A methodology for identification of a suitable drilling waste handling system in the Arctic region

Abstract – As the demands to reduce the environmental impact of oil and gas operations increase in the Arctic region, the need to identify suitable waste handling systems becomes more essential. The aim of this paper is to propose a methodology for identifying a suitable drilling waste handling system, by considering the distinctive operating conditions of the Arctic region. The proposed methodology can help the user to explore and assess waste minimisation, handling, treatment, and disposal techniques for Arctic drilling that fit a wide range of operating requirements and needs. By making use of the proposed methodology, a suitable waste handling system that ensures sustainability and fulfils HSE (health, safety, and environment) standards can be recommended. The application of the methodology is demonstrated by a case study of drilling waste handling practices in the Johan Castberg oil and gas field, located in the Barents Sea.

Key words: Arctic, drill cuttings, oil and gas industry, offshore drilling, waste handling, waste management

1. Introduction

As drilling operations become more demanding and move into environmentally sensitive areas such as the Arctic region, operators struggle to comply with stringent waste-discharge guidelines, while meeting drilling-performance demands (Guo et al., 2005, Boesch and Rabalais, 2003). Moreover, the Arctic ecosystem is very sensitive to pollution from drilling activities, and, in the case of damage, its recovery is very slow and in some cases, damage can be irreversible. Hence, understanding the complex interactions of the effects of drilling waste in an Arctic environment is particularly important in this region (Boesch and Rabalais, 2003, Neff, 1987). Furthermore, as the demands to reduce the environmental impact of oil and gas operations increase in the Arctic region, the need to identify suitable waste handling systems designed to handle and treat the generated waste streams is becoming compulsory (Bilstad et al., 2013, Hasle et al., 2009).

However, identifying cost-effective and efficient waste handling and management systems, which have a minimal environmental footprint, is one of the biggest challenges in the Arctic region (Paulsen et al., 2005). In addition, the operational performance of the chosen waste handling technologies or systems can be greatly influenced by the operating conditions of the Arctic region (Barabadi et al., 2015, Barabadi and Markeset, 2011). Moreover, the drilling waste handling systems to be deployed in this region must ensure protection of the marine ecosystem, permafrost, vegetation, groundwater, and wildlife which are unique in their nature (IUCN, 1993). Furthermore, the barriers that were implemented during the designing of waste handling systems can sometimes be inadequate to prevent pollution when there is accidental drilling waste discharge to the sea (Olsen et al., 2011).

When assessing suitable drilling waste handling systems, the Arctic should not be considered as one homogeneous region. Systems that are suitable for a specific Arctic or sub-Arctic region under certain conditions might be inappropriate in other circumstances or areas – in other words, there can be no 'one-size-fits all' approach. There are several definitions of the Arctic. For the purpose of this paper the defintion of 'Arctic' is adoped from the Arctic Monitoring and Assessment Programme (AMAP). According to the AMAP, the Arctic essentially includes the terrestrial and marine areas north of the Arctic Circle (66°32′N), and north of 62°N in Asia and 60°N in North America, modified to include the marine areas north of the Aleutian chain, Hudson Bay, and parts of the North Atlantic Ocean including the Labrador Sea.

In order to assure stringent waste-discharge requirements (such as zero discharge to the sea), to reduce environmental impacts of the waste, and to identify the most suitable waste handling system, a number of studies have been carried out. Moreover, several regulations and standards have been developed for waste management in the Arctic. For instance, the US Department of Energy (2000) established a conventional waste management technology identification module for managing drilling muds and cutting as well as guidelines for optimal waste management practices. The Canada Environmental Studies Research Fund (2004) prepared drilling waste management best practice, to provide a drilling sump options reference tool and to promote the proper management of drilling waste. Paulsen et al. (2005) demonstrated the procedures for achieving zero discharge in the harsh operational conditions. The Norwegian Petroleum Safety Authority (PSA) has also developed rules and regulations for conducting petroleum activities in the Arctic region. In particular, PSA Activity Regulation, Section 68 states that cuttings from drilling and well activities shall not be discharged to the sea if the content of formation oil, other oil or base fluid in organic drilling fluid exceeds ten grams per kilo of dry mass. The World Conservation Union, IUCN (1993) established guidelines for environmental protection during oil and gas exploration and production in Arctic and sub-Arctic onshore regions. Glickman et al. (2008) proposed an environmental performance standard and waste management toolbox for offshore drilling discharges. Det Norske Veritas (2009) assessed various international standards for safe exploration, production and transportation of oil and gas in the Barents Sea (part of the Arctic Ocean, north of Norway and Russia).

However, there is a lack of implementation of comprehensive as well as step-by-step waste handling system identification methodology, specifically intended for Arctic offshore drilling. Moreover, some of the available tools or methodologies are too cumbersome, time-consuming and generalised (Jonathan R. and Emma J., 2010, Sustainable and Ecological Management Working Group, 2014). Hence, developing a step-by-step methodology that supports and facilitates the decision-making process, can offer the solution to filling the gaps that exist in the present system identification practices. The aim of this paper is thus to propose a methodology for the identification of suitable drilling waste handling systems for Arctic offshore drilling. The rest of the paper is organised as follows: Section 2 discusses the challenges related to drilling waste handling activities in the region. Section 3 presents the proposed methodology. Section 4 presents a description of the illustrative case study and the application of the proposed methodology. Section 5 provides the conclusion.

2. Challenges for the drilling waste handling activities in the Arctic: An overview

To propose measures and address and mitigate unwanted events, the factors that can affect the performance of the waste handling system need to be understood. In the Arctic region there are several factors that can influence the drilling waste handling activities. These factors can generally be categorised as: environmental and climatic, geographical, and cost-related factors (Svensen and Taugbol, 2011, Heather et al., 2013, Ayele et al., 2013a). These factors depend on various variables and they also interact with each other. In combination, these factors will determine the performance of the drilling waste handling system, or the suitability of new drilling waste handling technologies in the region. Figure 1 shows some of the factors that need to be considered when preparing a drilling waste handling program, which is going to be deployed in the Arctic environment. Note that the list of factors is not in accordance with their importance.

((Figure 1))

2.1 Environmental and climatic influencing factors

Due to Arctic operational environmental and climatic factors such as large variations in temperature during a short period of time, sudden wind increase and large changes in wind direction, snow, and inadequate weather forecasting, it is expected that the uncertainty will be magnified and the risk associated with the drilling waste handling will be much higher than in the North Sea (Det Norske Veritas, 2009). In addition, the environmental issues in the region are of high importance and they are of the utmost importance for the companies responsible for developing the fields and for operating and maintaining the drilling waste handling facilities (Markeset, 2008, Barabadi, 2014). Moreover, any environmental damage during the drilling (including waste handling) activities may lead to political restrictions for future oil and gas production. Furthermore, any mishap can create negative publicity and a bad reputation for the operating company and other involved parties such as the operators of commercial waste disposal facilities.

During winters the oil and gas industry in the Arctic experiences long lead times due to drilling cuttings being frozen, stuck in skips while waiting to get emptied onshore for further treatment (Svensen and Taugbol, 2011). In some areas of the Arctic region, between 65 – 70% extra costs incurred during drilling waste handling activities are weather related (Martin, 2004). Moreover, the loading of mud skips or containers onto the transport ship by the use of cranes is a slow process, and severe weather can significantly affect the waste handling process (Martin, 2004). Since 1994, human error during crane lifting (including waste container lifting) activities has been responsible for 9 out of 10 fatal accidents on the Norwegian shelf (including the Barents Sea); the main reason is lack of concentration, which is caused by the environmental effect (Ayele et al., 2013a).

In general, for longer periods of time, especially during winter, the harsh weather may make the activity of drilling waste handling nearly impossible. Hence, to assure effective waste management, the severe operating environments of the Arctic region need to be considered during the planning phase.

2.2 Geographical influencing factors

Transportation and logistics are going to present a challenge to achieving the drilling waste handling system performance objectives while we operate in the Arctic, since the area is sparsely populated and has insufficient infrastructure (Martin, 2004). In addition, the shipping time to transport mud skips, material and personnel needed for the waste handling operation, and spare parts (required for the drilling waste handling system) will be considerably longer (Svensen and Taugbol, 2011, Ayele et al., 2013b). For example, since many of the manufacturers and the industrial service providers are located close to the oil and gas fields in the North Sea, in the south-west of Norway, the oil and gas fields in the Barents Sea are experiencing longer lead times. Ayele et al. (2013b) estimated that the adverse operational condition of the Arctic region can cause approximately 20% of prolonged delays throughout the year, in the course of the transport of the spare parts. In addition, the remoteness of the Arctic leads to limitations in a skip and ship supply chain in the region (Svensen and Taugbol, 2011).

Furthermore, the long-distance transporting of drilling cuttings to shore has an overall negative effect on the environment by increasing air pollution and solid waste generation (IUCN, 1993). Not only does it increase energy consumption (for ships, cranes, trucks and earth-moving equipment at waste disposal sites) but the increase in marine traffic could also have an impact on subsistence hunting. In addition, the movement of heavy equipment and supplies around the site may lead to considerable terrain disturbance (IUCN, 1993).

During winter periods especially, waste handling system and transporting machine breakdowns will cause a greater risk to system performance than in another period of the year. Even though we have a high level of reliability, the performance of the drilling waste handling system can easily be reduced if we have to wait for spare parts for extended periods of time. In the worst scenario a breakdown can last for a week or even a month due to the wait for the weather to improve. Thus, in the Arctic, to maintain good drilling waste handling system performance throughout the whole year, one must consider the geographical influencing factors during the planning phase.

2.3 Cost influencing factors

Cost factors will most often decide the acceptable level of system (including waste handling systems) performance with respect to capacity and availability (Markeset, 2008, Kayrbekova et al., 2011). Heather et al. (2013) summarised the cost aspect of the development of oil and gas fields in Arctic areas as follows: “distance from manufacturing centers requires that companies maintain equipment redundancies and a large inventory of spare parts; harsh weather requires specially designed equipment that can withstand the frigid temperatures; and higher wages are needed to bring on and keep personnel in the remote areas. Additionally, poor soil conditions can require additional site preparations for onshore facilities to prevent equipment from sinking; and unpredictable weather can hinder shipments of equipment and personnel."

Generally, the cost of a drilling waste handling system operation and design can be categorised into two main groups (Heather et al., 2013): *i)* internal cost factors – as a result of company decisions and goals. To a great extent these cost factors are managed by the company and, if necessary, can be changed. *ii)* external cost factors – not controlled by the company but will impact the overall cost and the decisions. Moreover, there are inherent risk factors for the chosen drilling waste handling system and the company tolerance for them. Risks related to the overall oil and gas market and the economic condition of the waste handling operator are the other external cost factors.

The cost of winterisation, which reflects the winterisation enclosures and heating systems to protect equipment and prevent freezing, is the other cost-driven factor in Arctic drilling. The additional cost factor when planning and performing drilling operations in the Arctic region is environmental related taxes. These taxes are defined as any compulsory, unrequited payment to general government levied on tax-bases deemed to be of particular environmental relevance (Sollund, 2007). Thus, when tax is imposed on a polluting or environmentally harmful substance or activity, it introduces an economic cost that the polluter, for instance the operator of the oil and gas company, will take into account when making the decision on whether or not to carry on exploration and production or how it is to be done and to what extent (Sollund, 2007).

Thus, the preferable way of looking at costs related to drilling waste management in the Arctic is to examine them in conjunction with the costs of the consequences of liability and environmental footprint. For example, discharging drilling waste contaminated with hydrocarbon into the sea will not only result in environmental damage and clean-up cost, but will also be of political importance. Thus, this consideration of the cost of the consequence allows every oil and gas company to have a plan based on the associated consequence of the chosen drilling waste handling system.

3. Methodology

Figure 2 shows a proposed methodology for identifying the suitable drilling waste handling system from available alternatives for Arctic offshore drilling. The methodology has four steps, which start with defining company goals and criteria (related to drilling waste handling systems).

((Figure 2))

Step 1: Defining drilling waste handling goals and analysing influencing factors

Zahorsky (2013) proposed five main steps that need to be considered while defining company goals. These five main steps are: *i)* specific (the goal should be well defined and focused), *ii)* measurable (the planned goals need to have targeted results), *iii)* achievable (the intended goals should not be beyond reach or outlandish), *vi)* relevant (the company goals should be based on the current conditions and realities), and *v)* time-based (there should be a defined time frame to accomplish the goals).

After defining the goals, subsequently, the main technological and operational influencing factors need to be identified and the impact reduction measures need to be formulated. These influencing factors are the characteristics of the environment, the geographical location, cost related factors and the cumulative uncertainties from various sources. Identifying these factors will reduce the probability of all types of risks and helps to improve the performance of the chosen system.

Afterwards, the next step is exploring drilling waste minimisation practices which are suitable and applicable in the Arctic region. Drilling waste minimisation methods are most often considered as an important part of a company's long-term plan. There are several drilling waste minimisation techniques and practices, which help with the reduction of the drilling waste in the region. Directional drilling (extended-reach drilling), drilling smaller diameters, use of fluids and additives with lower environmental impact, and usage of drilling techniques that consume less drilling fluid volume are among the most common drilling waste reduction measures in the region. Furthermore, the application of high technology 3-D and 4-D imaging techniques in Arctic oil and gas exploration allows for greater certainty that a drilled well will encounter oil and natural gas, reducing the number of wasted wells drilled looking for, but not finding, oil or natural gas (Ayele et al., 2013a).

The overriding factor that must be accommodated in the analysis of the potential waste minimisation techniques in the cold Arctic regions is the prevailing low temperatures. Cold temperatures reduce the performance of components of the drilling waste minimisation system, ranging from primary shale shaker and mud cleaner to screw conveyor. Furthermore, the viscosity of water-based mud increases significantly as temperature falls. Higher viscosity means slower flow and mixing rates, and consequently reduced performance of the waste minimisation systems. To address the above-mentioned problems and minimise the impact of cold temperature on the waste minimisation systems, Dahl et al. (2012) and Dahl et al. (2006) proposed waste minimisation techniques by optimising the performance of solids control systems in the Arctic environment. Moreover, Kroken et al. (2014) presented a fluid management vacuum conveyor system, that eliminates the traditional mechanical process of shaking the fluids and solids and consequently reduces the waste.

After assessing the available and applicable waste minimisation techniques, the next step is to describe and classify the drilling waste. These classifications are commonly based on the standards and regulations. In general, drilling waste can be classified into three categories, as waste produced by drilling with: *i)* water based drilling fluids or mud (WBM), *ii)* oil based drilling fluids or mud (OBM), and *iii)* synthetic based drilling fluids or mud (SBM). Table 1 illustrates the pros and cons of WBM and OBM. Then, after classifying the generated drilling waste, the waste can be categorised as hazardous and non-hazardous.

((Table 1))

Step 2: Assessing the applicability and suitability of offshore disposal techniques

The onshore drilling waste handling and treatment options would limit the Arctic drilling operational window significantly (Guo et al., 2005). This is due to the adverse meteorological conditions, the inadequate maritime transport facilities, the long distance to, and state of, current onshore disposal facilities, and the insufficient emergency response facilities in the region (Markeset, 2008). Hence, in Arctic offshore drilling, the operators need foremost to assess and explore the offshore disposal techniques rigorously. Moreover, offshore disposal techniques can be environmentally and economically sound disposal options in the region.

Offshore disposal: At this stage a comparative analysis between each of the proposed offshore drilling waste disposal techniques should be carried out. This analysis can help to assess and evaluate the advantages and disadvantages, and the potential impacts of each of the proposed disposal techniques on the surrounding environment (Melton et al., 2004). In general, offshore disposal can be classified into two: *i)* offshore discharge – treating and discharging the drilling waste to the ocean (sea) and *ii)* offshore re-injection – re-injecting the drilling waste offshore both in a dedicated re-injection well and/or in a dry (dead) well.

In the case of offshore discharge, which is applicable when WBM is used, a key component is the establishment of the environmental profile, which describes the site-specific environmental conditions of offshore drilling discharge activities (Glickman et al., 2008). Further, to increase the intensity of the drilling waste discharge planning, different seabed types (intertidal areas) such as areas with stones and gravel, rocky areas, and coral reefs should be studied and their response to waste discharge evaluated. For instance, the coral reefs are expected to be vulnerable for sedimentation of particles and exposure to chemicals from drilling solids and fluids (Jodestol, 2010). In addition, reduction of oxygen transfer to underlying deposits, during waste discharge, can potentially affect the coral reefs (benthic communities) (Melton et al., 2004). Moreover, the creation of "dead zones" in the local ecosystem, as a result of the accumulation of muds and cuttings, is another problem (Melton et al., 2004).

Hence, to eliminate and/or minimise the impact of offshore discharge on the coral reefs (as well as on other vulnerable benthic communities), a detailed visual survey should be performed of all potential coral locations within 500 m from the well location (Jodestol, 2010). Moreover, when significant coral reef communities are found within the 500 m, then all the generated drilling waste (solids and fluids) must be collected and hauled to a site at least 500 m away from any coral location (Jodestol, 2010). Further, local statutory drilling waste discharge regulations must implemented throughout the waste discharge process.

For instance, according to the current practices, discharges of water-based mud into the Norwegian part of the Barents Sea are evaluated based on: *i)* the expected characteristics of chemicals to be used for the drilling activity, *ii)* the quantities of drilling waste to be discharged into the sea, and *iii)* how the discharge will take place (for example discharging the drilling waste from the rig directly to the sea/ocean). In addition, before discharging the drilling waste, environmental impact assessments (EIA) are conducted in accordance with the Norwegian Petroleum Safety Authority (PSA) Activity Regulations § 64. Moreover, as a baseline requirement in the Norwegian part of the Barents Sea, each well is recommended to be drilled with water based drilling fluids, containing only chemicals selected from the Pose Little or No Risk to the Environment (PLONOR) list of green chemicals.

When offshore discharge is not allowed, for instance when OBM is used as a drilling fluid, then other methods of offshore cleaning of drilling waste and disposal should be employed. For instance, Murray et al. (2008) proposed friction-based thermal desorption, which allows the oil and water phases to be volatilised and then condensed and recovered, leaving dried and cleaned solids (cuttings) that can be disposed of. This method can allow the stringent HSE requirement in the hostile and remote Arctic areas to be assured.

Further, when OBM is used, slurry injection is the other alternative offshore disposal practice for drilling operations in the Arctic. The slurry injection technology involves grinding or processing the solids into small particles, mixing them with water or some other liquid to make a slurry, and injecting the slurry into an underground formation at pressures high enough to fracture the rock (Sirevag and Bale, 1993). The two most common forms of slurry injection are annular injection and injection into a disposal well (Nagel, 2005). Annular injection introduces the waste slurry through the space between two casing strings (known as the annulus); and the disposal well alternative involves an injection to either a section of the drilled hole that is below all casing strings, or to a section of the casing that has been perforated with a series of holes at the depth of an injection formation (Veil and Dusseault, 2003). For instance, on the Norwegian Continental Shelf (NCS), especially in the North Sea, re-injection of drilling waste into a dedicated well is one of the common practices (Nagel, 2005). For further details about the experiences with cutting re-injection in North Sea shale and the dos and don’ts in drilling waste injection, see e.g. Nagel (2005), Sirevag and Bale (1993) and Guo and Nagel (2009).

Different types of rocks have different permeability characteristics; slurry injection relies on fracturing and the permeability of the formation receiving the injected slurry (Nagel, 2005, Puder et al., 2003). Most annular injection jobs inject into shale or other low-permeability formations, and most dedicated injection wells inject into high-permeability sand layers (Puder et al., 2003). In spite of the type of rock selected for the injection formation, preferred sites will be overlaid by formations having the opposite permeability characteristics (high vs. low) (Veil and Dusseault, 2003, Puder et al., 2003).

Even though slurry injection is regarded as an effective approach for cuttings disposal, the process has associated risks and uncertainties (Guo and Nagel, 2009). For instance, some of the main hazards related to the slurry injection process are fracture growth, communication of the induced fracture with existing wells in the field, wellbore failure (wellbore instability), and the presence of local faults/fractures (the proximity of faults close to the injection/disposal zone has the potential for serious problems) (Guo et al., 2005). The impact of well intersection is that the annular pressure will increase to the fluid fracturing pressure; and the main risk associated with the high pressure on the annulus at the wellhead is a leak in one of the casings near the surface or at the wellhead, which would cause environmental contamination of the sea or a shallow formation (Guo et al., 2005). Hence, to eliminate or reduce the impact, the injection well or the disposal zone should be at least 200 m from local faults/fractures as well as any nearby well (Rutqvist et al., 2015).

Furthermore, under certain circumstances, the increased pore pressure resulting from the drilling waste re-injection process can trigger earthquakes (Nicholson and Robert, 1990). Consequently, as a result of the earthquake, the wellbore stability can be affected and in the worst case the wellbore may collapse (Nicholson and Robert, 1990). Thus, in such situations, the environmental contamination of the sea, especially in the Arctic, can be significant.

The other common problem related to slurry injection is operations-related challenges such as plugging of the casing or piping because solids have settled out during or following injection; excessive erosion of casing, tubing, and other system components caused by pumping solids-laden slurry at high pressure (Puder et al., 2003). Hence, for a successful re-injection process, the operators should evaluate the re-injection technique comprehensively. Further, when determining the cost-effectiveness of slurry injection, the three critical factors that need to be considered are (Veil and Dusseault, 2003): *i)* the volume of material to be disposed of – the larger the volume, the more attractive injection becomes in many cases; *ii)* the regulatory climate – the stricter the discharge requirements, the greater the likelihood that slurry injection will be cost-effective; *iii)* the availability of low-cost onshore disposal infrastructure.

In addition to the above offshore disposal methods, the operator can evaluate other suitable and applicable techniques to handle and manage the drilling waste. When the evaluation to dispose offshore is finalised, the result will possibly suggest two choices: *i)* offshore disposal of the drilling waste can be the favoured option, or *ii)* offshore disposal might not be suitable, then hauling the drilling waste back to shore could be the next available option.

Step 3: Assessing whether or not onshore disposal option is applicable and suitable

Onshore disposal: At this stage, different types of onshore drilling waste handling systems, such as landfill, composting, bioremediation methods, etc. need to be evaluated. When considering the onshore disposal alternatives, the first step is to explore the availability of onshore commercial drilling waste treatment and disposal facilities within a cost-effective radius. In other words, for the waste transportation cost to be manageable, the onshore disposal facilities must generally be located within an 80- to 120-kilometre radius from the nearest shore – which can be the main hub for oil and gas related activities in the region (US Department of Energy, 2000).

In the absence of drilling waste treatment and disposal facilities, the building of infrastructure needs to be assessed on a site-by-site basis. This will help to make the investment to build infrastructure worthwhile (Heather et al., 2013). For example, before the construction of a closed landfill cell in the region, the operator should assess and determine the most suitable method of lining the pit to prevent fluid seepage. Moreover, to ensure any seepage is detected and to take appropriate corrective action before any further damage occurs, careful monitoring procedures need to be established. Furthermore, the ice-infested water that accumulates in the open landfill cell due to the melting of snow during the spring should be removed to reduce the hydraulic head in the landfill cell (IUCN, 1993). Table 2 summarises the advantages and disadvantages of several onshore as well as offshore disposal techniques.

((Table 2))

Step 4: Decision making and monitoring

Finally, after a detailed assessment and comparative analysis of available techniques, the operator should make a decision and request permission from the regulators. The regulator will assess the permit request and also study and map the specified area. The specified area is the area in which the drilling and disposal activity will take place. Then, the regulator will or will not allow the proposed drilling waste handling practice. If the decision from the regulators allows the operator to apply the proposed drilling waste management plan, then the operator has to follow, implement, and monitor the plan. However, if the regulators do not allow the proposed plan to go ahead, then the operator has to re-assess and prepare another plan and submit it to the regulators for further evaluation. Once a decision is made, the next step is to monitor or follow up the overall drilling waste handling process and to ensure the fulfilment of the HSE requirement at every step of the process.

4. Illustrative case study

The proposed methodology will be demonstrated for offshore drilling, for the Johan Castberg oil and gas field (formerly Skrugard and Havis) located in the Barents Sea. The field is about 100 km north of Snøhvit, 150 km from Goliat and nearly 240 km from Melkøya, all in the Barents Sea, northern Norway. The development concept includes a floating production unit with a 280-kilometre pipeline to shore and a terminal for oil from the Johan Castberg field at Veidnes outside Honningsvåg in Finnmark, northern Norway (Statoil, 2011). Figure 3 illustrates the location of the field and other nearby oil and gas fields in the Norwegian part of the Barents Sea.

((Figure 3))

The descriptions and data, for the illustrative case study are based on the application for a permit to drill appraisal and production wells by Statoil (2011) and by EniNorge (2012) as well as a permit report from the Norwegian Climate and Pollution Agency (2010).

Defining company goals and criteria

The bottom line principle in the Barents Sea is that the oil and gas exploration activities shall be at least as safe as in the North Sea (Det Norske Veritas, 2009). For the appraisal well drilling, waste management goals and objectives are formulated to comply with: *i)* the Norwegian law of protection against pollution and waste (the Pollution Control Act, Chapter 2, §4 and Chapter 3, §11), *ii)* requirements for risk management during petroleum exploration (Petroleum Safety Authority Management Regulations, § § 3-6) and *iii)* to achieve zero 'hazardous' discharge.

Identification of influencing factors and formulation of impact reduction measures

Among the challenges identified, the most critical operations and technological challenges are summarised in Table 3. To combat these challenges, the development of a realistic barrier, as well as the reinforcement of the available barriers, has been carried out. These barriers can be technical, administrative, and organisational in nature. To address the impact of cold exposure on the waste handling personnel, the careful development of cold weather clothing materials, taking into consideration the tasks to be performed and the environmental conditions, has been suggested. This can guarantee comfortable sensations and good performance during exposure to cold weather (Ayele et al., 2015). To assure the system performance requirements, the drilling waste handling system has been designed to handle the cold climate and the significant variations in temperature within short periods of time.

((Table 3))

Waste minimisation and/or reduction practices

As part of the drilling waste reduction principle, the drilling fluid providers are requested to present a cradle-to-grave solution when bidding for contracts. In the cradle-to-grave solution, used drilling fluid is sold back to the supplier for reconditioning; it can then be resold to the operator after reconditioning at the same price as the new fluid (Paulsen et al., 2002). This practice, therefore, can help to significantly minimise the drilling waste, and the need for drilling waste disposal facilities will be reduced. Figure 4 shows the overview of the cradle-to-grave principle for drilling fluids.

((Figure 4))

Waste type description (classification)

The categorisation of the chemical usage for drilling activities in the Johan Castberg field is based on the Norwegian Petroleum Safety Authority Activities Regulations Chapter XI, §§ 62-63. During the appraisal drilling, all sections are drilled using water-based drilling fluids. The fluid is composed primarily of brine, bentonite and weight material (barite). All these chemicals are green and listed as PLONOR (Pose Little or No Risk to the environment) chemicals. In addition, there is usage of a limited amount of yellow chemicals – chemicals that, although not included in the PLONOR list, have an acceptable environmental impact. Moreover, there is no usage of chemicals in the red or black categories in the drilling operation as well as no usage of oil/synthetic-based drilling fluids. Red chemicals are chemicals that should be replaced according to Norwegian Climate and Pollution Agency (CPA) criteria. Black chemicals can only be discharged in exceptional cases by acquiring a special permit from the CPA. Table 4 shows the summary of the proposed chemical consumption during the preparation of the drilling mud (mud formulation) in the course of the exploratory drilling.

((Table 4))

Exploring offshore disposal options

The main offshore disposal techniques such as discharge of drilling waste into the sea and re-injection of the waste (waste contaminated with formation oil) into the underground formation have been evaluated. Generally, the cost of treating and discharging drilling waste is lower than the cost of re-injecting or hauling it back to shore (US Department of Energy, 2000). Hence, for the Johan Castberg appraisal, the option of discharge into the sea has been evaluated thoroughly, to reduce the overall waste handling cost.

In order to be able to discharge the drilling waste into the Barents Sea, the chemicals' constituents for the drilling mud formulation are selected based on the environmental and safety criteria of the Norwegian Climate and Pollution Agency. Table 5 shows the overview of well sections, the proposed type of drilling fluid, the total estimated amount of drilling fluids and cuttings to be discharged into the sea.

((Table 5))

Assessing the applicability of the offshore disposal option

To reduce the effect of the waste handling operation on local benthic fauna and the marine environment, an environmental impact assessment for the planned drilling and waste handling activity has been carried out. The assessment and monitoring survey results showed that, during the top-hole section drilling, as a result of the accumulation of muds and cuttings, it can be expected that a 10 to 100-cm-thick sediment layer thus bottom community will most likely decimate in this vicinity (near the well). For the lower sections' drilling, the waste has been released from the rig and the cuttings spread on its way through the water column to such an extent that it becomes difficult to find traces of it on the seabed. Lose particles could spread far from the site of the discharge; however, it will be diluted in the waters and will hardly be differentiated from the natural sedimentation in the area. Several studies showed that the environmental effects from the use of water-based drilling fluids are limited to a distance of 25 – 50 metres from the well location (Neff, 1987). Moreover, Statoil ASA (2007) results illustrated that cuttings will be distributed depending on current strength and direction, probably within a few tens of metres from the drilling well. Furthermore, the study shows that the new masses, new bottom surface and the recolonisation will start within the following year Statoil ASA (2007).

Hence, the plan to make use of water-based drilling fluid and to discharge the drill cuttings into the Barents Sea was submitted to the Norwegian Climate and Pollution Agency. Then the agency assessed: *i)* the planned discharge rates and durations, *ii)* the amount of drilling waste to be discharged, and *iii)* the vulnerability of the ecosystem to such a discharge. The assessment covers an area within a 65 km zone around Bjørnøya (Island in Barents Sea located at 74º30'N 19º00'E) which is defined as particularly valuable and vulnerable according to the management plan of the Norwegian Parliament Report No. 8 (2005-2006). The exploration wells in the Johan Castberg field are located at 145 km from this site. After comprehensive assessment and mapping of the surroundings of the Johan Castberg field, the result from the agency showed that there are no coral or other especially vulnerable fauna around the drilling activity area. In addition, the presence of fish eggs and larvae during the drilling period was unlikely.

Based on the results of the assessment and in accordance with 'zero' harmful discharge, the discharge of cuttings from the drilling activity will only affect an area of small spatial extent. Therefore, the Norwegian Climate and Pollution Agency permits the discharge of drilling waste fluids, drill cuttings as well as drilling chemicals into the Barents Sea.

However, to fully demonstrate the proposed methodology, the steps required to assess and explore various onshore waste handling systems are presented.

Assessing the availability of cost-effective onshore commercial disposal facilities

For the Johan Castberg case, the nearest onshore commercial waste treatment and disposal facilities are located in Hammerfest, northern Norway, around 280 km from the field. The operator examines the cost-effectiveness of sending the 'hazardous' waste from the drilling activities to these onshore commercial waste treatment facilities or building an infrastructure that can handle the generated waste. The result suggests that it is cost-effective to make use of the available commercial facilities, for the 'hazardous' waste, including waste contaminated with formation oil.

Evaluating the possibility of building an onshore waste treatment and disposal facility

To minimise the risk of future liability, in the absence of onshore disposal facilities, the operator has to explore the possibility of building its own onshore disposal facility. This has to be carried out as per compliance with the defined company goals, criteria and governing regulations. For the Johan Castberg field development case, the result recommends that it is better to send the 'hazardous' waste to the commercial facilities, to eliminate the responsibility of building, operating, and closing an on-site disposal facility.

Exploring various options to transport the waste to other disposal locations

In the case of the unavailability of cost-effective onshore commercial disposal facilities and due to the unsuitability of building a new disposal facility, the operator has to investigate the cost-effectiveness of transporting the drilling waste to another disposal location. For the Johan Castberg field development case, there is no need to transport the drilling waste to some other location.

Decision making

For the Johan Castberg appraisal drilling, discharge of the drilling waste fluids and cuttings into the sea has been selected and implemented as the most cost-effective and environmentally sound offshore disposal technique.

Monitoring (follow-up)

In the Arctic, operating conditions are expected to vary within a short period of time, and the monitoring process needs to check the frequently changing requirements. Thus, for the Johan Castberg project, monitoring (follow-up) of the performance of the chosen drilling waste handling system and the overall waste handling process places emphasis on what does work, what does not work, and what continues to work.

5. Concluding remarks

To comply with stringent waste-discharge requirements and assure operational performance, waste handling, treatment, and disposal techniques should be selected based on the goals of assuring the environmental compliance and minimising the volume of disposal waste. In this paper, a methodology for identifying a suitable drilling waste handling system in the Arctic region has been proposed. The proposed methodology helps the user to identify a suitable waste handling system for the region's offshore drilling activities, which assures the operational performance with a low level of environmental impact. Further, it also helps to assess the fulfilment of local statutory legislation and requirements as well as international standards, while developing the waste management plan that will result in more efficient operations and improved environmental protection. The illustrative case study demonstrates the step-by-step procedures required for making a decision and choosing the most suitable drilling waste handling system in the Arctic. The result of the case study illustrates that, for the Johan Castberg oil field development project, the most suitable drilling waste handling system is offshore discharge. The recommendation is based on the consideration that each well is drilled with water based drilling fluids only containing chemicals selected from the Pose Little or No Risk to the Environment (PLONOR) list of chemicals.

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References

Ayele, Y.Z., Barabadi, A. and Barabady, J. (2013a) 'Drilling waste handling and management in the High North'. *IEEE International Conference on Industrial Engineering and Engineering Management (IEEM).* 10-13 Dec. 2013, pp. 673-678.

Ayele, Y.Z., Barabadi, A. and Barabady, J. (2015) ‘A risk-based approach to manage the Occupational Hazards in the Arctic drilling waste handling practices.' Safety and Reliability: Methodology and Applications - *Proceedings of the European Safety and Reliability Conference, ESREL 2014*. pp. 1329-1334.

Ayele, Y.Z., Barabadi, A. and Markeset, T. (2013b) 'Spare part transportation management in the High North'. *Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions.* Espoo, Finland.

Barabadi, A. (2014) 'Reliability analysis of offshore production facilities under Arctic conditions using reliability data from other areas. *Journal of Offshore Mechanics and Arctic Engineering,* Vol. 136, 021601.

Barabadi, A., Gudmestad, O.T. and Barabady, J. (2015) 'RAMS data collection under Arctic conditions', *Reliability Engineering and System Safety*, Vol. 135, pp.92-99.

Barabadi, A. and Markeset, T. (2011) 'Reliability and maintainability performance under Arctic conditions.' *International Journal of System Assurance Engineering and Managemen*t, Vol. 2, pp. 205-217.

Bilstad, T., Stenberg, E., Jensen, B., Larsen, T. and Toft, M. (2013) 'Offshore drilled cuttings management', *AGH Drilling, Oil, Gas,* Vol. 30.

Boesch, D.F. and Rabalais, N.N.(eds.) (2003) *Long-term Environmental Effects of Offshore Oil and Gas Development*, CRC Press.

Canada Environmental Studies Research Fund (2004) *Drilling Waste Management - Recommended Best Practices*.

Dahl, B., Saasen, A. and Omland, T.H. (2006) 'Successful drilling of oil and gas wells by optimisation of drilling fluid solids control-a practical and theoretical evaluation', *IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition*, *2006*. Society of Petroleum Engineers.

Dahl, B., Saasen, A. and Omland, T.H. (2012) 'Optimised solids control in Arctic environments', *SPE Russian Oil and Gas Exploration and Production Technical Conference and Exhibition, 2012*. Society of Petroleum Engineers.

Det Norske Veritas (2009) *Barents 2020: Assessment of International Standards for Safe Exploration, Production and Transportation of Oil and Gas in the Barents Sea.* Det Norske Veritas (DNV).

Eni Norge. (2012) [Online]. 'Application for Permission to Commercial for Pollution Act for appraisal and Production Drilling in PL 229 Goliat' (In Norwegian) Available: http://www.klif.no/nyheter/dokumenter/horing/horing2012-322_soknad.pdf [Accessed 21/06 2013].

Glickman, A., Piper, W. and Ivan, C. (2008) 'Establishing an environmental performance standard and waste management toolbox for offshore drilling discharges', *SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, 2008*.

Guo, Q., Geehan, T. and Pincock, M. (2005) 'Managing risks and uncertainties in drill cuttings re-injection in challenging environments–field experience from Sakhalin Island'. SPE 93781, paper presented at the S*PE/EPA/DOE E&P Environmental Conference*. March 2005 Galveston.

Guo, Q. and Nagel, N.B. (2009) 'AADE 2009-NTCE-16-01: Do's and Don'ts in drilling waste injection with case examples'. *2009 National Technical Conference and Exhibition.* New Orleans, Louisiana.

Hasle, J.R., Kjellén, U. and Haugerud, O. (2009) 'Decision on oil and gas exploration in an Arctic area: case study from the Norwegian Barents Sea', *Safety Science,* Vol. 47, pp.832-842.

Heather, A.C., David, L.P., Terence, M.T. and Mihaela, D. (2013) *Arctic economics in the 21st century: the benefits and costs of cold*. A report of the CSIS Europe Program. Center for Strategic and International Studies.

IUCN (1993) 'Oil and Gas Exploration and Production in Arctic and Subarctic Onshore Regions: Guidelines for Environmental Protection'. E&P Forum. Gland, Switzerland and Cambridge UK.

Jodestol, K. (2010) 'Will drill cuttings and drilling mud harm cold water corals?' *SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, 2010*. Society of Petroleum Engineers.

Jonathan, R. and Emma, J. (2010) *Environmental Impact Assessment Tools and Techniques.* [online] http://green-recovery.org/wordpress/wp-content/uploads/2010/11/Module-3-Content-Paper.pdf (Accessed 20 April 2014).

Kayrbekova, D., Barabadi, A. and Markeset, T. (2011) 'Maintenance cost evaluation of a system to be used in Arctic conditions: a case study.' *Journal of Quality in Maintenance Engineering,* Vol. 17, pp. 320-336.

Kroken, A., Vasshus, J.K. and Grelland, T. (2014) 'Drilling waste reduction and improved HSE on Maersk giant utilising revolutionary lightweight vacuum conveyor system'. *Offshore Technology Conference-Asia, 2014*.

Markeset, T. (2008) 'Design for high performance assurance for offshore production facilities in remote harsh and sensitive environments.' *OPSEARCH,* Vol. 45, p. 275.

Martin, A. (2004) 'Drilling waste handling.' Patents, USA.

Melton, H., Smith, J., Mairs, H., Bernier, R., Garland, E., Glickman, A., Jones, F., Ray, J., Thomas, D. and Campbell, J. (2004) 'Environmental aspects of the use and disposal of non aqueous drilling fluids associated with offshore oil & gas operations'. *SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, 2004.*

Murray, A.J., Kapila, M., Ferrari, G., Degouy, D., Espagne, B.J.-L. and Handgraaf, P. (2008) 'Friction-based thermal desorption technology: Kashagan development project meets environmental compliance in drill-cuttings treatment and disposal'. *SPE Annual Technical Conference and Exhibition, 2008*. Society of Petroleum Engineers.

Nagel, N. (2005) '4,000,000 Barrels and Counting: Experience with Cuttings Reinjection in North Sea Shales.' *ARMA/USRMS, 05-782.*

Neff, J.M. (1987) 'Biological effects of drilling fluids, drill cuttings and produced waters', in Boesch, D.F. and Rabalais, N.N. (Eds.), *Long-term Environmental Effects of Offshore Oil and Gas Development*, CRC Press, pp.469-538.

Nicholson, C. and Robert, L.W. (1990) 'Earthquake hazard associated with deep well injection: a report to the U.S. Environmental Protection Agency I by Craig Nicholson and Robert L. Wesson', *U.S. Geological Survey Bulletin.*

Olsen, G.H., Carroll, J., Dahle, S., Larsen, L.-H. and Camus, L. (2011) 'Challenges performing risk assessment in the Arctic', in Lee, K. and Neff, J. (eds.), *Produced Water,* Springer.

Patel, A., Stamatakis, S., Young, S. and Friedheim, J. (2007) 'Advances in inhibitive water-based drilling fluids—can they replace oil-based muds?' *International Symposium on Oilfield Chemistry, 2007*. Society of Petroleum Engineers.

Paulsen, J., Norman, M. and Getliff, J. (2002) 'Creating near-zero discharge in Norway: a novel environmental solution', *World Oil*, Vol. 223, pp.37-41.

Paulsen, J.E., Hoset, H., Rørhuus, T., Larsen, V., Alm, D., Birkeland, O. and Marker, R. (2005) 'Exploration drilling in the Barents Sea; prevailing zero discharge regime challenges and learning from two recent exploration wells'. *SPE Asia Pacific Health Safety and Environment Conference and Exhibition, 2005.* Society of Petroleum Engineers.

Puder, M.G., Bryson, B. and Veil, J.A. (2003) 'Compendium of Regulatory Requirements Governing Underground Injection of Drilling Wastes.' Argonne National Laboratory for the U.S. Department of Energy, National Petroleum Technology Office.

Rutqvist, J., Rinaldi, A.P., Cappa, F. and Moridis, G.J. (2015) 'Modeling of fault activation and seismicity by injection directly into a fault zone associated with hydraulic fracturing of shale-gas reservoirs', *Journal of Petroleum Science and Engineering*.

Sirevag, G. and Bale, A. (1993) 'An improved method for grinding and reinjecting of drill cuttings.' *SPE/IADC 25758.*

Sollund, S. (2007) 'Environment taxes.' *Introductory presentation on Agenda, 2.*

STATOIL (2011) *Søknad om Tillatelse til Virksomhet etter Forurensingsloven for Letebrønn Skrugard Appraisal'* [online] http://www.klif.no/nyheter/dokumenter/horing2011-1597_soknad.pdf Accessed 21 June 2013).

STATOIL ASA (2007) 'Summary of SERPENT work 2006.'

Sustainable and Ecological Management Working Group (2014) *Sustainable and ecological management of stone resources and products.* [online] http://www.stonecourses.net/environment/benelca.html (Accessed 20 April 2014).

Svensen, T. and Taugbol, K. (2011) 'Drilling waste handling in challenging offshore operations.' *SPE Arctic and Extreme Environments Conference and Exhibition, 2011.*

The Norwegian Climate and Pollution Agency (2010) O*versendelse av Tillatelse etter Forurensningsloven* [Boring av Letebrønn 7220/8-1, Skrugard, PL 532]. Klima og Forurensnings Direktoratet.

US Department of Energy (2000). *The Drilling Waste Management Technology Descriptions* [Online]. Argonne National Laboratory and Industry Partners, ChevronTexaco and Marathon, under the U.S. Department of Energy's (DOE's) Natural Gas & Oil Technology

Partnership Program. Available: http://www.roughneckcity.com/uploads/Drilling_Waste_Management_Technology_1_.pdf [Accessed 12.05 2013].

Veil, J.A. and Dusseault, M.B. (2003) 'Evaluation of slurry injection technology for management of drilling wastes.' Argonne National Laboratory for the U.S. Department of Energy, National Petroleum Technology Office.

Zahorsky, D. (2013) *The 5 Steps to Setting SMART Business Goals.* [online] http://sbinformation.about.com/od/businessmanagemen1/a/businessgoals.htm (Accessed 24 August 2013).

Table 1. Water based fluids (mud) vs. oil based fluids (mud), modified from Patel et al. (2007)

Type of drilling fluid	Pros	Cons
Water based mud	▪ Minimum environmental impact - Reduced offshore liability - Reduced disposal cost ▪ Lower lost circulation potential ▪ Formation evaluation (logging) ▪ Kick detection ▪ Less expensive than oil based mud	▪ Potential for formation damage ▪ Borehole instability concern
Oil based mud	▪ Thermal and wellbore stability ▪ Lubricity ▪ Lower stuck pipe potential ▪ CO_2 and H_2S tolerance ▪ Solids tolerance ▪ Non-corrosive	▪ Environmental concerns - Toxic compounds - Slow degradation rates ▪ Occupational hazard concern - High vapour emissions - Aromatic hydrocarbons in the vapour are considered carcinogens ▪ Low kick detection ▪ High initial cost ▪ Formation evaluation (some wireline logs are not functional in OBM)

Table 2. Pros (+) and cons (-) of the common offshore and onshore disposal options in the Arctic, modified from Melton et al. (2004)

	Option	Economics	Operational	Environmental
Offshore Disposal	**Offshore discharge**	(+) Low cost per unit volume treated (+) No potential liabilities at onshore facilities (-) Potential future offshore liability (-) Cost of analysis of discharges and potential impacts (e.g. compliance testing, discharge modelling, field monitoring programs)	(+) Simple process with little equipment needed (+) No transportation cost involved (+) Low power and personnel requirements (+) Low safety risk (+) No shore-based infrastructure required (+) No additional space or storage requirements (+) No weather restriction (-) Management requirements of fluid constituents (most of the constituent chemicals should be from Pose Little or No Risk to the Environment (PLONOR) green list)	(+) No incremental air emissions (+) Low energy usage (+) No environmental issues at onshore sites (+) Low CO_2 emissions (-) Potential for short-term localised impacts on seafloor biology (benthic communities) (-) Lack of sufficient knowledge to determine the impact on benthic ecosystem (-) The accumulation of muds and cuttings could damage the seafloor and local ecosystem (creating "dead zones")
	Re-injection	(+) Enables use of a less expensive drilling fluid (+) No offsite transportation needed (+) Ability to dispose of other waste that would have to be taken to shore for disposal (–) Expensive and labour-intensive (–) Shutdown of equipment can halt drilling activities	(+) Cuttings can be injected if pre-treated, and proven technology (–) Extensive equipment and labour requirements (–) The application requires receiving formations with appropriate properties (–) Casing and wellhead design limitations (–) Over-pressuring and communication between adjacent wells (–) Variable efficiency (–) Difficult for exploration wells due to lack of knowledge of formations	(+) Elimination of seafloor impact (+) Limits possibility of surface and ground water contamination (–) Increase in air pollution due to large power requirements (–) Possible breach to seafloor if not designed correctly

Onshore Disposal	**Common to all onshore options**	(–) On-land transportation costs (–) Potential future liabilities (+) Waste can be removed from drilling location, eliminating future liability at the rig site	(–) Onshore transport to site (–) Safety risk to personnel and local inhabitants in transport and handling (–) Disposal facilities require long-term monitoring and management (–) The movement of heavy equipment and supplies around the site may lead to considerable terrain disturbance	(+) Reduces impact to the seafloor and biota (–) Potential for onshore spills (–) Air emissions and solid waste generation associated with transport and equipment operation
	Re-injection	(–) Expensive if existing site not available (–) Long-term liability	(–) Requires suitable geological formations (–) Requires suitable facilities	(–) Possible impact on groundwater (–) Air emissions from equipment use (–) Long-term liability
	Landfill	(+) Inexpensive relative to re-injection, thermal processing and incineration (–) Potential future liabilities of surface and ground water impact	(–) Requires appropriate management and monitoring; may have requirements on maximum oil content of waste (–) Land requirements	(–) Potential groundwater and surface water impact (–) May be restrictions on the oil content of waste (–) May be limited by local regulations
	Composting	(+) Inexpensive relative to re-injection, thermal processing and incineration (–) Potential future liabilities of surface and ground water impact (–) More costly than land-spreading	(+) Requires limited space and equipment (+) More rapid biodegradation than land-farming (+) More efficient in cold climates (–) Requires substantial handling	(+) Minimal potential for groundwater impact (+) Biodegradation of hydrocarbons (–) Air emissions from equipment use and off-gassing from degradation process (–) Runoff in areas of high rain may cause surface water contamination

Table 3. The most critical operational and technological challenges during the waste handling of Johan Castberg appraisal drilling

Challenges	Description
Remoteness	- Remoteness of the sub-Arctic creates several critical challenges which directly impact safety of waste-handling personnel. These include communication problems due to lack of IT infrastructure and satellite coverage, emergency response and contingencies, supply, and working condition. - Logistics can be very challenging, and waste handling equipment reliability is a major concern. Special considerations need to be paid to logistics requirements with respect to selection, transportation and storage of resources such as material and personnel (Markeset, 2008). - Due to remoteness of the location, rescue operation will be difficult and costly if any accident happens; distance to market, manufacturers and spare parts suppliers is also a critical challenge (Markeset, 2008).
Harsh climate and environmental conditions	- The climate is cold with significant variations in temperature within short periods of time; these temperature variations may create additional challenges (such as a direct effect on the crane operation during handling of drilling waste) and also will involve a higher degree of improvement maintenance than we have in other places in the world. - The extremely sensitive ecosystem of the Barents Sea presents real challenges in order to minimise the total offshore discharge and emissions to the environment and to preserve the Arctic deep-water ecosystem. - The presence of rare &endangered species, fisheries, and the slow environmental impact recovery make the Barents Sea an environmentally sensitive area.
Winter darkness (Polar night)	- Some people's emotions are simply more vulnerable to weather changes than others. Someone prone to a low mood on dark, cold days will likely experience a depressive winter when there is a prolonged string of similar days in terms of weather. - In the Barents region winter days are characterised by less or no sunlight and extreme coldness and you start feeling gloomy. Darkness reduces the operational effectiveness and decision-making ability, and it causes discomfort from cold stiff hands and feet, runny nose and shivering (Markeset, 2008). This can cause more human errors and unexpected damage.
Technical	- Some of the expected technical challenges while operating in the Barents Sea (Markeset, 2008) are: - Embrittlement of steel, plastics and composites causing failures at loads that are routinely imposed without damage in a warmer climate. - Increased energy requirements for routine operations and higher fuel consumption due to greater rolling resistance. - Generation of static electricity that can destroy computers and control circuitry.

Table 4. Proposed chemical consumption during the mud formulation (Statoil, 2011)

Type of chemical	Total consumption amount (tons)	Estimated discharge into the sea (tons)
Green chemicals	1466.2	753.8
Yellow chemicals	88.3	28.2

Table 5. Summary of total proposed amount of discharge of drilling fluid and drill cuttings (Statoil, 2011)

Section	Type of drilling fluid	Discharge into the sea	
		Drilling fluid [m³]	Drill cutting [m³]
9 7/8¨ (Pilot Hole)	Seawater w / high viscosity chemicals	298	22
36¨	Seawater w / high viscosity chemicals	227	41
26¨	Seawater w / high viscosity chemicals	567	89
	KCI/GEM/Polymer	206	85
17 1/2¨	Seawater w / high viscosity chemicals	666	61
12 1/4¨	KCI/GEM/Polymer	105	84
8 1/2¨	KCI/GEM/Polymer	129	21
Total		2198	403

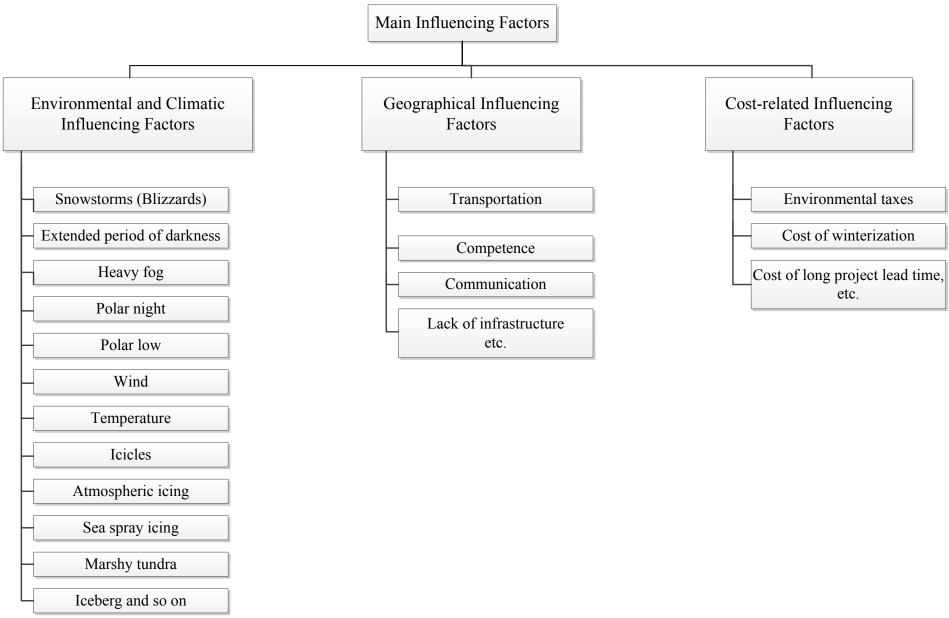

Figure 1. Overview of factors that can influence the drilling waste handling system in the Arctic

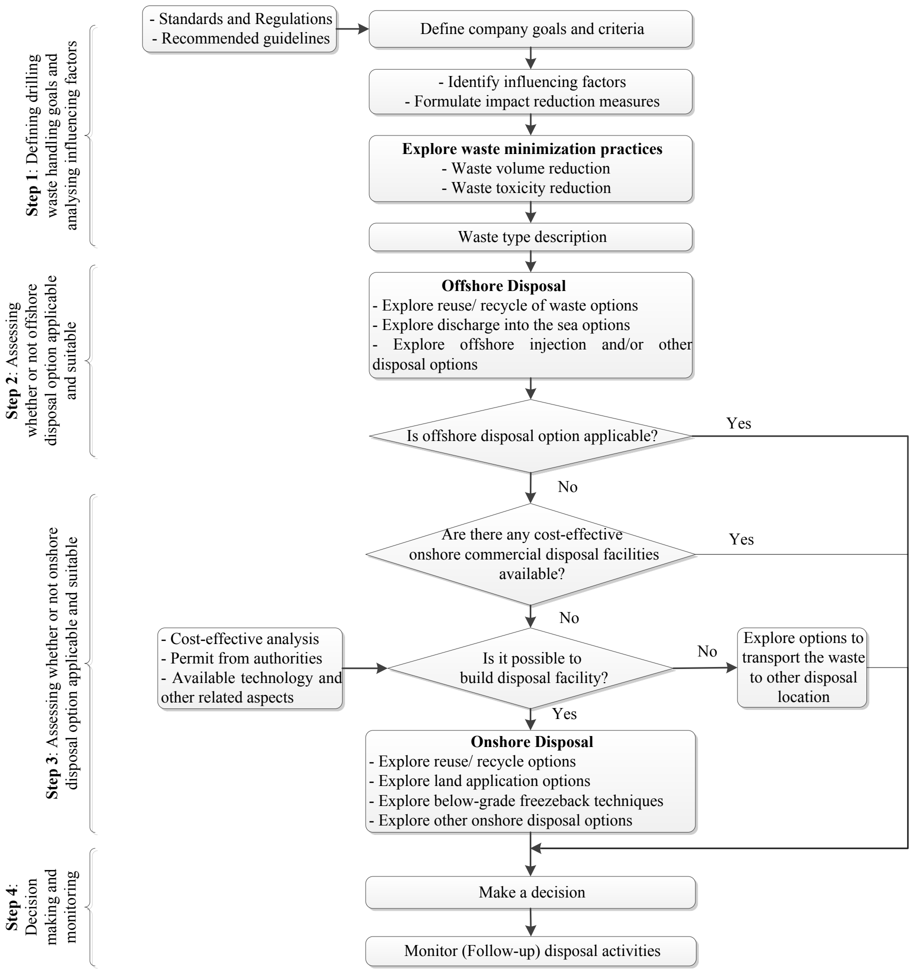

Figure 2. Proposed methodology for identifying suitable drilling waste handling systems for offshore drilling activities in the Arctic region

Figure 3. Johan Castberg (Skrugard and Havis) Field © Google Earth

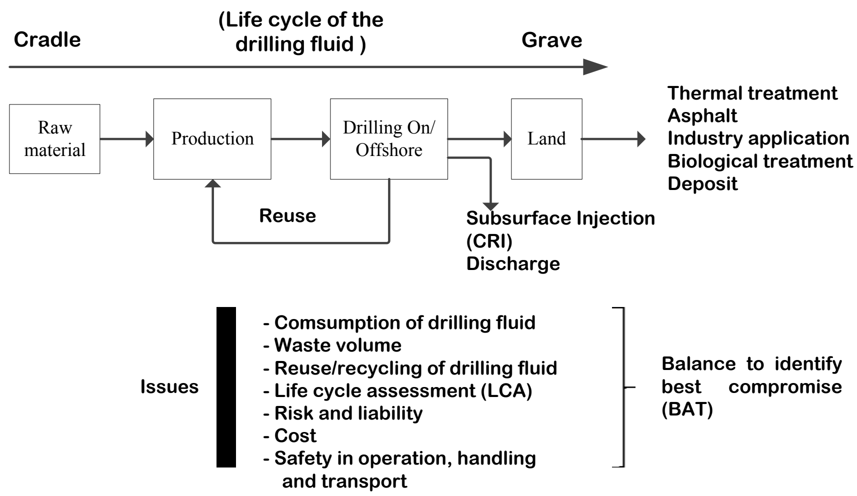

Figure 4. Schematic of cradle-to-grave principle, adapted from Paulsen et al. (2002)