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DRILL CUTTING AND WASTE INJECTION ASSURANCE IN THE BARENTS SEA

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ABSTRACT
The increase in drilling and exploitation of oil and gas resources in the Barents Sea has raised concerns regarding the pollution of the marine environment from drilling waste discharges into the sea. Drilling waste is mainly comprised of drill cuttings that are transported to the surface, and drilling fluid used for drilling wellbores. Integrated waste management practices then need to be in place to reduce the pollution risks associated with drilling operations. Various options are available for handling waste, such as reuse, recycling and disposal - all of which rely on transporting the waste to the shore. In addition to the high costs and requirements for establishing waste handling infrastructure in remote locations, there is a risk of waste discharge into the sea associated with transporting waste to shore. Waste re-injection is another widely practiced solution that entails injecting the drilling waste into the appropriate subsurface formations. The complexity of waste injection requires an integrated operation, especially in the Barents Sea due to the severe weather conditions and their associated uncertainties. The aim of this paper is to discuss the various factors that need to be considered for a reliable waste injection operation, including the surface and subsurface associated risks. Handling such risks is vital to developing a reliable injection operation and avoiding rig downtimes**.**

INTRODUCTION
The Barents Sea is recognised as a shallow-water ecosystem, which is of the richest oceanic areas in the world and among the most productive regions in the Arctic marginal seas. It has a high biological production of fish and mammals. It is among the most environmentally sensitive areas in the Norwegian Continental Shelf (NCS) that plays key roles in Norway economy. It provides an important habitat for a variety of sea birds (Matishov et al., 2004, Sakshaug et al., 1994). In this regard, sea pollution has become of the main environmental concerns as oil and gas companies are expanding their operations in the Barents Sea. Produced water as well as drill cuttings and waste are among the major contaminants entering the sea from regular oil and gas operations.

Until the mid-1990s, the discharge of cuttings with oil-based drilling mud was the main source of hydrocarbon-type pollution of the North Sea in NSC (Bakkea et al., 2013). In 1996, the concept of zero discharge was introduced in the White Paper No. 58, requiring that the new field developments must avoid harmful discharges into the NCS (Ministry of the Environment, 1997). Some treatments are then required to clean the wastes and meet the environmental regulations before any discharge into the sea. However, there are still some contaminants and wastes, which must be shipped to the shore for further treatment and disposal. Considering the remote locations of oil and gas drilling platforms in the Barents Sea and its severe weather conditions, waste transportation to the shore faces a variety of risks. High transportation costs and permanent disposal of wastes in areas with less-developed infrastructures are other concerns with regard to this waste handling option.

Drill cuttings and waste injection (WI) is a another waste handling option that is defined as the injection of the drill cuttings and other wastes generated during drilling operation as a slurry into the selected subsurface formations through one of the pre-drilled wellbores. This method is often considered as the most preferred waste disposal technology in terms of cost effectiveness and environment compatibility in remote and environmentally sensitive regions. Hereafter the term waste is used to refer to the drill cuttings and other types of wastes produced during a drilling operation, such as mud, water used for cleaning the rig floor, collected rain and snow on the platform, etc.

WI is performed by applying an injection pressure and initiating a disposal fracture in the formations, where the waste slurry is pumped into (Gumarov et al., 2012, Shokanov et al., 2007). Most importantly, in this method, while eliminating the risks associated with other alternatives, wastes and cuttings are disposed permanently in the subsurface (Gumarov et al., 2012, Louviere and Reddoch, 1993). Besides, in the remote Arctic locations, where sea ice restricts ship-to-shore options, WI can present opportunities for a year-round drilling operation as this technology handles the waste as the produce (Guo et al., 2005).

However, to perform a successful WI operation, a number of factors must be studied carefully, such as the volume of waste and drill cuttings, their chemical and physical properties, subsurface characteristics, surface facilities (Guo et al., 2005, Paulsen et al., 2005, Shokanov et al., 2007). In this view, a WI operation requires a well-integrated teamwork involving surface facility engineers, drilling engineers, production engineers, geologists, economists and environmentalists.

In the Barents Sea, WI assurance requires additional considerations due to the uncertainties in the severe weather conditions such as snowdrifts, icing events, low temperatures, polar low pressures, winds, sea ice and icebergs, etc. The high cost of operation in such remote locations with harsh operating conditions requires a year-round drilling operation. In this regard, providing a reliable WI operation is of crucial importance. In 2007, 2009, and 2010, several large waste spills occurred in the North Sea due to the leakages from injection wells (Bakkea et al., 2013), implying the unreliability of the corresponding WI wells in the long-term. Such spill scenarios in the Barents Sea can result in devastating environmental damage and threaten the fish stock and food chain.

The aim of his paper is to discuss and highlight the WI assurance and its contributing factors in the Barents Sea. This paper addresses the surface risks associated with re-injection of drill cuttings and wastes in the Barents Sea considering its severe weather conditions. Moreover, by highlighting the subsurface-related risks, this study focuses on the factors influencing the reliable and year-round WI operation. In this regard, the required criteria to accomplish a successful injection practice is also presented and discussed.

DIVERSE AND SEVERE OPERATING CONDITIONS IN THE BARENTS SEA

The Barents Sea reaches the Arctic Ocean and Franz Josef Land in the north. It borders the Greenland and the Norwegian Sea in the west, the Kara Sea and Novaya Zemlya in the east, and the coast of Norway and Kola Peninsula in the south. The average depth of the Barents Sea is approximately 200 m and the maximum depth in the Norwegian sector reaches 513 m, while it exceeds 600 m in the Franz Josef Land. However, in the central part and costal parts of southeastern and Svalbard Archipelago, water depths is generally less than 100 m (ISO, 2010, Matishov et al., 2004).

There are generally two main water current systems in the Barents Sea, shown in Figure 1. The warm Atlantic water currents enter the Barents Sea between the northern coast of Norway and Bjørnøya, and then flow towards East and Northeast. After being mixed with the cold currents flowing from North and Northwest, they leave the Barents Sea between Novaya Zemlya and Franz Josef Land. The North-western Barents Sea is dominated by Arctic water with below-zero temperature and decreased salinity, flowing southeast (ISO, 2010, Matishov et al., 2004, Tantsiura, 1959). The different patterns of such currents create a diverse metocean and sea-ice conditions in the Barents Sea. This causes a considerable variation in air and surface (water) temperature, sea-ice extent and thickness, sea ice-covered and open-water periods, waves, winds, currents, and presence of icebergs. For example, while the annual minimum air temperature in the northern regions varies from -39°C to -20°C, the southern areas experience an annual minimum temperature of -9°C to -6°C (ISO, 2010).

Atmospheric and spray icing events are other characteristics of the Barents Sea that can threaten the reliability of the equipment and operations. Polar low pressures that are often associated with strong winds, sudden decrease in air temperature, snow showers, and heavy icing events are other meteorological phenomena that happen in the NCS from September until May. Figure 2 shows the yearly frequency of polar low pressures in the NCS.

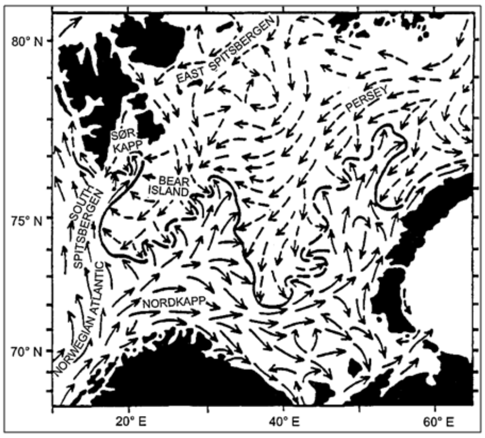

Figure 1. Schematic of main water masses in the Barents Sea (Tantsiura, 1959)

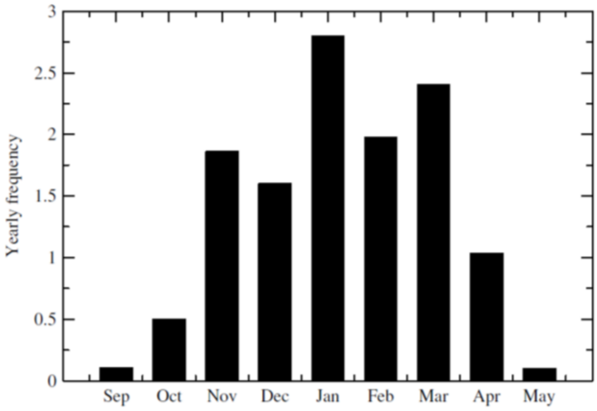

Figure 2. Frequency distribution of polar lows in the NCS according to the observations from 2000 – 2009 (Noer et al., 2011)

PLANNING FOR WASTE INJECTION OPERATION

Despite the outstanding milestones that WI can present in the Arctic offshore, a number of preliminary studies on the factors playing key role in the long-term reliable WI operation must be performed in the planning phase. Limited understanding and poor characterization of such factors and their associated uncertainties can potentially endanger the environment and cause extended rig downtimes.

Amount of Waste

There are generally two main sources of wastes in drilling operations including drill cuttings and rig wastes. With relative to the capital investments, the cost-effectiveness of the WI rises with the amount of wastes to be injected. This implies that WI injection becomes more economically attractive for large field developments (Gogan et al., 2010). Drill cuttings, produced while drilling the top hole section, can be dumped into the sea given that a water-based mud (WBM) is used and the mud additives meet the environmental regulations (Paulsen et al., 2005). Cuttings produced while the reservoir section is being drilled into, however, are contaminated with hydrocarbon compounds and thus are considered as waste. With effect from 1993, discharge of cuttings into the NCS with an oil content of more than 1% is prohibited (Research council of Norway, 2012). Drainage water from precipitations and wastewater from cleaning the rig floor and other purposes are other types of waste (Paulsen et al., 2005). To estimate the amount of drilling cuttings, one may consider the following items:

- Number of wells
- Drilling rate of each wellbore (the volume of drill cuttings per unit time can be determined from drilling rate)
- Well geometry (length of reservoir section and well radius)
- Amount of liquid waste which consists of waste drilling mud, dirty brines, oily drains and rig wastes
- Volume of required water for slurrification

Well Planning for Waste Injection

Correct placement of WI well is vital to have a successful and reliable WI project. For this purpose, suitability of the subsurface geological structure and a correct well trajectory are two important factors, which must be thoroughly studied and investigated during the WI planning phase. Placing injection wall away from the production wellbores eliminates the interference of disposal fractures with other production wellbores, or waste channelling into the reservoir sections (Gogan et al., 2010). This is of particular importance in offshore drilling operations, where the injection well is being drilled from the same platform. A thorough understanding on the subsurface geology ensures the injection well has adequate capacity for containment of the waste. Since the injection of waste creates fractures in the subsurface formations, where waste slurry enters into, reliable information on the formation axial stresses, permeability, porosity, and neighbouring faults and discontinuities is required (Guo et al., 2005, Gogan et al., 2010, Guo et al., 2007). Such information can be obtained from early seismic data, log analysis, mud logging, and coring. Figure 3 illustrates a typical WI well, with desired overlaying low permeable formation (shale caprock).

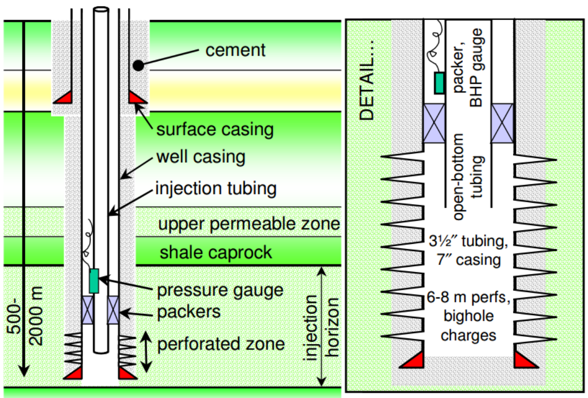

Figure 3. Schematic of a typical WI well (Sanfilippo et al., 2009)

Another parameter that contributes to the waste injection well planning is the availability of suitable injection layer with adequate depths and thickness with flat-laying sedimentary structures. Presence of formations with very low permeability between the injection zone and upper layers enhances the long-term injection security as it prevents the waste to migrate to the surface (Sanfilippo et al., 2009). Acquiring reliable information on subsurface structures and formation properties becomes crucial if the waste is planned to be injected through a production wellbore, where the production casing is isolated from injection one by some packers.

Fracture Simulation and Storage Mechanism

To assess the containment of disposed waste, the extent and width of disposal fractures as well as the maximum achievable upwards growth should be studied carefully during the WI planning phase, for which fracture simulation is a common method. Figure 4 depicts a typical fracture simulation result that shows the fracture upwards growth, and fracture length and width. It also illustrates the waste containment because of the presence of a stronger layer above the injection formation. If several layers are selected as candidates for WI, performing a hydraulic fracture simulation can aid in selecting the most suitable formation. In this regard, information on the lithology of the neighbouring formations, formation structure and its thickness, porosity, permeability, and geomechanical properties are required (Guo et al., 2005, Gogan et al., 2010, Guo et al., 2007).

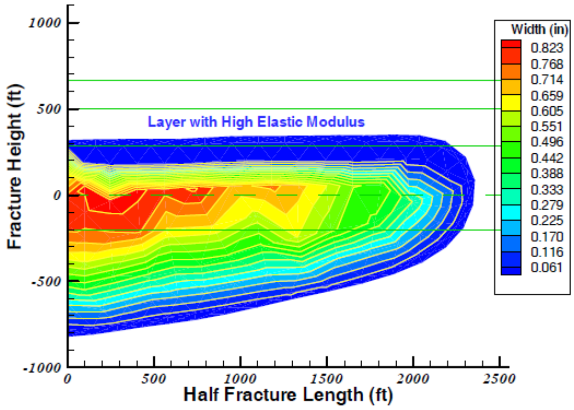

Figure 4. A typical fracture simulation (Guo et al., 2007)

Fracture simulation can also be used to design the optimum injection procedure and slurry properties such as viscosity, gel strength, solid content, etc. Depending on waste generation rate, a continuous or intermittent injection approach may be chosen. In continuous slurry injection, the fractures may have extended length. In intermittent slurry injection (also known as batch process), approximately the same amount of slurry is injected and then the well is shut in for some time, after which the next batch is injected. This method allows the disposal fracture to close onto the cuttings and to dissipate any build-up of pressure in disposal formation (Abou-Sayed et al., 2002).

Surface Facility Design

To implement a WI project, three main steps should be followed (Gogan et al., 2010, Sanfilippo et al., 2009, Shokanov et al., 2007, Guo et al., 2007):

- Collecting and slurrifying drill cuttings
- Conditioning, testing and injecting resultant slurry
- Monitoring

Figure 5 shows a schematic of the waste collection, slurrification, and injection units. Prior to waste collection step, the return flow from the wellbore must be processed in a series of solid control equipment, where the cuttings are separated from the drilling mud. The separated cuttings are collected and ground up (if needed) for further slurrification in the mix tanks when additional water is added to prepare the slurry. The prepared slurry is then routed to holding tanks for conditioning and regulating its rheology, water content, viscosity, etc. Injection pumps then pump the slurry into the injection well with a predetermined rate and pressure.

To this aim, major surface equipment for a centralized offshore WI facility consists of a slurrification unit, high-pressure injection pump and high-pressure pipe-work, slurry and water tanks with transfer pumps. Auxiliary facilities and equipment include cuttings reception tank, control room, laboratory for slurry testing, mobile vacuum unit, forklift for chemical pallets transfer, winterization system, excavator with a clamshell to transfer cuttings from cutting reception tank to slurrification unit, and a viscous spacer tank. A number of monitoring devices are also required to record the injection pressure, rate, shut-in pressure, slurry properties, and injected volume with time (Guo et al., 2007, Sanfilippo et al., 2009, Rodriguez et al., 2007, Guo et al., 2006).

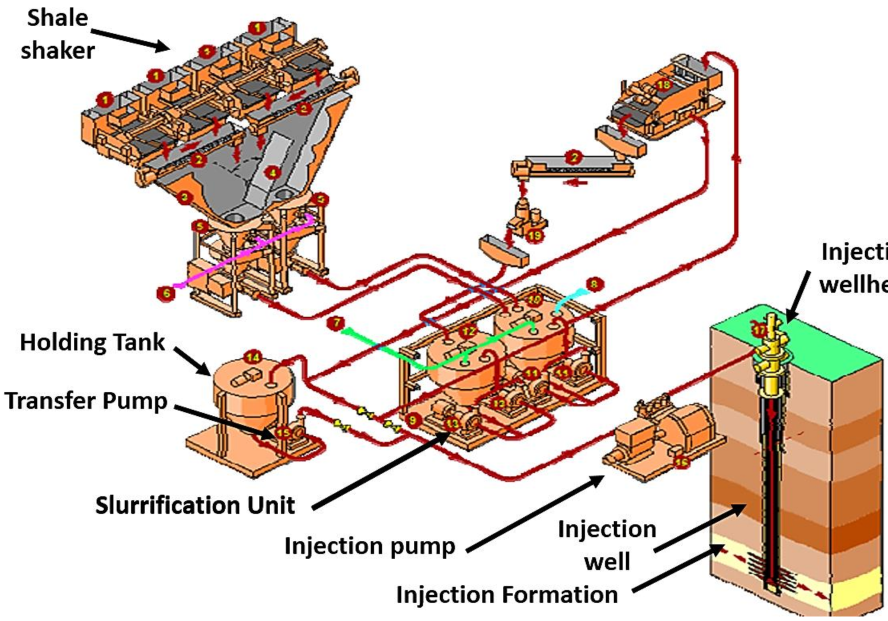

Figure 5. Surface facilities for waste collection, slurrification, and injection (Guo et al., 2006)

To design the required surface facilities, three sets of requirements must be met: i) technical requirements, ii) the ones related to the remoteness of the platform locations and level of infrastructure, and iii) a set of requirements related to the severe weather conditions and harsh operating environment.

Technical requirements include cutting and waste production rate, slurry properties, WI rate and pressure, storage tanks with sufficient volume, to name but a few. For instance, injection pumps are chosen based on the rheological properties of slurry (e.g. viscosity, corrosiveness, density, etc.), required injection rate, and required pressure (Guo et al., 2007). According to the defined injection procedure, a set of reliable data acquisition equipment and a laboratory unit are required for continuous monitoring and real-time measurement of the injection parameters and slurry properties. Injection parameters include downhole pressure, wellhead shut-in pressure, pump discharge pressure, rate, and cumulative injected volume. By slurry properties, one often refers to specific gravity, sand content, plastic viscosity, gel strength, yield point, distribution of slurry particle size, bacterial activity, settling tendency, as well as oil, water, and solid content of the slurry (Gogan et al., 2010, Fragachan et al., 2007).

The requirements related to the remoteness, infrastructure, and operating conditions vary from one location to another. Generally, the surface facility design must include the adverse effects of harsh operating environment on the performance of collection, slurrification, injection, and monitoring devices. Potential effects of operating environment on the slurry, drilling mud and slurry additives should be accounted for, as well. In the next section, a detailed discussion of such requirements is presented under the term “surface-associated uncertainties”.

COMMON ASSOCIATED UNCERTAINTIES

There are a number of uncertainties associated with the parameters contributing to WI planning, which can be divided into categories related to surface and subsurface conditions. WI plans are generally prepared before drilling operation itself commences. In this regard, the required information on subsurface structures and formation properties are based on seismic data, modelling, or extrapolation of the data obtained in drilling and development of other wellbores in that field or neighbouring ones. Another set of subsurface-associated uncertainties are related to the performance of the downhole facilities. Uncertainties associated with surface facilities and operations are mainly related to the adverse effects of the severe weather conditions.

Subsurface Associated Risks

Different sources of uncertainties are present in subsurface formation parameters. One category is the uncertainties imposed by the simulation analysis and models used, for instance, for fracture propagation, quantification of formation properties, as well as estimating batch volumes, injection pressure and rate, and fluid flow in the porous media. Another category is related to the accuracy of the data acquisition, monitoring, and measuring devices, such as log data, coring results, mud logging data, real-time fluid measurements (e.g. mud, formation fluid, and slurry) and rock properties (e.g. petrophysical and geomechanical properties). Uncertainties in subsurface structures such as presence of discontinuities, faults, and permeable or impermeable neighbouring formations are another important category that may greatly affect the WI project results.

Limited knowledge on WI planning parameters, and poor characterization of their associated uncertainties can cause a failure in WI process and consequently result in stoppage of drilling operation. For instance, a number of common risks to the WI process are listed below (Rodriguez et al., 2007, Sanfilippo et al., 2009):

- WI well plugging due to solids settling
- Waste channelling behind casing due to poor cement quality
- Fracture breach to surface
- Fracture intersection with nearby wells, faults or other geo-hazards
- Reaching disposal domain capacity
- Injection pressure build-up due to solids packing in the disposal fracture or near-perforations area
- Injectivity loss due to limited fracture entry.

A continuous monitoring and real-time measuring the slurry properties and injection parameters can aid in minimizing the subsurface risks associated with injection process. The results can be used to collaborate closely with field operations who can provide recommendations to be implemented in operational procedures. For example, monitoring the annular and tubing pressures of the injection well and the neighbouring ones for any pressure increase throughout the injection operation can give an early indication of excessive fracture length growth or over-pressurizing of an intermediate formation (Guo et al., 2007).

Generally, a waste slurry leakage and interruptions in injection process is often associated with a combination of mechanisms. A multidisciplinary effort is then required to assess the assurance of WI operation. A probabilistic approach to modelling the injection process can aid in dealing with uncertainties and increasing the injection assurance.

Surface Associated Risks

Another category of uncertainties that may threaten the WI assurance is related to the performance of the surface facilities, such as failures in injection pumps, plugging of the lines, and power outage. Proper configuration of the surface facilities while strictly adhering to properly developed procedures and provision of backup for critical mechanisms can cope with the shortcomings due to the uncertainties associated with equipment performance, improve the injection assurance, and thus reduce the injection interruption risks. A thorough reliability and availability assessment of the collection, slurrification and injection facilities can present a basis for decision makers to establish a framework in order to meet the injection requirements. As an example, they may need additional redundant injection pumps, or adequate number of spare parts for the critical components. The availability analysis gives an indication of the system downtime, which can be further used as a basis for provision of storage or holding tanks for the wastes and slurry until the system is restored to its functioning state. In this regard, one may need to have a closer view on availability performance concept.

Availability is defined as "the item's capability of being used over a period of time" (Stapelberg, 2009). This definition implies that in order to increase the availability of a system, one needs to reduce the probability of the failure of the equipment, and if a failure occurs, adequate maintenance activities should be performed to restore the failed equipment to its operational state. Additionally, both the reliability and availability of the systems are dependent on the conditions under which the system is operating. In cold climate regions, low temperatures may adversely affect the performance of the equipment units by altering the properties of metals, plastics, polymers, lubricants, etc. A series of winterisation measures are then required to cope with the effects of the severe weather conditions. Insulation, sheltering, using temperature resistant materials, are examples of winterisation measures, which require considerable amount of energy.

Low temperatures can affect the properties of the slurry as well. Higher viscos slurry requires more pressure to keep the injection rate at a constant desired level. Higher pressures may cause failures in pump, tubes, connections, etc. Redundancy provision can also improve system reliability and avoid extended downtimes. As an example, the slurrification unit may need to have dual slurry transfer pumps connected via pipe manifolds. Back up injection pumps can also greatly improve system availability if the primary pumps are failed. However, to avoid interruptions in drilling operations, storage tanks may be required to collect the cuttings so that the drilling operation is ongoing while either of collection, slurrification, and injection units are down. Different additives may be required to cope with the impacts of low temperature environment on the rheological properties of the slurry.

Remoteness and uncertainties in weather conditions can contribute to extended downtimes in WI operation by causing delays in spare part provision plans. Harsh weather conditions can negatively affect human performance resulting in extended maintenance times.

One of the main sources of uncertainties in availability assessments of the WI surface facilities is lack of operational data on the performance of various equipment units that accounts for the negative impacts of severe weather conditions. The data available in the regions with normal climate conditions may be used as a basis. However, some modifications to such data may be required to account for the effects of operating environment. The same issue stands for the maintainability assessments and the required time for corrective maintenance actions.

CONCLUSIONS

The successful application of WI technology and lessons learned from such activities, may illustrate the technical viability, efficiency and economic benefits despite the challenging surface environment. However, a thorough understanding of the subsurface formation properties and geological structures play a key role in making the final decision and selecting the most appropriate injection formation. For this purpose, a multidisciplinary team including drilling engineers, reservoir engineers, production engineers, mud engineers, geomechanical engineers, well logging and well testing specialists, subsurface and general geologists, facility engineers, environmentalists, and economists, need to work closely to assess the viability of the WI operation compared to alternative waste handling options. Even if the analyses may approve that the WI is the most economically beneficial and less environmentally harmful option for waste handling in the Barents Sea, a continuous monitoring of injection and slurry parameters is necessary to avoid failures in WI operating.

Lack of operational data on the performance of the surface facilities increases the level of uncertainties associated with their availability performance under severe weather conditions. Taking appropriate precautions and following a conservative approach may be required to reduce the effects of such uncertainties. Appropriate steps should also be taken to avoid interruptions in drilling operations. That include winterisation measures, design modifications, adding redundant equipment, and storage tanks to collect the waste if the WI system is down.

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