit and using problems.

Table 1: some chemical de-icing types and their properties

| Chemical dicer | Benefits | Problem and environment impact |
|---|---|---|
| Sodium chloride | Effective temperature down to -9.4°*C* ; Cheap ; Easy to use; De-ices rapidly at high temperatures; Low BOD | Corrosive to steel and aluminium ; Can be toxic at high levels; Rapidly decreases in effectiveness as temperature decreases |
| Calcium chloride | Effective deicer to -31.6°*C*; Used as solid or liquid | Can be irritant to eyes; skin and respiratory tract; May leave an oily residue; Corrosive to steel and aluminium |
| Magnesium chloride | Effective down to -15°*C*; used as solid or liquid | Corrosive to steel and aluminium, zinc, silver ; May leave an oily residue |
| Potassium acetate, Calcium acetate, Sodium acetate | Effective deicer to -26.1°*C* and -31,6°*C*; Non corrosive to most metals, Environmentally benign | Corrosive to galvanized steel, zinc, silver |
| Format (Potassium and Sodium) | Potassium has effective deicer down to -15oC ;Almost non corrosive to most metals; Environmentally benign | Corrosive effect on galvanized steel, zinc, silver |
| Ethylene and propylene | Effective deicer down to -50°*C* and -59°*C*; Not easily washed away ; Non corrosive to metals and surfacing materials | Slippery on decks and walkways; High BOD; Ethylene glycol is toxic to humans even at low levels |
| Urea | Non corrosive to metals and surfacing materials | Releases ammonia and nitrates to water courses ; Ineffective below about -7°C ;Very high BOD |
| Ice Bite | Low Effective de-icer to -35°*C*;Organic product and environmentally benign; Low corrosion; High viscosity | Smell bad |
| GeoMelt | Low Effective de-icer to -30°*C;* Organic product and environmentally benign; Low corrosion | Smell bad |

### 3.2.2. Ice phobic Coating

The purpose of coatings is to increase the hydrophobicity and ice-phobicity of surfaces. However, highly hydrophobic surfaces are not necessarily highly ice-phobic. The goal of most coatings is to cause ice to shed off surfaces from its weight alone. For this to occur, the adhesion strength of ice to the substrate must be less than the shear stress that the ice exerts because of its weight[1]. The physicochemical properties of coatings causes decrease in ice and snow accumulation in exposed areas by reducing adhesion strength of ice to a substrate. The formed ice is therefore removed easily due to its weight and wind force. The efficiency of ice phobic coating depends on water-repelling surface properties and by low adhesion of already formed ice. Surface wettability is challenging to control, and requires knowledge in chemistry, physics and geometry. It is required that super-hydrophobic are rough enough and it should have low surface energy[22, 23]. Wetting is the ability of a liquid to maintain contact with a solid surface, resulting from intermolecular interactions when the two are brought together. Surface can be divided in two main group wet surface and non-wet surface. Wenzel model and Cassie-Baxter Model are used to model the wet surface. The Wenzel explains contact angle enhancement due to roughening. Wenzel model explains where water droplets make full contact with the rough surface below. The Cassie-Baxter model explains where water droplets sit on top of the rough surface protrusions with air trapped below. Dependent on whether super-hydrophobic surfaces follow the Wenzel model or the Cassie-Baxter model, they are either sticky or slippery, which causes the droplets to get pinned down and not roll off, or they roll off easily when the surface is tilted. Ice phobic coating technology varies widely in material properties, chemistry, and design[24].

### 3.2.3. Protective Cover

Protective covers are constructed by flexible materials, which are strong, water-proof, light- weighted and fire retardant. Covers do not de-ice themselves in the wind, but it is easier to de-ice object manually, when they have been covered. And by tying the tarps loosely, the ice breaks when the tarp is removed. However, it must be considered when tying is tight, the ice forms according to the object, and is more difficult to remove[3].

### 3.2.4. Manual de-icing Methods

Manual de-icing methods are use of tools such as: hammers, baseball bats, deck hands, shovels, and crowbars, to break and crush ice, lift ice overboard and scrape it from surfaces. Even with innovating de-icing technologies, manual methods are still valuable and required in cases where other technologies prove ineffective. Wooden tools are preferred when removing ice, because steel and iron tools can cut cables, and cause damage to paint and material under the ice[3, 13].

## 4. APPLICATION OF ICE PROTECTION TECHNOLOGIES IN THE ARCTIC REGION

An offshore platform is a complex production facility and different type of icing can be built on differ components. However some part of platform are more critical from icing perspective such as decks, stairs, walkways, and helicopter landing pads, windows, cranes, winches, and flare boom. Some technologies can be more applicable to certain ice types, and therefore the type of the ice need to be considering in a deicing technology selection. Based on the location and the type of the different equipment a suitable technology should be select for ice protection. An overview over existing technologies that can be used to reduce impact of icing at different locations on platforms is shown in Table 2 [3]. This table can be used as a guideline for selecting de-icing methods for different parts of offshore production facilities.

However, considering the complexity of Arctic atmospheric phenomena unexpected icing situations can occur. For example on 17  January 2006 the unexpected storm named Narve hit the Snøhvit LNG production facilities on Melkøya , in north part of Norway outside the Hammerfest  and heavy ice build on the equipment( Figure 1). The production stopped for several days and workers were evacuated from Melkøya 19 January and transported by boat to Alta and Lakselv.

Figure 1. Icing on Snøhvit LNG production facilities

Hence, in this situation some of these methods need to be used simultaneously.  For example for deicing of moon pool in additional of coating, high volume fluids and infrared can be used together. In additional of the ice type, there are other factors which provide by arctic operational condition which need to be considered in design of the deicing technology for different part of offshore Arctic.

Table 2: Platform functional areas versus ice protection technology[3]

| | 1[a] | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stability | X | X | X | X | X | X | | X | | 0 | |
| Integrity | X | X | X | X | X | X | | X | | 0 | |
| Fire and rescue | | X | X | | X | X | X | 0 | | | 0 |
| Communications | | X | X | | X | | X | 0 | 0 | 0 | |
| Helicopter pad | X | | | | X | X | | X | | | 0 |
| Air vents | | X | X | 0 | X | | 0 | X | 0 | | |
| Flare boom | X | X | X | | | | | 0 | | 0 | 0 |
| Handles, valves | | 0 | | | X | X | X | X | | | 0 |
| Windows | X | 0 | | | X | | | X | | | |
| Cranes | X | X | X | | | 0 | | 0 | | 0 | 0 |
| Winches | X | X | 0 | | 0 | X | X | X | | | 0 |
| Stairs | X | | X | | X | X | X | X | 0 | | |
| Decks | X | | X | | 0 | X | X | X | 0 | | |
| Railings | | 0 | 0 | 0 | 0 | X | | X | | 0 | 0 |
| Hatches | | X | | X | X | X | | X | 0 | | 0 |
| Cellar deck | | X | X | 0 | X | X | X | 0 | | | |
| Moon pool | | X | X | 0 | X | X | X | 0 | | | |

X indicates a stronger match than does a 0. Empty cell indicates no match.
1. Chemicals; 2. Coatings; 3. Design; 4. Expulsive; 5. Heat; 6. High-Volume Fluids; 7. Infrared; 8. Manual; 9. Piezoelectric; 10. Boots; 11. Covers.
[a] Technology key.

The Arctic is a sensitive environment with great resources of different fish species, planktonic organisms, bird habitats and mammals, which makes the area vulnerable. In addition it has harsh condition and challenging nature in which difficult to operate. There are several factors that can influence the select and appliance of ice protection method on offshore structure in the Arctic. These factors can be categorized as[2]:

- Harsh operational condition
- Lack of infrastructure
- Distance to the Market
- Sensitive environment and wilderness

To deal with these challenges and reducing icing hazards on offshore platforms an effective structural design is most important and the first step of working in the Arctic. For example large-diameter structures or flat surfaces will have fewer icing problems, than structures with small objects. Moreover, by changing the superstructures design from cylindrical to conical, it is possible to reduce load effects of 50% or more[25]. However it must be considered that by focusing on design to protect platforms from ice, other platform operations can be prevented. However, design cannot prevent the icing completely and other deicing technology need to be used, in this part the effect of arctic operation conditions on the mentioned deicing technology in section 3 will be discussed.

### 4.1. Passive ice protection methods

***Chemicals:*** Offshore facilities have a variety of surfaces to which chemicals can be applied to as de-icing or anti-icing. Chemical ice protections are effective and easy to use but they require horizontal surfaces for optimal operation. Use chemicals on lattice structures and open-grid decks and stairs will be difficult and can be ineffective because of runoff unless they are completely filled with ice.  Chemicals de-icing can cause corrosion in applied surface and they may have environment impacts. Hence the cost of using the chemicals de-icing in long run can be unacceptable. Moreover because of corrosively, the impact of selected chemicals de-icing method on desirable surface and equipment need to be investigated before usage. However the main challenge in using the chemicals de-icing is arctic condition is come to the filed when the harsh clime conditions is combined with sensitive environment and wilderness. The wave, rain and wind can wash them into the sea and reapplication required. Moreover, the chemical method much be implemented by the maintenance crew which in very time consuming and  risky task and in some time of the winter it is not possible to go outside.

***Manual:*** Manual de-icing requires no electrical energy, is less effective and often leaves significant amounts of ice behind, and may also damage structures and accelerate wearing. However, some areas of offshore platforms where large ice accumulations occur can be inaccessible for manual de-icing. Moreover, some objects such as sensors, lighting, windows, fire and -gas sensing systems and antennas cannot be easily de-iced manually because they are delicate or because they are inaccessible. Manual deicing method is environment friendly method; it does not have any negative impacts on the environment and free of maintenance. However, harsh operational conditions in the arctic require personnel to work in severe weather, and dangerous conditions such as slippery decks. Hence, de-icing in cold and wet conditions, risks crewmembers health, hypothermia, and loss overboard, this may be fatal[13]. Moreover, in some cases like the polar low storm or very low temperatures it is not possible to do the outdoor job more specifically deicing. Moreover, de-icing by crewmembers may have interface by their regular jobs.

***Ice phobic coating:*** The operational conditions in the arctic make a lot of problem for outdoor maintenance activity hence using the ice phobic coating which needs little or no maintenance activity is very attractive in Arctic areas. Moreover, it has no effect on sensitive arctic environment. However, contamination of the surface can decrease ice phobic qualities of coating. Furthermore, ice phobic coating has finite performance lifetime and a layer of coating may be taken away when the ice is released form the surface. The ice phobic coating could work alone, but it is more effective if use with an active de-icing technology such as hydrothermal technique.

***Protective cover:*** Protective cover like tarps are ineffective as ice protectors, and in the Arctic area with harsh condition operations and spatially high winds speed, it is difficult to install them and can be carried away. Equipment covered with tarps is unavailable to use. Tarps require storage space when not in use, and on offshore structures space is limited.

### 4.2. Active ice protection methods

***Electrothermal methods:*** in conventional de-icing, the heater is thermally connected to the ice, the structure, and the outside environment. This makes heat losses inevitable, and requires high-energy consumption. The large power demand of offshore installations in Arctic area is in most cases covered by their own gas, and greenhouse gas emissions from power production are high. De-icing technologies with high consumption of energy have negative impacts on the sensitive environment and wilderness in the Arctic. There are several methods and materials used in electrothermal ice protection technology. These new methods use much lower energy and have higher effectiveness then conventional de-icing, but in some of them complex technology have been used and they may require regular maintenance. Lack of infrastructure in the Arctic combine with harsh conditions may lead to spare part delay and unacceptable down time which need to be considered when using these technologies.

***Infrared:*** Infrared de-icing technologies use less power than thermal method because infrared radiation travels through air and it hits an absorbing surface. In the other word heat directly warms objects, rather than warming the air. This style of heater is particularly useful in areas where unheated air flows through. Infrared systems in harsh operational condition could be damaged by waves, and operations could be diminished by large quantities of spray and wind, which can cause cooling of the emitter surface. Infrared systems need regular maintenance activities. Moreover, it can overheat materials such as composites and cause explosions if gas is nearby.

***High-Velocity Water, Air and Steam:*** High-Velocity Water, Air, Steam requires regular maintenance activities (correct and preventive maintenance) and has high-energy consumption. In the harsh operation condition like the Arctic, it is uncertain if the system could work near the sea surface because of high winds and possible wave wash. The reaction force of high-velocity water jet nozzles is often too great to be handheld, especially if the operator is on a slippery surface. Moreover, darkness in winter time is another challenge for using this method correctly. High-velocity jets may not be safe to use on safety equipment such as fire equipment, sensors, antennas, and life rafts -and boats.

As mentioned the de-icing technologies may have effect on the human, safety, environment and asset (HSEA). Risk assessment is well known technique to quantify and qualify the risk related to a concern and recognize hazard. A hazard is defined as a situation with a potential for causing harm to human safety, the environment, property or business. Risk assessment can be applied in qualitative and quantitative approach. In quantitative risk analysis each risk associate with an activity should be evaluate and classified into predefined class (such as high, medium, or low) depending on the severity of impact and the probability of the event occurring. A severity classification of using mentioned ice protection method is presented in Table 3. In this table four classes of severity are defined and the related definitions for HSEA are described. Table 4 shows the severity of failure or side effect of using described passive and active de-icing method in the Arctic region. As the Table 4 shows the passive methods have less effect on HSEA compare to the active methods. Moreover the coatings are the most attractive passive ice-protection method, as it has no risk for the environment, personal or asset.

Table 3. The severity classification of using de-icing technologies

| Hazard classification | Health and Safety | Environment | Assets |
|---|---|---|---|
| **High** | Potential for long term serious injuries or fatalities | Long-term disruption of the ecosystem or long-term exposure to chronic health risk | Major damage |
| **Medium** | Potential for Injury leading to 10 or less days away from work | Short -term disruption of the ecosystem | Medium damage |
| **Low** | Potential for first aid or medical treatment required | Pollution with minimal acute environmental or public health impact | Minor damage |
| **Very low** | No effect | No or negligible effect | Negligible damage |

Table 4. The severity of failure or side effect of using ice protection methods in the Arctic region

| Methods | Sub-method | Risk | | |
|---|---|---|---|---|
| | | Environment | Health and Safety | Asset |
| Active methods | Electrothermal | Low | Low | Medium damage |
| | Infrared | Low | Medium | Medium damage |
| | High velocity water, Air, Steam | Very low | Medium | Minor damage |
| Passive methods | Manual | Very low | High | Minor damage |
| | Chemical | Medium | Medium | Medium damage |
| | Protective cover | Very low | Medium | Negligible damage |
| | Ice phobic coating | Very low | Very low | Negligible damage |

## 5. CONCLUSION

In Arctic area superstructure and atmospheric icing is a threat to offshore operations and maintenance. Icing reduces safety of personnel and can cause unacceptable downtime. Hence, in additional of effective design a suitable de-icing technology should be select to reduce the ice hazard. There are technologies that are used in non-marine environments such as aviation that they can be used for Arctic offshore production facilities. However, operational conditions of Arctic (lack of infrastructure, sensitive environment and wilderness, distance to the market and harsh operation condition) will affect the performance and limit their usage. More specifically the discussion points out that there are insufficiencies with the electro thermal, mechanical and chemical methods used for ice-protection in harsh and remote conditions. Some of these insufficiencies involve energy consumption, personnel requirement in hazardous conditions and adverse environmental impact.

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# Paper II

# DRILLING WASTE MINIMIZATION IN THE BARENTS

# Drilling Waste Minimization in the Barents Sea

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*Abstract* - **With the increasing demand for energy over recent decades, the Arctic region has become an interesting area for future exploration and development. The Arctic region has a harsh and sensitive environment at a remote location. Hence, effective handling and management of waste is becoming essential to ensure fulfillment of health, safety, environmental, and quality requirements in the Barents Sea. In this paper the available technologies and methods which can be used to minimize the drilling waste will be reviewed.**

*Keywords* - **Barents Sea, Drilling mud, Drilling waste, Reinjection,**

## I. INTRODUCTION

During oil and gas drilling operations various types of wastes are generated, which mainly can be classified into three main categories, i) drill cuttings, ii) drilling fluid and iii) slop and wastewater. Drill cuttings are materials removed from the wellbore during a drilling operation, mostly solids, which are the largest source of drilling waste. They have an angular configuration and range in size from clay-sized particles (~2µm) to coarse gravel (> 30 mm) [1]. Dumping of drilling fluids (muds) occur in several situations, for instance, when increase of solids in the content of the drilling fluid cannot be treated by adding fresh mud. It may also occur when drilling a new formation interval requires a drilling fluid with different properties.

Contamination of drilling mud with cements or other contaminants may also results in a fluid that is no longer usable [2]. Slop and wastewater, which is a waste stream, and generated when drilling or displacement fluid, melted snow, water rain runoff, and firewater become contaminated with drilling fluid components. Additionally, slop can be the wash water from routine cleaning operations such as cleaning of pits, drill floor, shaker room, pump room, accidental discharge of chemicals, or leakage of lubricants that needs to be cleaned up for personnel safety reasons. This also generates a considerable quantity of slop. Depending on geographic location, operational practices and rig configuration, the daily volume of drilling slop can vary from 100 to 500 barrel per day [3].

The Barents Sea is a challenging area for oil and gas activities due to low temperatures, sea ice, polar low pressures, poor visibility and seasonal darkness, etc. Less developed infrastructure may create several challenges such as limitations to the logistics of supplies, material and personnel required for the operation and maintenance activities. Additionally, since the Barents Sea has great resources of different fish species, planktonic organisms and bird habitats, which makes the area vulnerable, is under strict rules by the Norwegian environmental regulation to prevent the adverse effects of discharges of hazardous chemicals to sea from petroleum operations [4].

For each well the volume of drilling wastes range from 1000 to 5000 $m^3$, avoiding waste generation minimizes the problems associated with waste management. Hence, waste minimization is given the highest priority in the waste management hierarchy. Moreover, waste volume reduction will expand the choice of waste treatment options, reduce waste management costs, reduce energy consumption, reduce regulatory compliance concerns and enhance public perception of the company and the industry as a whole [5].

Oil and gas operators have not enough experience related to the waste handling in harsh and sensitive Arctic environments. However, in other areas they have adapted new technologies and modified drilling processes to generate less drilling waste at the source [6]. Moreover, the high performance equipment is used to treat the fluids and cuttings in order to maximize the removal of sand and sludge cuttings. This leads to maximize reuse and recovery of drilling fluid. Considering the challenging operational conditions in the Barents Sea, selection of appropriate methods for management, and residue wastes generated during exploratory and development drilling is an essential step of drilling planning.

In this paper the available methods for disposal of drilling waste will be reviewed in Section 2. Thereafter in section 3, methods, technologies and equipment that have high effect on the minimization of drilling waste will be presented.

## II. HANDLING OPTIONS FOR DRILLING WASTE IN THE BARENTS SEA

Fig. 1 shows the waste management hierarchy. It shows that by avoiding waste from arising, costs are typically reduced and environmental benefits will be

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increased. In Waste management hierarchy waste disposal is the less preferable method. However as it is not possible to avoid, reduce, reuse, recycle or recover all generated waste, disposal and treatment is unavoidable step in waste management plan of oil and gas activities. With regards to waste disposal and treatment, there are three options available in the Barents Sea: *i)* re-injection into the subsurface formations, *ii)* discharge into sea; *iii)* transport to the shore for further treatment/disposal options.

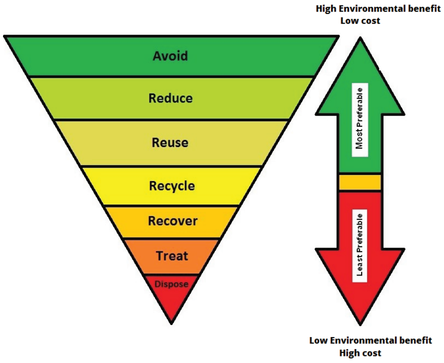


Fig.1. Waste management hierarchy [7]

*A. Transport of waste to the shore in Barents Sea*

A typical offshore well can generate in excess of 1000 tons of cuttings and require several hundred skips. In a typical offshore operation, all these skips have to be lifted onto a boat, transported to the rig, lifted up onto the rig, and lifted to the filling station on the rig (Fig. 2). Once filled with cuttings, the skip is lifted away from the filling station, down onto the boat, and finally lifted off the boat when it returns to the shore base. This means six or more crane lifts are required for each skip filled, and at 200 skips per well this amounts to 1200 individual crane lifts per well [8].

Fig. 2. Cuttings collection boxes installed on supply vessel [8]

There are many HSE issues connected to this and the number of crane lifts makes this a high-risk method due to Barents Sea operational conditions such as polar low and high wind in the area. The environmental effect causes a lack of concentration, and the reason for the human errors. Falling objects can be dangerous during operations; trapped fingers or bodies are also in danger. Nine out of ten fatal accidents on the Norwegian shelf is caused by human error during crane lifting activities. Cutting can be frozen in skips causing long waiting time to get emptied as it happened during the winters of 2009 and 2010 in NCS. Availability of lifting equipment is another challenge, which can be reduced significantly because of the operational conditions [3,9].

In general, waste shipped to shore is challenging for fulfilling the requirements for safety, logistics and environment due to remote and sensitive areas and harsh climate conditions in the Barents Sea. Moreover transport waste to shore for treatment has also a negative effect on the environment by increasing air pollution, energy consumption and also increasing the marine traffic.

In the Northern parts of Norway, waste treatment facilities are poorly developed. Hammerfest is the northernmost location where SAR has established drilling waste treatment facility, for disposal of water-based drill cuttings. However, final treatment is still handled further south due to capacity and technical limitations. The only place that has complete treatment for other drilling waste than water-based drill cuttings and the facility for final treatment of both slop and oil-based cuttings in Northern Norway is Sandnessjøen, which is located far south from the Barents Sea [10].

*B. Re-injection*

The next drilling waste handling option is reinjection of drilling waste into underground formation. The injection pressure must be high enough to fracture the subsurface formation. Moreover, the solid should be injectable hence it must be transformed into slurry, during which the volume of the waste increases by the factor of 5-6 [4, 11]. In certain geological situations, formations may be able to accept waste slurries at an injection pressure below the pressure required to fracture the formation. In 2009 it was found that there had been loss of integrity through the injection process in some injection wells on the Norwegian continental shelf (NCS), which caused fractures up waste to the seabed. These findings lead to closing of several cuttings injectors, and others were given limitations to the volumes and rates injected [12].

In Norway the share of cuttings and slop that was re-injected dropped from above 50 percent in 2006 to 40 percent in 2009, 20 percent in 2010 and below 8 percent in 2011 due to formation fractures causing leakages from disposal wells [10]. Some subsurface geological structures are not fit for waste reinjection therefore evaluation of the geological conditions that favor the re-injection process is needed. Requirements and regulation for underground injection in the Barents Sea needs to be assessed, because governing authorities are strict as to approve reinjection, and they do this on a case-by-case basis.

*C. Discharge into the Sea*

In this option drills cuttings usually are treated to remove as much of the drilling mud as possible and are discharged to the sea. Drilling muds containing cuttings are circulated through several separation devices on the rig to separate the drill cuttings particles from the drilling mud. The Convention for the Protection of the Marine Environment of the North-East Atlantic (the OSPAR Convention) was presented to the former Oslo and Paris Commissions in Paris on September 22, 1992. The Convention came into effect on March 25, 1998. OSPAR developed environmental guidelines for offshore oil and gas operations in the OSPAR region.

The OSPAR countries with offshore oil and gas resources (mainly Norway, the United Kingdom, and the Netherlands) independently use these guidelines to the unique environmental and political conditions of the regions of the North Sea, Norwegian Sea, and Barents Sea under their jurisdiction. The Norwegian Pollution Control Authority (SFT) uses a color-code system for chemicals and substances used and discharged offshore in the OSPAR area. They have divided relative hazard of chemicals used and discharged offshore into four categories: black, red, yellow, and green. The black and red categories include the most harmful or hazardous chemicals, while those in the yellow and green category pose no or little risk to the environment (PLONOR). According to SFT all chemicals intended for use and discharge offshore should be put through tests for the biodegradability, bioaccumulation and acute toxicity unless the substance is on the PLONOR list [9].

## III. MINIMIZATION OF DRILLING WASTE IN THE BARENTS SEA

Fig.3 shows three main categories that include implementation of the most preferred methods, systems and strategies, to minimize the drilling wastes, which need to be transfer to the onshore. The categories are *i)* minimization of drill cuttings *ii)* reduce amount and level of contaminated drill cuttings by appropriate drilling mud selection and *iii)* optimize onsite drilling waste treatment.

*A. Selection of drilling mud*

The volume of waste generated from a drilling operation is highly dependent on the type of drilling fluid. Drilling-fluid selection in the Barents Sea requires evaluation and consideration of numerous factors; the most important are performance of drilling mud, formation properties and behavior, environmental regulations, available waste management facilities in the area, economics, environmental conditions and absolute minimum waste for disposal onshore. In the Barents Sea, the use of water-based drilling mud (WBM) had been completely dominant. Components employed in WBMs have a lower chemical stability and it is a safer option from the perspective of lowering risk of harmful exposure to the local marine environment. Basically, WBMs are designed for separation from cuttings on the rig where the major parts can be discharged to sea opposite to oil-based mud, which produce high drilling waste and all of it must be transported to shore for treatment [4].

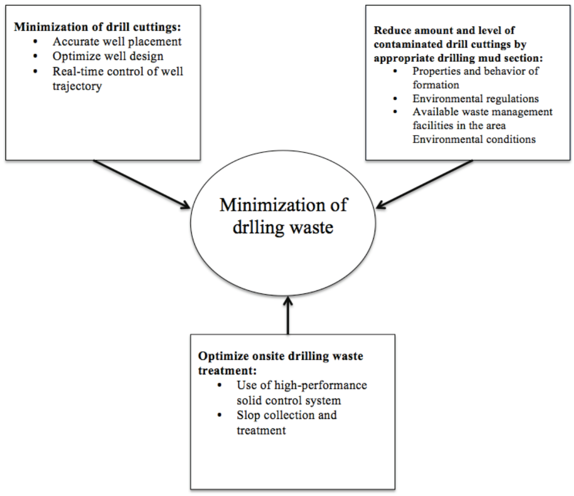


Fig. 3. Minimization of drilling waste strategies

In exploration wells water-based drilling mud should be the preferred choice. However, in case of long wells, more than 50 degrees they should be drilled by smaller diameter holes or in high reactive shale's, WBMs may not be a suitable selection. WBMs do not have the highly inhibitive quality so shale's are prone to sloughing and swelling that can cause stuck pipes, and washouts, whereas the latter can increase drilling waste. However, high performance water based mud (HPWBMs), which normally contain chemicals from yellow groups, are developed for shale dispersion inhibitor in reactive shale's and provide wellbore stability in complex wells [12, 13].

During drilling the top-hole sections, there is no way to return drilling mud or cuttings to the rig and all waste is deposited to the seabed, therefore seawater is the best choice to use as drilling mud in the top hole. Seawater with viscous fluid pills is used to drill the top-hole sections in almost all wells in the Norwegian Barents Sea. Statoil has been using WBM containing KCl/Polymer/Glycol-systems in Johan Castberg field and it is planned to use in Ensis field for sections 17 ½, 12 ¼ and 8 ½ as the primary choice when inhibitive water based drilling fluids with relatively good technical performance is required [14].

*B. Minimization of drill cutting*

Some aspects of well planning such as avoiding drilling of dry wells, accurate well placement and planning the most optimized well trajectory are key factors in reducing the total amount of generated drill cuttings. For this aim, detailed information about characteristic and behavior of subsurface formations is vital. This includes information about; composition and physical properties of the formations; accurate location of the reservoir; fluid migration and distribution; thickness of different formations; subsurface geological features such as fault, fold, and salt domes [15, 16].

There are different sources where such data can be acquired, such as previous drilled or abandoned wells (i.e. their well logs, well tests, and coring data), 3D/ 4D seismic activities and remote sensing surveys. By use of satellite -and airborne images and geological interpretation, it is possible to generate start models before the 3D or 4D geophysical surveys, and where information collection on the ground is required, 3D seismic surveys are used. This leads to more accurate placements of the drilling; reduces the number of drilled dry holes, as well as reducing the drilling waste generated. Moreover, acquiring more detailed data on the subsurface characteristics may improve the mud preparation and selection of its additive [15, 16].

Using the advance drilling method such as slimholes (wells that have reservoir sections of 6 inches or smaller in diameter and at least 90% of the well has been drilled with a bit of six inches or smaller), extended reach and multilateral wells are effective ways to reduce the waste in complex wells. For example in multilateral wells, only one main well is drilled and then other lateral wells, smaller in diameter, are drilled to reach the resources. This is of particular interest, where subsurface formation consists of multiple small zones at different depths that need several vertical wells to achieve the designed recovery rate. In multilateral and extended reach wells, they share the upper portion of the well and the upper portion of each well is larger in diameter than the lower portion of the same well and this reduce volume of drill cuttings [11]. In Goliat field in the Barents Sea, 11 wells have drilled horizontally with an average horizontal length of 1500m. Seven of these are horizontal production wells in the Kobbe reservoir and four horizontal production wells in Realgrunnen and of the four wells drilled in Realgrunnen, three are as multilateral wells . Furthermore, preventing the well from deviations by using the real-time well trajectory control is another method which can reduce the drilling cuttings [1, 17].

### C. Optimizing onsite drilling waste treatment

On the drilling platform, the mixture of drilling fluid and cuttings returned from wells are collected for treatment to control solids and recycle the drilling fluid back down the hole. Solid control system, vacuum collection system and waste and slop treatment system are main part of onsite waste treatment which have a major effect on maximizing recovery and reuse drilling mud. The process contributes to discharging of most part of drill cuttings into sea. Solid control system works to minimize the loss of drill fluids and maximize the recovery and reuse of the costly drilling fluids (Fig.4). The solids-control equipment selected for a well drilling program depends on the drilling fluids used, formation characteristics and the specific cuttings disposal requirements.

Vacuum Collection System (VCS) collects and moves drilled cuttings within a totally enclosed environment, minimizing spills and contamination. This system utilizes integrated shale conveyor technology, vacuum system, cuttings transport and real-time monitoring systems. Moreover, drilling slops and wastewater must be collected in a tank (slop water tank) and subjected to purification to meet the environmental discharge regulation. To minimize waste volume, it can be possible to recover useable drilling fluids from slop waste, recondition the fluid if needed, and recycle it back into the active system.

However, reliability, maintainability, supportability and availability (RAMS) of this equipment are the main concerns in the Barents Sea. An effective plan should be established for winterization of these equipments. For more discussion about the effects of operational conditions on RAMS see Ref.3.

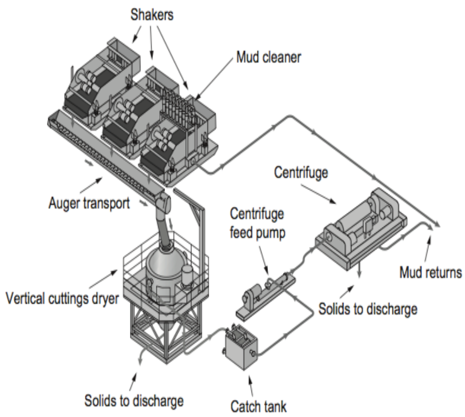

Fig. 4. Solids-Control System

## IV. CONCLUSION

Oil and gas operators have adapted new technologies and modified drilling processes to generate less drilling waste. Waste minimization has major benefits for oil and gas companies by reducing costs used for waste management and disposal, and enhance public perception of the company and the industry as a whole. The oil and gas industry in the Barents Sea has restrictions about selection of suitable drilling waste management options due to environment condition, regulatory requirements and poorly developed waste treatment facilities in the area. In the Barents Sea, the use of water-based drilling fluids had been completely dominant because it is safer choice from the perspective of lowering risk of harmful exposure to the local marine environment and it is basically designed for separation from cuttings on rig and most part of drill cuttings can be discharged to sea.

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# Paper III

# ICING AND PERFORMANCE OF OFFSHORE PRODUCTION FACILITIES IN COLD CLIMATE REGION

# Icing and Performance of Offshore Production Facilities in Cold Climate Region

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*Abstract* - **Ice accretion affect performability of offshore production facilities in various ways, including repair time and failure rate. Moreover, it can increase the power losses, life cycle costs and safety hazards. There are few studies and systematically collected information about the impact of ice accretion on performability and its concepts (reliability, maintainability, quality, safety and sustainability) for Arctic offshore production facilities. This paper will discuss the effects of different types of ice accretion on the performability of Arctic offshore production facilities. Then, to quantify their effect on the production facilities´ performability, an icing performability index is developed.**

*Keywords* - **Ice types, Icing hazard, Maintainability, Quality, Reliability, Safety, Sustainability**

## I. INTRODUCTION

Studies show that the world demand for oil is set to increase 37% by 2030.This demand leads the industry to harvest energy in more distant and climatically harsh areas such as the Arctic region. Over 28% of the world's undiscovered oil and gas petroleum reserves are expected to be in the Arctic region where the share of the offshore is approximately 84% [1]. Considering the unique and challenging Arctic operational conditions, the designed system must be dependable, safe as well as economical viable. Such systems must be able to minimize environment pollution, and require minimum quantitative of raw material and energy. Design for performability is appropriate approaches that can able designers to meet these important goals. Performance engineering is the entire engineering effort that goes into improving the performance of a system that not only ensures high quality, reliability, maintainability and safety but also is sustainable. Figure 1 shows the performability concept of a system [2]. An operational condition has a great effect on the performability of the production facilities [1-5]. Ice is one of the most hazardous operational conditions in cold regions. Ice accretion is defined as the process of ice build-up on the surface of an object. Ice accretion can reduce the performability of production facilities significantly [6]. In a place like the North Sea icing is considered more as a nuisance, but in Arctic harsh climate condition it can provide much more operation, maintenance and safety problems such as injury. Moreover, in the Arctic, such events can be very frequent, and hence, according to the accident pyramid concept they can lead to fewer but more serious accidents like fatalities [5, 6]. Ice may build up different form (such as frost, sleet, and glaze) based on the equipment shape, meteorological parameters (such as air temperature, wind speed, cloud liquid water content, cloud droplet spectra) and the elevation of equipment from the sea level. Offshore platform is a complex system with a lot of equipments in various shapes, which makes them susceptible for different types of icing and icing problems. Sea spray and atmospheric icing are two main sources of ice accretion on offshore production facilities [4].

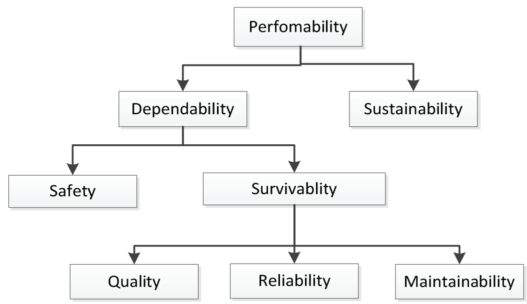


Figure 1: Performability concept [2]

To reduce the effects of ice on the production performability, two main approaches can be considered *i)* removing the ice after accretion (de-icing) and *ii)* preventing the production facility from icing (anti-icing). Many active and passive anti-icing and de-icing techniques have been used in different industries such as electric power [6-10]. However, Arctic offshore operational conditions provide new challenges for application of these methods and they have limitation of usage due to harsh and sensitive environment, lack of infrastructure as well as distance to the market [1]. To develop an effective practical solution and increase the performability of production facilities, one must have a comprehensive knowledge about the different types of ice, how they form and where they appear on offshore production facilities. Moreover, it is very important to know how and how much they can affect the different concepts of performability. There are few studies and systematically collected information about the impact of superstructure or atmospheric ice on offshore production facilities performability. In this paper the different types of ice accretion and their effect on performability of

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offshore production facilities will be discussed. Then in order to quantify their effects on performability, a concept of icing performability index is developed.

## II. TYPES OF ICE ON PRODUCTION FACILITIES

As mentioned, ice accretion on offshore production facilities can be categorized in two main groups *i*) atmospheric icing and *ii*) sea spray icing or superstructure icing [6].

Atmospheric icing is defined as the processes where falling or drifting raindrops, refrozen wet snow or drizzle forms accretions on an object that is exposed to the atmosphere[6,8]. Based on the procedure, feature and physical appearance, atmospheric icing can be categorized into: glaze (density 900 kg/m$^3$) from precipitating cold-water droplets that hit a surface and freeze upon impact, rime (density 600 to 900 kg/m$^3$) resulting from droplets in fog, sea smoke or cloud drops that hit a surface below 0°C and freeze, sleet (density 900 kg/m$^3$) which are raindrops that have been frizzed before hitting surfaces, frost (density 100 kg/m3) resulting from direct transformation of water vapor to ice and wet snow (density 300 to 600 kg/m$^3$) [10-11]. Icing processes are complex, and there are great difficulties in predicting its rate by empirical methods. Atmospheric icing rates can be estimated by equation (1) which is described below [6,8]:

$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 \omega . A . V \qquad (1)$$

where $M$ is the mass of the ice accretion during time $t$, $\alpha_1$ stands for the collision efficiency of the particles when particles hit an object. Factor $\alpha_2$ stands for the collection efficiency of the particles that hit objects. Factor $\alpha_3$ stands for the accretion efficiency. These three conditioned factors vary between 0 and 1. Factor $\omega$ stands for the mass concentration of particles in the air, factor $V$ stands for the particle velocity and $A$ stands for the objects cross-sectional area [6].

Sea spray icing is a dominant source of ice accumulation on stationary offshore structures and shipping industries in the Arctic and Sub-Arctic. The sea spray droplets are carried by the wind and hit objects in their way. When the air temperature is colder than the freezing temperature of seawater, approximately –2°C, freezing spray occurs [6]. Sea spray icing can accumulate over 1000 MT of ice on a platform [13] which can provide stability, and operation -and maintenance hazards. Sea spray icing on stationary offshore structures is significantly different from sea spray icing on ships. Spray is generated on ships by heaving and pitching as the ship interacts with the waves it is moving through. However, sea spray icing on stationary offshore platforms is generated when wind-blown water droplets, caused by whitecaps on the ocean surface, interacts with a part of the platform structure and freeze. [12]. Moreover it is expected that sea spray icing is more severe at lower heights above the ocean surface, both because the droplets tend to evaporate as they are transported from their source and because larger droplets tend to fall out of the spray cloud because of gravity. On the other hand, no ice is expected to accrete near the waterline where the structure is warmed up by the water as waves and swell wash over it. Ice will also accumulate on top of horizontal surfaces as water flows off vertical surfaces or drips off cables, handrails, and other elevated components when it is not cold and windy enough to freeze the impacting droplets immediately. There have been several models developed to help predict ice accretion, notably the ICEMOD and RIGICE [11-16]. Based on the wind speed and temperatures, ice accretion forecast map for ships have been developed and are available. However, considering the difference between ice generation in the offshore production facilities and ships using this model can not provide trustable results. Recently, researchers have developed models to calculate the sea spray icing on offshore production facilities. Jones and Andreas [12] developed a model to calculate the icing rate on cylinders with axes perpendicular to the wind direction as:

$$\frac{dI(z)}{dt} = \frac{U(z)}{\rho_i} \int_{r_{\min}}^{r_{\max}} E(U,r,D) \frac{dW(r,z)}{dr} dr \qquad (2)$$

Here, *I(z)* is ice thickness on the front of a cylinder with diameter *D, t* is time, *U (z)* is wind speed at height *z*, $\rho_i$ is ice density and *E(U , r, D)* is the collision efficiency of the droplets with the cylinder, *W(r,z)* is spray liquid water content and can be calculated by[12]:

$$\frac{dW(r,z)}{dr} = r_w \frac{4}{3} pr^3 \frac{dC(r,z)}{dr} \qquad (3)$$

Figure 2 shows the potential ice accretion areas on a drilling rig.


Figure 2: Potential ice accretion areas on a rig[8]

## III. ICING AND PERFORMABILITY

Icing may have different effects on performability elements (sustainability, safety, quality, reliability, maintainability), below; some of the main effects will be discussed briefly.

*A. Effects of icing on sustainability:* The word "sustain" comes from the Latin *sustenare* meaning "to hold up" or to support, which has evolved to mean keeping something going or extending its duration. The sustainability principle requires that the products and systems use minimum material (dematerialization), and minimize the use of energy throughout their entire life cycle (extraction phase, manufacturing phase, use phase) and they should use non-hazardous materials and should be highly recyclable at the end of their life. Minimizing the use of matter minimizes the impact of the extraction phase and minimizes total material flows. The objective of environmental sustainability is to increase energy and material efficiencies, preserve ecosystem integrity, and promote human health and happiness by merging design, economics, manufacturing and policy [2]. The effect of icing and low temperatures on the sustainability can be due to increase of energy consumption, increase in the use of materials and increase in the use of processes and products that are used for ice protection and heating. The large power demand of offshore installations in the Arctic area is in most cases covered by their own gas, and greenhouse gas emissions from power production are high. De-icing technologies with high consumption of energy have negative impacts on the sensitive environment and wilderness in the Arctic. Moreover use of hazardous chemical ice protection cause degradation the environment quality; increase the produced waste and serious environmental consequences.

*B. Effects of icing on reliability:* According to (IEV191-12-01) the definition of reliability is "*the ability of an item to perform a required function over specified time and under the specified conditions*". The main effects of icing on the reliability of equipments can be categorized in *i)* Static ice loads *ii)* Wind action on iced structures and equipment*; iii)* Dynamic effects*, iv)* Damage caused by erosion and by falling ice. The load of accreted ice can easily deform or damage elements (claddings, etc.), and damage also might occur if the ice has not fallen off before forces have grown too great. Moreover sagging of ice on equipment may be exposed to unexpected ice loads because the ice sags downwards and covers or presses on the elements. Tension forces from ice accretion in some material such as steel and cables increase considerably. Cables experience significant icing problems and are a cause of system failure when iced too heavily, especially when water sources are wind-driven and cables are oriented at nearly right angles to the wind direction. It makes ice accumulation on only one side. The torsional weak cable then rotates down, or twists, because of the weight of the ice accumulating on the side, and more ice accumulates on the new exposed face. This process, if occurring for a long enough time, can cause cables to rotate multiple times with a spiral of ice enveloping them. Antennas and antenna structures can easily be overloaded by accreted ice. In particular, small fastening details are weak when increased load is added on top of other actions, because the ice may easily double the normal load [11]. Icing on structures and equipment will increase wind drag by changing of dimensions and weight, shapes and drag coefficients. Moreover icing on structures and equipment can change their natural frequencies, which is a significant factor influencing the dynamic behavior and control of the systems. If a structure is heavily iced, its natural frequencies decrease to great extends due to its increased reactive mass. Shedding and breaking of ice, which normally are due to increasing temperature, small deflections and vibrations from higher parts of structures have high potentially destruction on lower equipment. Moreover falling ice may cause important dynamic vibrations and stresses in the structures. In some cases icing and snowdrift erosion effects are critical factors, which should be considered in the design and operation phase. Ice and snow, combined with large temperature variance, will cause erosion damage.

*C. Effect of icing on Quality:* Quality of a product is a measure of the degree of conformance to applicable design specification and workmanship standards. If quality can be thought of as the excellence of a product at the time it is delivered to the customer, reliability is used in the engineering context to describe the ability of a product to work without failure during its expected time in use [2]. A product's reliability therefore depends upon how well it is designed to withstand the conditions under which it will be used, the quality of manufacture, and how well it is used and maintained. Quality can be classified into two types: design qualities and manufacturing qualities. In design quality by understanding the environments involved and the stresses that can be applied can prevent wear out failures and overstress failures. Materials that are common in more benign weather conditions require early assessment for material selection and performance aspects such as accuracies, efficiency, and operational energy requirements in the design process to confirm integrity under arctic or subarctic conditions over the full life cycle of the facility. On the other hand, manufacturing qualities pertain to the manufacturing processes used when producing products that incorporate desired design qualities. In the case of machine tools, such qualities would correspond to dimensional variances, surface roughness and processing accuracy. Variation of parameters and dimensions, leading to weakening, component mismatch, incorrect fits, vibration, etc. The effect of icing on the quality of systems has not been well studied. The effect of icing on the quality can show itself on the installation phase. In the presence of ice on installation phase it can for example increase the first time failure more.

*D. Effect of icing on maintainability:* The formal definition of maintainability according to IEV (191-02-06) is: "*the ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated* *procedures and resources*". The main attributes of maintainability are: standardization, interchangeability, troubleshooting, special tools, mounting proof, ergonomics, removal/installation, ease of handling, accessibility, safety precautions and skill level. In general, the operational conditions such as icing can contribute in changing the maintainability performance of an item by affecting i) Maintenance crew, ii) Components and maintenance tools and iii) Maintenance support.

In cold conditions maintenance crew should wear warming clothes and gloves, which can increase the measurement of body dimensions and reduce the mobility and hand dexterity. Sometimes temporary shelters to protect the personnel from freezing weather and wind need to be considered. The problem of sheltering is that they can reduce mobility and limit the working area. Slippery pathways can also reduce the mobility of maintenance crew. Emergency safety protection equipments (e.g. eye wash or showers) can be affected in icy conditions. The most common problem mentioned by maintenance personnel is the lack of satisfactory access to the equipments requiring maintenance attention. Maintenance supervisors and foremen estimate that a 30% savings in overall maintenance time could be achieved if access to equipment were ideal or unrestricted. Icing may change the accessibility of the failed item by changing their appearance and the shape. Improper accessibility can increase access, replace and removal time of failed component. Equipment labels are improving the maintainability. Labels should be accessible in visual limits and located in well-lighted places. Icing can fail or obscure the equipment labels over time and they need to be replaced in systematic manner. Under such conditions multi-unit plants in which both units are identical or highly similar in appearance offer special opportunities for maintenance errors. Ice conditions cause several problems for safe and quick passage of personnel and materials. Maintenance shops should be located in central locations to minimize traverse time between the shops and equipment requiring attention. However, the ice accumulation snow drifting (accumulation of the snow in specific location) or atmospheric icing, can dictate the maintenance shops´ location far from the central locations. Effective communication is very important in maintainability. Ice on antennas can cause insufficient communications coverage impeded telephone conversations for example between the operator and repairperson. Moreover, crane, lifting or hoisting provisions devices are the key elements in maintenance of equipment. Ice can adversely affect reliability and availability of this equipment.

*E. Effect of icing on safety:* The general definition of safety is the condition of being protected against physical, social, spiritual, financial, political, emotional, occupational, psychological, educational or any other types of consequences arising from failure, damage, error, accidents, harm or any other event that could be considered undesirable. This can take form of being protected from an event or from exposure to something that can cause health or economic losses [2]. Icing on platforms can be dangerous for personnel. Wet snow especially, can be slippery and the risk of falling and other accidents are present. Snow and ice on burner booms can lead to explosion, fire or accumulation of toxic gases if the snow is over the burner booms load rating [8]. Snow accumulation on valves inhibits manual operation and the ability to see position indication. Removing glaze is difficult, it is hard, and less than 1 mm glaze ice can cause danger for personnel and equipment. Disabled wrenches and cranes, and locking cables are common results. Glaze also coats antennas, windows, randomness, hatches, rescue -and firefighting equipment and valves. Frost causes slippery conditions and can be dangerous. All horizontal surfaces can frost, including windows where visibility can be impaired [6]. Rime ice is a big contributor to icing on tall stationary sea structure, for example rigs. Rime can affect both personnel and equipment such as: antennas, railings, cables, booms and derricks. Melting rime can cause pieces to fall down and create hazard for personnel. Rime on stairs, deck and other surfaces can cause slippery hazards that can result in accidents. Sleet accumulation occurs on horizontal surfaces such as stairs, decks, hatches, cables and helicopter landing pads and produces a slipping hazard [10]. The majority of investigators agree that the greatest hazard to drill rig safety is sea spray-created superstructure icing [11]. High weight caused by sea spray accumulation is an issue for buoyancy and stability, and can cause platform sinking, in addition to the fact that icing increases the wind resistance of the superstructure. Moreover sea spray icing can cover boats´ lifesaving apparatus, and deck firefighting equipment, which are vital and critical equipment. Operational delay and unnecessary costs are caused by slippery handrails, ladders, decks, icing on deck cargo, winches and helicopter platforms [8, 16].

## IV. ICING PERFORMABILITY RISK INDEX

Considering the different types of icing effect and variety of the effects on different equipment's performability, it is necessary to develop a standard factor in order to asset the effects of icing on different elements and the performability of the equipment. Performability has 5 principle elements (reliability, maintainability, quality, safety and sustainability) and 2 dependent elements (dependability and survivability). As mentioned, icing has different types of effect on these elements. Ryerson [11] developed a qualitative risk index for different parts of the offshore drilling rig. However, he only considered the safety factor and the other elements of the performability have not been considered. Considering the effect of the icing on quality, reliability and maintainability, the icing survivability index, *ISI* can be developed as:

$$ISI = \alpha_q I_q + \alpha_r I_r + \alpha_m I_m \quad (4)$$

where, $I_q$, $I_r$, $I_m$ are the icing risk index for quality, reliability and maintainability of a specific item respectively, $\alpha_q$ , $\alpha_r$ *and* $\alpha_m$ are shows the weight of different element of survivability where $\alpha_q + \alpha_r + \alpha_m = 1$. The icing risk will be changed from 0 to 10, where 0 shows no icing risk on reliability, maintainability or quality and 10 shows very high effect on these elements. The criticality and required availability of an item will decide the weight of the different survivability elements. Moreover, considering the icing risk index for safety, $I_s$ , The icing dependability index, *IDI*, of an item can be calculated as:

$$IDI = \beta_{sur.} ISI + \beta_S I_S \quad (5)$$

where the $\beta_{Sur.}$ and $\beta_s$ show the weight or importance of survivability and safety on dependability and where $\beta_{Sur.} + \beta_s = 1$. Finally the icing performability index can be calculated by:

$$IPI = \gamma_{Dep.} IDI + \gamma_{su.} I_{su.} \quad (6)$$

where, $I_{su}$, *is* the icing risk index for sustainability and $\gamma_{Dep.}$ and $\gamma_{su.}$ show the weight of survivability and dependability on performability where $\gamma_{Dep.} + \gamma_s = 1$.

TABLE I:
ICING RISK INDEX FOR DIFFERENT ELEMENT OF PERFORMABILITY

| Performability element | Sea spray icing | Atmospheric icing | | | | |
|---|---|---|---|---|---|---|
| | | Snow | Glaze | Rime | Frost | Sleet |
| Quality | 10 | 8 | 7 | 7 | 3 | 2 |
| Reliability | 10 | 8 | 9 | 6 | 3 | 1 |
| Maintainability | 10 | 9 | 9 | 8 | 5 | 5 |
| Survivability ($\alpha_q$=0.33, $\alpha_r$=0.33 $\alpha_m$=0.33) | 10 | 8.25 | 8.25 | 6.93 | 3.3 | 2.64 |
| Safety | 10 | 10 | 7 | 7 | 4 | 3 |
| Dependability ($\beta_{Sur.}$=0.5 , $\beta_s$=0.5) | 10 | 9.125 | 7.625 | 6.96 | 3.65 | 2.82 |
| Sustainability | 10 | 8 | 5 | 5 | 3 | 3 |
| Performability ($\gamma_{Dep.}$=0.5 , $\gamma_s$=0.5) | 10 | 8.56 | 6.31 | 5.9 | 3.325 | 2.91 |

Table 1 shows the numerical example for calculation the icing performability index for helicopter panel on an offshore platform located on the Arctic region. As this table shows the most hazardous type of icing for helicopter panels is Sea spray icing with *IPI=10* and sleet has the minimum effect among the different types of icing with *IPI=2.91*.

## IV. CONCLUSION

Design for performability is an effective way to meet the design goal for a complex operational condition such as the Arctic region. Design for performability imply less environmental pollution, less material and energy requirements, waste minimization, and finally conservation and efficient utilization of available resources, which in turn result in minimum life-cycle costs. Ice has significant effects on performability of equipment. To manage and minimize icing effects on performability it is necessary to study how, when, how much and which type of ice will be accumulated on different items. Thereafter their effects should be quantified by appropriate approach. This paper has reviewed the effect of ice on performability element and then a concept of icing performability index was developed.

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