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# Abstract

The significance of a proper Drilling Waste Management has increased in the Petroleum Industry throughout the years. Development of a sustainable Drilling Waste Management is often associated with complying with zero hazardous discharge in drilling operations as well as prevalent rules and regulations. In this process more focus has been directed towards finding and developing a best available technique, which should include a proper handling, processing, transportation and disposition of the material without the potential for causing adverse affects to the environment.

Several assessments have previously been conducted to determine if the treatment method Thermomechanical cuttings cleaner (TCC) could potentially be considered a best available technique for offshore treatment of drill cuttings. The results from these studies have indicated several benefits of implementing the TCC method offshore. However, there is still remaining work that needs to be done before this discussion is complete.

The objective of this research was to conduct a pre-study of untreated and treated cuttings, and water fraction from TCC treated cuttings to set a possible foundation for the upcoming OLF study on TCC for offshore treatment of drilling waste. This also included an assessment of the TCC method as an offshore treatment method against current rules and regulations in Norway, and an evaluation of potential discharge of water fraction from TCC.

Implementation of an offshore treatment method of drilling waste has not yet been successful in Norway. Thus, most of the produced drilling waste is sent onshore for treatment and subsequently disposed at landfills. Due to this, the objective of this research also included an evaluation of the solid fraction from TCC treatment against requirements for the three different categories for landfill in Norway. In addition the eligibility of direct discharge of water fraction from TCC treatment was evaluated against local onshore discharge requirements.

In order to characterize the solids and water fraction from TCC treatment, analysis was conducted on both untreated and treated drill cuttings and heavy slop as well as the recovered water phases. Results from the untreated and treated solids indicated a high percentage removal of test parameters such as hydrocarbons, PAH and BTEX during TCC processing. However, the removal efficiency was relatively low for heavy metals. Observations from the recovered water phases indicated that most of the BTEX evaporates together with the water, while only some of the PAH will follow the water phase.

Discharge limit set for processed water in Norwegian Continental Shelf (NCS) is 30 mg oil per liter of water as a weighted average for one calendar month. The detected oil in water concentration in retrieved water phase after TCC treatment was 14.8 mg/l, well below the requirement. According to the prevalent discharge limit, discharge of the recovered water

phase could therefore be a potential outcome if the TCC unit were to be implemented offshore.

The oil-on-cuttings concentration in treated drill cuttings and slop was also below the discharge requirements set for the NCS. Samples of treated drill cuttings constitute of 3.3 and 2.8 g oil per kg of dry material in sample 2 and 3, respectively. While treated slop consist of 2.1 and 2.0 g of oil per kg of dry material in sample 7 and 8, respectively. This upholds the requirements of 10 grams of oil per kg of dry material.

Even further studies are required in order to assess the possibility of direct discharge of the treated drill cuttings offshore. This could include a further assessment of the chemical composition of treated drilling waste, chemical fate during TCC processing, particle fate and potential effect to the environment if discharged.

Comparing limit values for organic parameters in inert waste against treated drill cuttings, showed too high concentrations of TOC and mineral oil. Thus, it was concluded that the drill cuttings was unsuitable for disposal at inert landfills. However, the treated waste upholds the leaching limit values and organic parameters for disposal at hazardous waste landfills.

The retrieved water phases after TCC processing indicated a TOC concentration above the discharge limit of 1000 mg/l set for Halliburton Mongstad. In addition the oil-in-water and mercury concentration was too high for recovered water after treatment of heavy slop and drill cuttings, respectively. Due to this it was concluded that the recovered water is not clean enough to be directly discharged onshore after TCC treatment. It was recommended to implement additional treatment in order to decrease the TOC and oil-in-water concentrations below the discharge limits set for Halliburton Mongstad.

Weaknesses in the experimental method used in this work include uncertainties affiliated with collection of representative samples. This is due to difficulties associated with estimation of how long processing time a batch of untreated heavy slop or drill cuttings requires, from the time it enters the TCC unit until it leaves the unit as a treated powder. In addition there is the possibility of retrieving samples which are not homogenous, rendering inconsistencies in the results. Since no parallel tests were performed of the analysis's it is difficult to compare and evaluate if the values retrieved are correct or too influenced by uncertainties. Thus, it was suggested to perform parallel tests in order to verify the results.

# Contents

# List of Figures

# List of Tables

# Abbreviations

| | |
|---|---|
| BAT | Best Available Technique |
| BTEX | Benzene, Toluene, Ethylbenzene and Xylene |
| DWMP | Drilling Waste Management Plan |
| EIF | Environmental Impact Factor |
| EIR | Environmental Impact Reduction |
| EWL | European Waste List |
| HSE | Health Safety and Environment |
| KLIF | The Norwegian Climate and Pollution Agency |
| LOQ | Level of Quantification |
| LSOBM | Low Soilds Oil Based Mud |
| MU | Uncertainty of Measurements |
| NA | Not Applicable |
| NAF | Non-Aqueous Fluids |
| NCS | Norwegian Continental Shelf |
| NIVA | Norwegian Institute for Water Research |
| OBM | Oil Based Mud |
| OLF | The Norwegian Oil Industry Association |
| PAH | Polycyclic Aromatic Hydrocarbons |
| PCB | Polychlorinated Biphenyl |
| PLONOR | Pose Little Or NO Risk |
| SBM | Synthetic Based Mud |
| TCC | Thermomechanical Cuttings Cleaner |
| TFM | Total Fluid Management |
| TC | Total carbon |
| TG | Thermogravimetry |
| THC | Total hydrocarbons |
| TIC | Total inorganic carbon |
| TOC | Total Organic Carbon |
| TS | Total solids |
| WBM | Water Based Mud |

# 1. Introduction

The process of drilling oil and gas wells generates large volumes of drilling wastes, including drill cuttings and slop. Drill cuttings derived from the use of water-based muds (WBM) are usually discharged to sea. On the contrary, due to the high concentrations of oil, cuttings derived from the use of oil-based muds (OBM) are not approved for such disposal. On the contrary, drilling waste associated with the use of OBM are looked upon as a hazardous waste and the regulations concerning disposal of such drill cuttings has become even more stringent throughout the years. Thus the significance of a proper Drilling Waste Management has increased in the petroleum industry (Al-Ansary and Al-Tabbaa, 2007).

In order to manage these wastes in a proper way that corresponds with the current regulations and guidelines, it is important to look at elaboration of existing viable treatment techniques. The further development of the technology Thermomechanical Cuttings Cleaner (TCC) is a good example of this. Initially this method was used as an onshore waste treatment method. However, developments in the technology has allowed for this process to be moved from onshore to offshore, internationally. The actual mechanism behind this technology is still the same. Nevertheless, some small adjustments were necessary in order for the technology to comply with offshore rules and regulations.

The TCC method consist of a thermal desorption technology, where oil and water are evaporated from solid material by heat and subsequently condensed. Heat is generated through a friction process, where the end products consists of three separate fractions; recovered oil, water and solids. The process will produce an oil-on-cuttings level consistently below 1 % by weight, upholding legislative requirement for discharge in many places, including NCS. General requirements for NCS is 10 grams of oil per kg of dry material, as defined in regulation 2010-04-29 no. 613 *Regulations relating to conducting petroleum activity, §68* (Halliburton (Baroid Surface Solutions), 2011). Benefits of this process are treatment of drill cuttings near source of waste, thus it will provide a positive contribution to overall environmental impact, mainly due to elimination of transport to shore and to treatment site.

Offshore treatment of drill cuttings has become a viable method of cuttings handling over the last few years, and it should be a natural method to evaluate in early phase waste management selection process. However, offshore treatment of drilling waste has not yet been successfully implemented in Norway. This is mainly due to the fact that the end-result after treatment is still considered a waste which needs to be disposed of in a proper way. Thus most of the treated drilling waste currently goes to landfills. Recent years have shown an increase in volume of drill cuttings sent to shore for treatment, and the abundance on landfill has therefore also increased (Svensen and Taugbol, 2011). Given the high drilling activity, both ongoing and planned offshore Norway, future prospects indicates that the generation of drilling waste will most likely not diminish in the nearest future (Svensen and Taugbol, 2011).

The objective of this research is to

1) Propose a sampling and analysis program to characterize solids and water fraction from TCC to be used as input data in risk assessment and environmental impact modeling of discharge.
2) Conduct a pre-study of untreated and treated cuttings, and water fraction from TCC treated cuttings to set a possible foundation for the upcoming OLF study on TCC for offshore treatment of drilling waste.
3) Evaluate solids fraction from TCC treatment against requirements for the three different categories for landfill in Norway.
4) Evaluate water fraction from TCC against regulations for offshore discharge.
5) Assess the TCC method as an offshore treatment method against current rules and regulations in Norway.
6) Evaluate eligibility of direct discharge of water fraction from TCC treatment against local onshore discharge requirements.

The results will be evaluated against various requirements stated in applicable regulations and local discharge permits.

# 2. Theory

When evaluating an established technology, it is beneficial to have an insight on how this technology has evolved, as well as how the history has affected this process. This chapter is meant to present relevant theory behind drilling waste management, the development of the TCC technology and to shed light on relevant rules and regulations concerning waste disposal.

## 2.1. Drilling mud

When drilling oil or gas wells, drilling mud or drilling fluids are added in order to aid the process. Drilling muds are basically condensed liquids, containing chemical additives and heavy minerals that are circulated through the drilling pipe to perform numerous functions (Khan and Islam, 2007). The main purpose of adding drilling mud is to (Halliburton, 2012):

- ✓ Control subsurface pressures
- ✓ Stabilize the wellbore
- ✓ Cool and lubricate the drill bit
- ✓ Carry cuttings to the surface

Normally drilling fluids is classified according to their continuous liquid phase, which can vary from water, mineral oil, or non-aqueous fluids such as esters, olefins and linear paraffin (Leonard and Stegemann, 2009) . The main types of drilling fluids used in drilling operations are OBM and water-based mud (WBM). In addition a new mud type has been developed, called synthetic-based mud (SBM). When selecting which type of drilling fluid to be used in a drilling operation, different factors such as complexity of drilling operation, formation, reservoir conditions, temperature and pressure needs to be considered (Fink, 2003, Norwegian Petroleum Directorate, 2011). For instance, the Norwegian Petroleum Directorate (2011) points out that in certain situations choosing WBM could potentially lead to larger risks associated with operational problems. Hence OBM is often utilized in technical challenging environments where the performance of WBM is not adequate. This is usually applicable when drilling the lower sections of the wells, including the reservoir section(Norwegian Petroleum Directorate, 2011). Concerns are particularly affiliated with drilling with WBM in reactive shells, deep wells, and horizontal and extended-reach wells (Argonne National Laboratory et al., 2007e). Table 2-1 illustrates some common characteristics as well as individual traits between the different types of drilling fluids mentioned.

**Table 2-1: Characteristics of OBM, SBM and WBM**

| Characteristics | OBM | SBM | WBM |
|---|---|---|---|
| **Base:** | Mineral oil | Synthetic oil | Saltwater |
| **Recycling:** | When possible | When possible | No recycling |
| **Drilling performance:** | Excellent | Good | Limited in technical challenging environments |
| **Generation of drill cuttings:** | Large volumes of drill cuttings | Large volumes of drill cuttings | Larger volumes when not discharged directly to sea |
| **Toxicity:** | Higher toxicity compared to SBM and WBM | Lower toxicity compared to OBM | Low or no environmental impact |
| **Discharge of cuttings:** | Not allowed | Not allowed | Can be discharged to ocean if composed of environmentally friendly chemicals |

The scope of this thesis will focus on drill cuttings derived from the use of OBM, thus details concerning composition of drilling mud in the following section will be limited to those of OBM.

## 2.1.1. Composition and characteristics of OBM

OBM mainly consists of mineral oils, barite and chemical additives. The continuous phase in OBM consists of oil dispersed with water. Table 2-2 gives an illustration of the main components in OBM. The amount of water in OBM will normally range between 5 % - 40 %(Halliburton (Baroid Surface Solutions), 2009). According to Skjeggestad (1989), an emulsifier is added to the OBM, in order to prevent the water droplets from coalescing and creating separated layers of oil and water. He further states that if the water content exceeds 40 % it can potentially create problems concerning viscosity and emulsion-stability. The formation being drilled in contains water, and some water will therefore be transported to the mud system from the drill cuttings. Thus sustaining a water-in-oil emulsion is important in order to disperse water from formation into the oil phase (Skjeggestad, 1989).

**Table 2-2: Components of OBM (Halliburton (Baroid Surface Solutions), 2009)**

| Main components: | Normal additives: |
|---|---|
| 50-95 % base oil or linear paraffin<br>5-40 % water<br>Primary emulsifier<br>Secondary emulsifier<br>Polymers<br>Weighting material ($BaSO_4$ and $FeTiO_3$)<br>Salts (mainly $CaCl_2$)<br>Bentonitt<br>Polyamides<br>Amine treated lignite | Defoam or antifoam<br>Corrosion inhibitor<br>Deposit inhibitor<br>Lubricants<br>Dispersion agent<br>Other products for controlling loss of filter<br>Biocider |

In the past, diesel was normally used as the oil phase in mud systems. However in 1980 there was a change in procedure concerning the use of diesel as continuous phase

(Skjeggestad, 1989). According to Skjeggestad (1980), this was due to concerns regarding toxic effects associated with diesel, mostly towards the aromatic components present in diesel. Thus diesel has gradually been replaced by less toxic paraffin oils or mineral oils, which contains less aromatic compounds (Skjeggestad, 1989). Additional developments have been made with regards to the chemical content of OBM. For instance, some OBM types are composed of green and yellow chemicals making them more environmental friendly (Halliburton, 2012).

When selecting a base fluid, it is important to assess several physical properties with regards to performance, health, safety and environmental characteristics (Walker et al., 2010). The primary objective of introducing OBM in drilling activities was to take advantage of its beneficial qualities when drilling in water sensitive formations such as shale and clay(Skjeggestad, 1989). Due to the characteristics of the oil, the formation will not be affected by the oil nor create swelling of the clay (Skjeggestad, 1989). The high content of calcium hydroxide ($Ca(OH)_2$) used in OBM will also prevent corrosion as well as neutralizing incoming flow of sour gases such as hydrogen sulfide ($H_2S$) and carbon dioxide ($CO_2$) (Skjeggestad, 1989).

## 2.2. Drilling waste

During drilling activities many types of wastes are generated. The two main types of drilling waste generated are drill cuttings and slop water, which is further elaborated in chapter 2.2.1 – 2.2.4.

### 2.2.1. Definition of drill cuttings

Drill cuttings are comprised of crushed sedimentary rock fragments produced during drilling activities. These rock fragments will be contaminated with drilling fluids ranging from diesel oil, mineral oil, olefin, ester or water (Norwegian Petroleum Directorate, 2011, ASME Shale Shaker Committee, 2005). According to Skjeggestad (1989), drill cuttings will consist of different types of solids depending on the type of formation being drilled in, such as silt, sand, shale or clay. Due to these variations in both the composition of formation rock being drilled in and type of drilling fluid used, the contaminants present in drill cuttings will vary accordingly (Leonard and Stegemann, 2009). Contaminants present in drill cuttings include petroleum hydrocarbons such as aliphatic hydrocarbons and polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCBs) and heavy metals such as barium, zinc, mercury, lead, nickel, chromium and arsenic (Leonard and Stegemann, 2009).

A typical drilling waste will normally consist of 70 % mineral solids, 15 % water and 15 % oil in volume (Halliburton, 2012). The particle size of drill cuttings will vary with the formation type, length of well and type of drill bit utilized (Skjeggestad, 1989). Typically, drill cuttings generated from operations in the North Sea will consist of sandstone and shale, with a particle diameter ranging from 10 μm to 10-20 mm(Page et al., 2003).

### 2.2.2. Separation of drill cuttings

After transportation of drill cuttings to the surface of the well, they will be transported back to the drilling rig via the mud stream, were the drill cuttings are separated, as shown in Figure 2-1. It is very important to separate out the drill cuttings during the first circulation pass. According to Skjeggestad (1989), this will prevent the drill cuttings from being circulated back into the well, where it will be crushed in even smaller pieces by the drill bit. The most common method for separation of drill cuttings from the drilling mud is to use a shale shaker (Halliburton, 2012). The shale shaker consists of large, flat sheets of wire mesh or sieves of various mesh sizes (Halliburton, 2012). Vibrations of the sieves will transport the drill cuttings across and off the screens, while drilling mud flows through the mesh and is directed back to drilling fluid system (Skjeggestad, 1989). However, even after this activity there will still be some remaining oil on the cuttings (Norwegian Petroleum Directorate, 2011).

**Figure 2-1: Oil based drill cuttings separated from the drilling fluid (Jensen and Halliburton, 2012)**

### 2.2.3. Definition of slop

According to a technical report from Halliburton (2009), slop is an expression which is often used for all oil- or soap containing waste fluids and discarded drilling fluids, generated during offshore drilling activities. It covers a wide spectrum of waste fluids, from wash water and produced water, to used drilling- or well fluids and waste oil. An average slop usually contains a water/oil/solids ratio of 80/10/10(Halliburton, 2012). The following citation from this report defines slop in connection with treatment of used drilling- and well fluids defined as waste, as follows:

*"Slop is waste fluids generated from discarded drilling- and well fluids consisting of water, oil and chemicals/solids with an oil content > 30 mg/l".*

The technical report then points out that slop consists of molecules with great variations in molecular weight as well as components with varying range of concentrations. This therefore makes it difficult to carry out reliable measurements on each separate component in the slop. Normal practice is instead said to involve utilizing composition parameters, such as total organic hydrocarbons (TOC), aromatic compounds, heavy metals, salinity and specific gravity. These parameters will according to this report, help with planning and dimensioning of intermediate storage plant and treatment facility onshore.

### 2.2.4. Separation of slop

Many drilling operations can generate slop, such as tripping of drill strings and tank- and pit washing on board of a rig. According to Halliburton (2009), most of the drilling rigs today are closed rigs, which mean that all the surface water will be collected. Thus all slop generated during drilling operations will be collected in a storage tank. Halliburton indicates that approximately 200 to 500 m$^3$ of slop per month are produced at a typical rig in Norway (Halliburton, 2012).

According to a technical report from Halliburton (2009), the separation of oil and water in slop is connected to the oils weight and solubility in water. Most of the oils in slop are more or less insoluble in water. In addition most of the oils in slop weigh less than water, which gives them the ability to float on the water surface. The combination of these properties makes it easy to separate the oil from the water(Halliburton (Baroid Surface Solutions), 2009). The report further points out that when oil comes in contact with water, the oil components will dissolve in the water according to their respectively hydrophilicity. The components in the base oil will therefore be either dissolved in water, in water free parts in the liquid such as hydrocarbons, or adsorbed to suspended particles.

## 2.3. Drilling Waste Management

Historically, it was common to manage oil field waste in the most convenient and least expensive manner without taking much consideration towards environmental impact (Veil, 2002). However, gradually more awareness has been given to environmental aspects concerning drilling waste management, and today it is an important factor considered in the oil industry (Veil, 2002).

Different factors affect the amount of drilling waste being produced during drilling activities. The following causes is mention in Drilling Fluid Processing Handbook by the ASME Shale Shaker Committee (2005), which include hole size, solids control efficiency, the ability of the drilling fluid to tolerate solids, amount of drilling fluid retained on the drilled cuttings and the ability of the drilling fluid to inhibit degradation or dispersion of drilled cuttings.

According to the ASME Shale Shaker Committee (2005), the characteristics of the drilling waste will influence where and how the waste will be disposed of. Emphasis is put on the importance of considering potential effects of the waste, such as effects to the seabed, to the water column, and to the air/water interface. In this context the ASME Shale Shaker Committee (2005) considers the WBM as relatively benign, while diesel OBM will affect the water surface, water column and seabed. Thus cuttings generated while using OBM are not discharged into the sea.

The purpose of drilling waste management is basically to minimize the volume of waste generated, and if possible to gain practical benefits from the waste products (Halliburton, 2012). In order to achieve this, it is important to develop a sound Drilling Waste Management Plan (DWMP). The DWMP will provide guidelines regarding the utilization of drilling and completion fluids related to overall drilling waste management, such as for waste minimization measures and handling of the waste itself (Halliburton (Baroid Surface Solutions), 2011). Establishing proper performance indicators can also be viewed as an essential part of the management plan (Halliburton (Baroid Surface Solutions), 2011). This will include instructions on how to measure the performance indicators, as well as how to report the results and ensure an experience transfer (Halliburton (Baroid Surface Solutions), 2011).

There is no uniform preferred strategy for waste management, as it will vary according to the user. However, one commonly used strategy is illustrated in Figure 2-2.

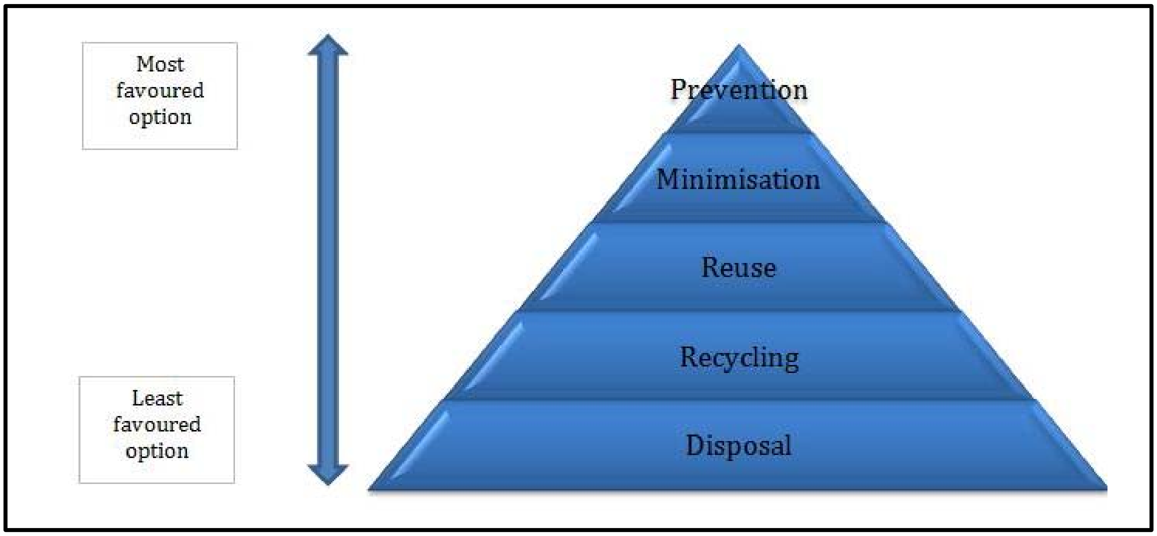

**Figure 2-2: Pyramid strategy for waste management (Halliburton (Baroid Surface Solutions), 2011)**

According to a report from Halliburton (2011), the following explanation can be used on Figure 2-2:

- ✓ "Prevention" – consider if you need to consume, or use anything at all.
- ✓ "Minimization" – If you do need to use – use as little as possible.
- ✓ "Reuse" – If you can – reuse what is left over, for the same purpose next time.
- ✓ "Recycling" – If reuse is not possible, find other uses for the material.
- ✓ "Energy recovery" – example: burn, recover and use the energy.
- ✓ "Disposal" – this is the least desirable outcome, leave or burry at disposal site.

With some small adjustments, the strategy in Figure 2-2 can be rewritten as the "5R Hierarchy". This is an internationally recognized strategy for drilling waste prevention, which is illustrated in Figure 2-3. Minimizing or preventing drilling waste from being generated is a process that should be a natural part of project planning (Halliburton (Baroid Surface Solutions), 2011). When generation of drilling waste has occurred, reuse can be considered as the next option, according to a technical report form Halliburton (2011). Waste segregation on the rig then becomes an important factor. Direct reuse of drilling waste is often impossible, thus all reuse is normally done onshore (Halliburton (Baroid Surface Solutions), 2011).

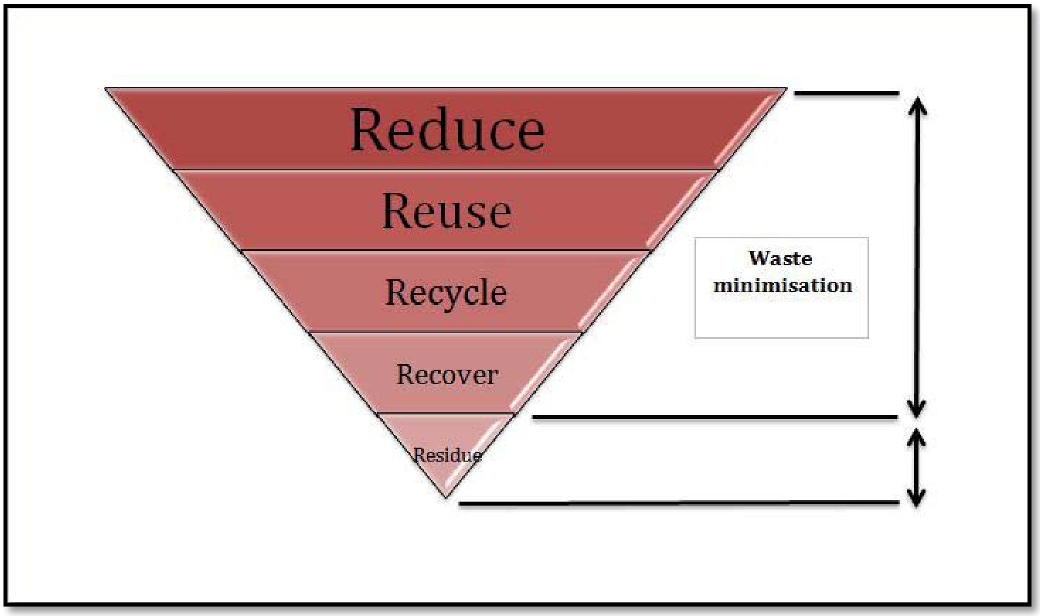

**Figure 2-3: Waste minimization prioritized strategy (Eia and Hermandez, 2006)**

These different approaches towards waste management shown in Figure 2-2 and 2-3, are illustrated in chapter 2.3.1 – 2.3.3, as respectively waste minimization, recycle/reuse and disposal.

### 2.3.1. Waste minimization

Waste minimization is maybe the most effective key strategy in order to reduce the costs and environmental impact affiliated with drilling waste handling (Svensen and Taugbol, 2011). This is a possibility which is thoroughly explored by the Oil and Gas Industry, where two general approaches to waste minimization have been developed. These two approaches are often referred to as total fluid management (TFM) and environmental impact reduction (EIR) (ASME Shale Shaker Committee, 2005).

The main focus of TFM is to reduce waste generation by minimizing or reusing fluids used in drilling operations (ASME Shale Shaker Committee, 2005). One possibility would be to drill more sections with WBM, thus allowing discharge of the cuttings to the sea. However experience has shown that WBM has its limitations especially when drilling under technical challenging environments(Svensen and Taugbol, 2011). Thus the challenge is to find a WBM that has technical qualities similar to OBM (Svensen and Taugbol, 2011).

According to ASME Shale Shaker Committee (2005), EIR is based on an evaluation of the environmental impact of a project in an attempt to reduce the impact. This method consists of an evaluation of the chemical components in the fluids. In addition certain environmental parameters such as toxicity, biodegradation potential, persistence, bioaccumulation and heavy metal concentrations are collected on each of the chemicals. The chemicals are then thoroughly evaluated and the chemical with the least environmental impact is selected (ASME Shale Shaker Committee, 2005). Thus choosing muds and additives with lower environmental impacts, like SBM is a good option for waste minimization (Veil, 2002). Properties such as lower toxicity, higher biodegradability and lower bioaccumulation potential, makes SBMs more environmental friendly compared with OBMs (Veil, 2002). In addition SBMs share some of the desirable drilling properties of OBMs (Veil, 2002). According to Argonne National Laboratory et al (2004e), another possibility could be to substitute some of the key drilling fluids with more environmental friendly products. One example could be to substitute barite with hematite ($Fe_2O_3$) or ilmenite ($FeTiO_3$). This could reduce the mass loadings of potentially harmful substances to the environment(Argonne National Laboratory et al., 2007e).

According to a technical report from Halliburton (2011), reduction of slop volumes at point of origin is viewed as one of the biggest contributors to waste minimization. Due to the high water content in the slop, an offshore slop treatment unit installed on the rig could for example provide an ideal solution for waste minimization. The report points out, that this would give the possibility of reusing wash water with subsequent reduction in use of water for washing operations. With an offshore slop treatment unit, the wash water could be continuously treated and reused in cleaning operations, thus reducing the total volume of slop generated.

### 2.3.2. Recycle/reuse

When drilling companies utilizes OBM or SBM during drilling operation, the fluids are usually recycled when possible. According to Halliburton (2011), reuse of drilling- and completion fluids is one of the most important waste minimization measures. It is important to achieve a suitable level of reuse of drilling fluids without compromising the performance. Implementing this minimization measure will according to Halliburton consequently reduce the consumption of chemicals and fluid volumes, loss of fluid over shakers, discharges and waste amounts.

After some time the mud might lose some of its physical and chemical properties necessary for successful drilling, and in order to regain these properties the mud needs to be processed (Argonne National Laboratory et al., 2007f). Collected mud is transported onshore for restoration of desirable properties and dispatched offshore after treatment (Norwegian Petroleum Directorate, 2011). This practice helps reduce the use of chemicals in drilling operations. However, in some cases the mud will be to degraded, thus it will not be economically feasible to reuse them (Argonne National Laboratory et al., 2007f).

According to Argonne National Laboratory et al. (2007f), there are a variety of methods that can be implemented on drilling rigs in order to capture clean mud for reusing purposes. Pipe wipers, mud buckets, and vacuuming of spills on the rig floor are just some examples that could be implemented. If no actions are taken to capture this mud, it will just be discarded.

Reuse of drilled cuttings is also an important aspect of waste handling in offshore operations. Before the cuttings can be reused they need to be processed with respect to hydrocarbon content, moisture content, salinity and clay content (Argonne National Laboratory et al., 2007f). These factors will vary depending on the intended use of the material(Argonne National Laboratory et al., 2007f).

There are several methods available for reuse of drilled cuttings, such as road spreading, as construction material and restoration of wetlands. In the process of road spreading, drilled cuttings are used to stabilize surfaces that are subject to erosion (Argonne National Laboratory et al., 2007f). According to Argonne National Laboratory et al. (2007b), the oily-cuttings will function in the same way as traditional tar-and-chip road surfacing. However, certain requirements and regulations need to be fulfilled if this method were to be implemented.

According to Argonne National Laboratory (2007f), the hydrocarbon fraction needs to be removed first, before drilled cuttings can be used as construction material. This can be achieved with thermal treatment followed by a screening or filtering, creating a relatively clean solid material. The end-material can then be utilized as fill material, daily cover material at landfills, and aggregate or filler in concrete, brick or block manufacturing (Argonne National Laboratory et al., 2007f).

Another interesting method for reuse of treated drilled cuttings is as a substrate in the restoration of coastal wetlands (Argonne National Laboratory et al., 2007f). Several projects have been conducted in using treated drilled cuttings in restoration of damaged wetlands in Louisiana (Kelley and Mendelssohn, 1995). However this method is still in the development phase.

### 2.3.3. Disposal

At the moment there are several disposal options for drilling wastes, however which type of disposal method to choose will depend on different factors. The relevant regulations and legislations concerning that specific area or type of waste will obviously affect the choice. In addition the costs and logistics will play a central role in the decision making process. Some disposal options are more relevant and cost-effective to assess onsite, leaving fewer disposal options for drilling activities conducted offshore since offshore disposal options are more limited (Halliburton, 2012). Last, but not least, the chemical content of a drilling waste and its physical characteristics will also affect which disposal methods that is most relevant. Some of the available disposal options for drilling waste is mentioned below (Argonne National Laboratory et al., 2007a):

- ✓ Onsite burial (Pits, Landfills)
- ✓ Land application
    - ✓ Land farming
    - ✓ Land spreading
- ✓ Discharge to sea
- ✓ Offsite disposal to commercial facilities
- ✓ Slurry injection / Re-injection
- ✓ Salt caverns

The disposal options of most relevance in Norway will be elaborated in more details in chapter 2.4 and 2.5 under offshore disposal options and onshore disposal options, respectively.

### 2.3.4. Trends in Drilling Waste Management

According to Statistics Norway (2010), a total of 1.2 million tons of hazardous waste was sent for approved treatment in 2010, giving a 14 % increase from the previous year. Statistics Norway further points out that the amount of hazardous waste sent for approved treatment has increased with an astonishing 114 % from 1999 to 2010. This is partly explained by improved collection and reporting. In addition some waste types have been reclassified as hazardous waste during this period (Statistics Norway, 2010).

Numbers from Statistics Norway (2010), shows that approximately 450 000 tons out of the total amount of hazardous waste in 2010 was due to waste containing oil from the petroleum industry, shown in Figure 2-4. This includes 246 000 tons of oil-drilling waste from offshore activities, an increase of 85 % from the previous year. This increase was mainly due to technical problems associated with reinjection of waste into the wells, which will be further elaborated in chapter 2.4.2 (Statistics Norway, 2010).

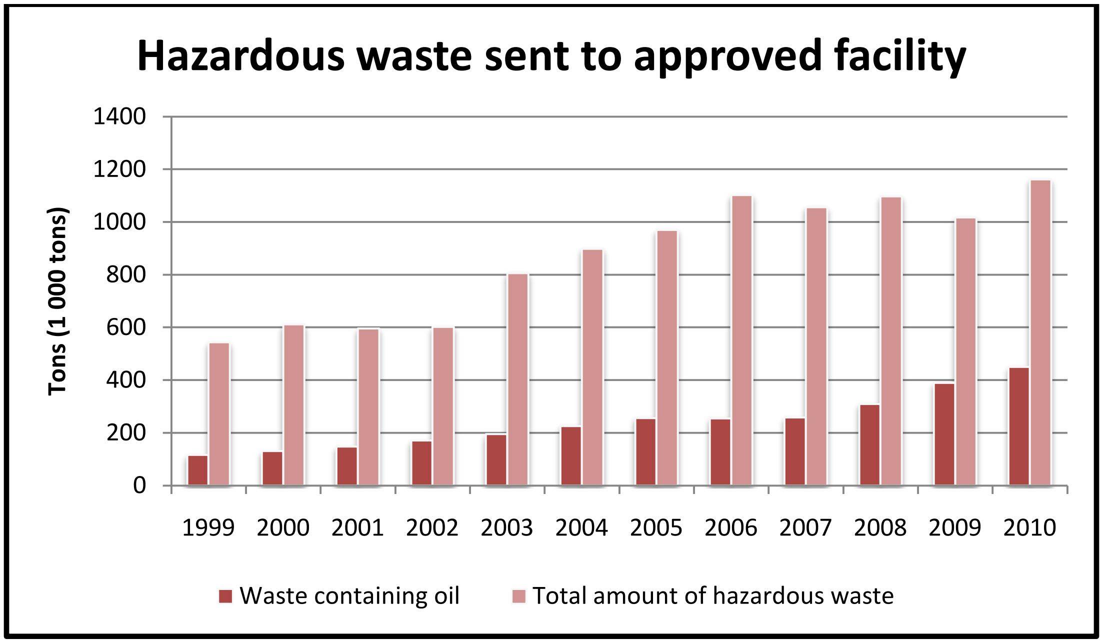

**Figure 2-4: Hazardous waste sent to approved facility, 1999 to 2010 (Statistics Norway, 2010)**

Increased drilling activities on the NCS have obviously increased the volume of drill cuttings sent onshore for treatment. This increase in volume is also affiliated with the recent technical problems affiliated with re-injection of drill cuttings (Svensen and Taugbol, 2011). Extensive measures have been made in order to avoid future leakages from re-injection wells (The Norwegian Oil Industry Association (OLF), 2011). Figure 2-5 illustrates this recent trend in disposal methods for drill cuttings. In 2010 the volume of drill cuttings re-injected was nearly 30 000 tons, while the volume drill cuttings sent onshore for treatment was approximately 80 000 tons.

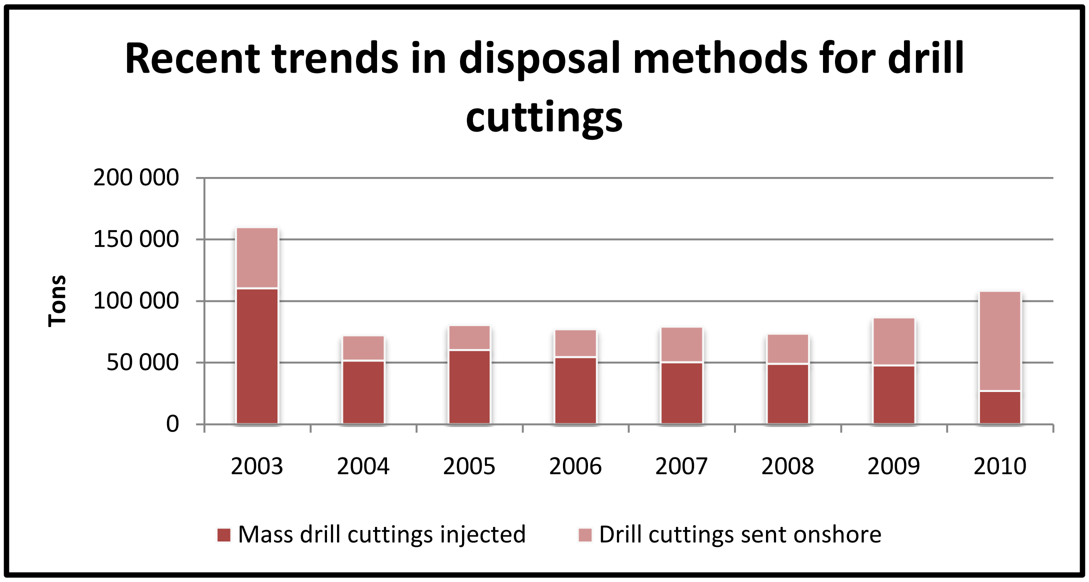

**Figure 2-5: Trends in disposal methods for drill cuttings, OBM (The Norwegian Oil Industry Association (OLF), 2011)**

There are a lot of health, safety and environmental (HSE) risks associated with transportation and deposition of drill cuttings onshore (Halliburton, 2012). According to a report issued by the Norwegian Petroleum Directorate regarding a study on petroleum operations in the North Sea (2011), these risks are mainly due to several reloading and transportation rounds, with heavy crane lifts etc. Increased energy costs and discharges to air are also affiliated with transportation, delays, treatment, deposition and the increased need for alternative solutions for deposition. The need for more disposals of drill cuttings onshore causes increased transportation, which again will increase the energy consumption. According to this report, this increase in energy consumption will contribute to the discharge of greenhouse gases. The need for more human resources on rig, boat and onshore will also increase the expenses affiliated with transportation (Norwegian Petroleum Directorate (Occupational group for the North Sea and Skagerrak), 2011).

This report developed by the Norwegian Petroleum Directorate (2011), further states that 140 000 ton of oil-containing drilling waste was sent onshore from the Norwegian shelf in 2009. This volume included both drilling fluids and drill cuttings. The diesel consumption associated with transportation of drill cuttings onshore was calculated to be 92 kg/ton cuttings, which equals a discharge of 305 kg $CO_2$ per ton cuttings. These numbers are calculated on the basis of Statoil's operations on the Uranus well in the Barents Sea, taking into consideration the diesel consumption from transfer of cutting onto supply vessels, the lay time of the supply vessel and transportation to a waste disposal site (Norwegian Petroleum Directorate (Occupational group for the North Sea and Skagerrak), 2011).

ConocoPhillips conducted a study on Eldfisk A, which compared the total energy consumption of re-injection of drill cuttings versus transportation of drill cuttings onshore(Norwegian Petroleum Directorate (Occupational group for the North Sea and Skagerrak), 2011). The total energy consumption affiliated with re-injection was 899 784 kJ per ton. However, transportation of drill cuttings onshore showed a total energy consumption of 1 875 159 kJ per ton, which is more than two times as high as for re-injection(Norwegian Petroleum Directorate (Occupational group for the North Sea and Skagerrak), 2011).

## 2.4. Offshore disposal options

When dealing with drilling waste generated offshore, the number of options for offshore disposal is limited. Normally the waste is taken to shore for treatment and disposal, but direct discharge to the sea and reinjection into the ground could in some cases be a suitable option (ASME Shale Shaker Committee, 2005).

According to a technical report from Halliburton (2011), the selection process of one of these options will depend on several factors. The following factors are mentioned:

- ✓ Economical
- ✓ Risks and safety
- ✓ Environmental
- ✓ Type and amount of drilling- and completion fluids to be used
- ✓ Time
- ✓ Logistic (distance to shore, weather, climate, frequency of supply vessels, etc.)
- ✓ Amount of waste (number of wells, size and length of sections, type of operations, etc.)
- ✓ Availability, or lack, of suitable geological formation for waste disposal in formation
- ✓ Onshore infrastructure for drilling waste handling
- ✓ Possibility of drilling waste treatment on the rig, or within field
- ✓ Adjacent existing injection wells

### 2.4.1. Direct discharge

As mention previously, direct discharge of drilled cuttings and associated waste fluids was the most common method used offshore in the early days. This was often used because it simplified operations as well as being an inexpensive method (ASME Shale Shaker Committee, 2005). However, due to an increased attention to how the environment is affected by this activity, restrictions have been made on direct discharge of drilled cuttings to the sea (ASME Shale Shaker Committee, 2005). New regulations implemented in Norway in 1991 states that discharge of drill cuttings exceeding 1 % oil-on cuttings by weight is not permitted (Norwegian Petroleum Directorate, 2011). This has basically ceased all discharge of drill cuttings derived from the use of OBM, as well as encouraged the development of WBM. Since the WBM consist of mostly green and some yellow chemicals, direct discharge is allowed when drilling with WBM (Norwegian Petroleum Directorate, 2011). However, this is not applicable in vulnerable environments such as the Barents Sea. Here direct discharge is only allowed when drilling upper section since the drilling fluid usually consist of seawater (Norwegian Petroleum Directorate, 2011).

### 2.4.2. Re-injection

In the process of re-injection, the cuttings need to be slurrified in order to be re-injected into a formation down hole. This is achieved by using a slurrification unit to slurrify the cuttings at surface and grind them down in size(Svensen and Taugbol, 2011). According to the ASME Shale Shaker Committee (2005), the slurrification unit is normally comprised of two or three slurry tanks with a capacity of around 100 – 150 bbl. Prior to the slurrification unit, large particles and junks are removed in a shale shaker. Next step is to collect the cuttings and fluids into slurry tanks, which consist of circulating slurry pumps. Due to the special design of the slurry pumps the particles are broken up into natural grain size (ASME Shale Shaker Committee, 2005). Slop or water and viscosifiers are also added in order to make a suitable slurry.(Svensen and Taugbol, 2011). When the slurry reaches an acceptable consistency it is transported to a holding tank before it is re-injection into the formation (ASME Shale Shaker Committee, 2005).

If the well in question is not being used in the future, the slurry can be re-injected directly back into the well (Norwegian Petroleum Directorate, 2011). Otherwise it is possible to re-inject the slurry into a separate reservoir, where the slurry will penetrate pores and cracks in the formation(Norwegian Petroleum Directorate, 2011). During pumping of the slurry into the formation, it is important that the pumping pressure exceeds the fracture pressure (ASME Shale Shaker Committee, 2005).

According to the ASME Shale Shaker Committee (2005), weak and unconsolidated sands are often viewed as the optimal injection target. This is due to the sands ability to fluidize and repack, which in turn will accommodate considerably large volumes of waste. It is also important that the injection zone contains a good seal above the zone. Thus it is suggested to perform careful geotechnical surveys before the reinjection starts in order to choose an appropriate zone.

Svensen and Taugbol (2011) present Statoil’s experiences and status for drilling waste management and treatment in offshore operations in their article “Drilling Waste Handling in Challenging Offshore Operations”. They point out, that since the slurrification and re-injection occurs near the source of waste, the energy consumption is minimized and the environmental impact is reduced. Re-injection of cuttings is also believed to be a more economical method as opposed to transportation to land for further treatment and disposal. Due to this, re-injection of cuttings has been regarded as the preferred method for drilling waste handling. However, in the last years some problems have developed with regards to the injection procedure. According to Svensen and Taugbol (2011), it has been discovered that some of the cuttings injection wells on the NCS has lost its integrity, causing fracturing. This has created limitations regarding volumes and rates injection for some injection wells, while several injection wells have been closed. Due to these changes in injection procedures, even more waste was sent onshore for treatment and disposal. This created a capacity problem as well as increased expenses (Svensen and Taugbol, 2011).

## 2.5. Onshore disposal options

If the situation does not permit the selection of one of the offshore disposal methods, then the alternative is to transport the drilling waste onshore for further treatment and disposal. Several techniques has been established onshore for cleaning of drill cuttings, such as grinding, direct thermal desorption, and indirect thermal desorption (Khan and Islam, 2007).

### 2.5.1. Transportation and handling of drilling waste

Transportation of drill cuttings onshore can either be done using skips or bulk tanks. According to a technical report from Halliburton (2011), the main difference between these methods lies in how the cuttings are transferred from rig to supply vessel. A skip and ship operation uses skips which are lifted by crane to supply vessel, while a bulk operation transfers cuttings through a hose to a suitable tank on a supply vessel. Several factors needs to be considered in order to choose the right method to use for shipment of cuttings. The following factors are mentioned as examples in this report:

- ✓ Rig type and size
- ✓ Duration of operation (one well, field development, etc.)
- ✓ Type of fluid (OBM, WBM)
- ✓ Layout of shaker room, chute, loading area, offloading stations, etc.
- ✓ Level of rig modifications required
- ✓ Crane availability
- ✓ Supply vessel availability
- ✓ Geographical location
- ✓ Manpower requirement

Drill cuttings are normally received on base either in skips or bulk tanks. Here they are stored in designated areas prior to shipment to a suitable treatment site (Halliburton, 2012).

According to this report, slop is normally received via supply vessel bulk system, offloaded directly onto onshore storage tanks. Slop received onshore can be categorized in three general categories according to further handling; slop for reuse, slop for processing and slop for thermal processing.

The report further explains that slop categorized as suitable for reuse are stored on base prior to being transferred to tank/mixing tank for reuse. The slop needs to be analyzed thorough before it can be reused. If the slop is categorized as suitable for slop processing, it is transferred to a slop processing unit. Here the oil and solids are removed. Solids removed are shipped to thermal treatment plant, while the water either are returned for recycling in production of new drilling fluid or transferred to treatment for disposal. The report then points out that slop categorized for thermal treatment are considered the heaviest part of fluid received. This typically consists of the portion settled at bottom of receiving tanks, which has no reuse potential and cannot be treated through slop processing (Halliburton (Baroid Surface Solutions), 2011).

## 2.5.2. Onsite burial

Burial is one common onshore disposal method for drilling wastes, where excavations such as pits and landfills are used in order to dispose of the waste(Khan and Islam, 2007). According to Khan and Islam (2007), this disposal method offers the advantages such as simplicity, low-cost technology, and requires limited surface area. One disadvantage, however, is the potential for groundwater contamination if the burial is not executed correctly. In addition liability costs are also mentioned as a possible result if contaminated wastes are buried in the process.

### 2.5.2.1. Pits

Pit burial is a method which is often associated with onshore drilling operations, since a strategic placement of the pits near the drilling site will minimize the costs affiliated with transportation of the waste (Khan and Islam, 2007). In addition, this placement of the pits near a well site, can also help minimize spillage of waste materials (Argonne National Laboratory et al., 2007d).

According to Argonne National Laboratory et al. (2007d), all remaining hydrocarbon products floating on the surface of the pits are recovered while the liquids are collected and disposed of. Normally the liquids are disposed of in an injection well. The remaining cuttings in the pit are covered by utilizing native soil. Then the surface is graded and the area is revegetated with native species. This is done in order to prevent water accumulation and to reduce the potential for erosion and promote full recovery of the areas ecosystem (Argonne National Laboratory et al., 2007d).

According to Khan and Islam (2007), onsite pit burial is not necessarily a good option for wastes that contain high concentrations of oil, salt and biologically available metals, industrial chemicals, and other materials with harmful components. This is due to the potential of chemical migration from the pit and into water resources. In order to prevent migration to the groundwater, Khan and Islam recommend utilizing a pit location of at least five feet above any groundwater.

#### 2.5.2.2. Landfills

Landfills are used for disposing of large volumes of municipal, industrial, and hazardous wastes. According to Khan and Islam (2007), a landfill consists of a bottom liner overlaid by a geological barrier. This is developed in order to prevent contamination of the soil. During non-active periods when the landfill is closed, a top liner will be drawn over the wastes. In addition, two collection pits are constructed for collection of rainwater and subsequent leachate (Khan and Islam, 2007).

Khan and Islam (2007) also points out that this type of burial usually results in anaerobic conditions. Such conditions will limit any further degradation when compared with wastes that are land-spread or land-farmed, where the conditions usually are aerobic.

### 2.5.3. Land application

Khan and Islam (2007) describe land application as a form of bioremediation, which allows the natural microbial population of the soil to metabolize, transform, and assimilate waste constituents in place. In order to achieve a sufficient bioremediation, they point out that it is important that the waste application is within the assimilate capacity of the soil. In addition the waste application should not destroy soil integrity, create subsurface soil contamination problems, or cause other adverse environmental impacts. In order to achieve an optimal land application result, Khan and Islam mentions the addition of water, nutrients and other amendments as a beneficial action. This is said to increase the aeration of the soil as well as the biological activity, thus prevent the development of unfavorable conditions which could potentially promote leaching and mobilization of inorganic contaminants.

It is normal to distinguish between two main types of land application methods, namely land farming and land spreading. In the process of evaluating which type of land application method that is most suitable as a waste management option, factors such as site topography, site hydrology, neighboring land use, and the physical and chemical composition of the waste and resulting waste – soil mixture should be considered (Argonne National Laboratory et al., 2007c).

#### 2.5.3.1. Land farming

According to Khan and Islam (2007), land farming is a biological process, which has been used as a disposal and treatment site for oily petroleum wastes for years. They explain that the land farming process consists of controlled and repeated application of wastes to the soil surface. The microorganisms in the soil will then biodegrade hydrocarbon constituents, dilute and attenuate metals, as well as transform and assimilate waste constituents. This is a natural process, which can take several years to remediate (Khan and Islam, 2007).

Khan and Islam (2007) refer to previously studies which have indicated that land farming does not adversely affect soils. It may actually benefit certain sandy soils, due to an increase in their water-retaining capacity, as well as a reduction in fertilizer losses. The inorganic compounds and metals are dilute in the soil, and in some cases incorporated into the matrix.

Argonne National Laboratory et al. (2007c) lists several advantages of land farming, such as simplicity, low capital costs, the ability to apply multiple waste loadings to the same parcel of land, and the potential to improve soil conditions. They also mentions some disadvantages, including high maintenance costs, potentially large land requirements and required analysis, testing demonstration and monitoring. The fact that higher molecular weight petroleum compounds biodegrade more slowly than lower molecular weight compounds is also of great concern. Repeated applications can therefore lead to accumulation of high molecular weight components, which in turn can increase soil-water repellency, affect plant growth, reduce the ability of the soil to support a diverse community of organisms, and make the land farm unusable without treatment or amendment (Argonne National Laboratory et al., 2007c).

According to National Laboratory et al, (2007c), wastes containing large amounts of oil and various additives could potentially have diverse effects on parts of the food chain. Parameters listed under special concerns are pH, nitrogen, major soluble ions (Ca, Mg, Na, Cl), total metals, extractable organic halogens, oil content and hydrocarbons. Wastes containing high levels of biologically available heavy metals and persistent toxic compounds are considered unsuitable for land farming, since these substances has the potential to accumulate in the soil to a level that makes the land unfit for further use (Argonne National Laboratory et al., 2007c).

### 2.5.3.2. Land spreading

According to Khan and Islam (2007), land spreading and land farming shares the same biodegration process of the organic constituents in the waste. The difference, however, lies in the application of the waste. Land farming only consists of a one – time application of the waste to a parcel of land. This is done in an attempt to preserve the subsoil's chemical, biological and physical properties by limiting the accumulation of contaminants and protecting the quality of surface and groundwater (Khan and Islam, 2007).

Argonne National Laboratory et al. (2007c) points out that it is necessary to calculate a loading rate in order to determine the land spreading area. Then factors such as absolute salt concentration, hydrocarbon concentration, metal concentration, and pH level after mixing with the soil, must be taken into consideration. After the land spreading area is determined, drilling waste is spread on the land and incorporated into the upper soil zone. The purpose of this is argued to enhance hydrocarbon volatization and biodegradation. The land is then managed in such a way that the soil system is able to degrade, transport and assimilate the waste constituents (Argonne National Laboratory et al., 2007c).

Advantages such as low treatment costs and the possibility of improved soil characteristics are some examples listed by Argonne National Laboratory et al (2007c). Some disadvantages are also mentioned, such as the need for large land areas, relatively slow degradation process and the need for a vast amount of analysis, tests and demonstrations.

### 2.5.4. Commercial disposal facilities

Some of the onshore disposal methods mentioned above is often affiliated with onsite disposal options. However, in some situations an onsite disposal method is not applicable. Commercial disposal facilities are often used by the oil and gas companies in Norway for various reasons. Generally it is often connected with the fact that regulatory agencies with jurisdiction may not allow onsite disposal for certain types of drilling wastes or in specific locations (Argonne National Laboratory et al., 2007b). It can also be affiliated with lower costs or an issue of liability (Argonne National Laboratory et al., 2007b). This could be the case if an operator has a relatively small volume of waste, then it might be more cost-effective to send it to a commercial disposal facility instead of constructing, operating and closing an onsite facility (Argonne National Laboratory et al., 2007b). In addition, some operators may prefer the waste to be managed by someone else and thereby forwarding some of the responsibility.

Commercial disposal facilities are often viewed as the preferred onshore disposal method in Norway. Such a commercial disposal facility may entail several approaches for waste disposing, including land farming, landfills and pits (Halliburton, 2012). Some facilities also include treatment of the waste before disposing or reusing them, such as biologically-, chemically- or thermal treatment (Argonne National Laboratory et al., 2007b). However, if the right means is available, some of the other methods previously mentioned could also be a reasonable choice (Halliburton, 2012). Examples of commercial disposal facilities in Norway, includes NOAH, TWMA and Franzefoss Gjenvinning AS located in Mongstad, Langøya and Eide, respectively (Halliburton, 2012). NOAH is considered the largest commercial disposal facility, while TWMA and Franzefoss Gjenvinning AS only include the waste disposal site as a part of their operations (Halliburton, 2012). The costs affiliated with commercial disposal facilities, will obviously vary depending on different factors, such as disposal method used and location of the disposal facility (Argonne National Laboratory et al., 2007b).

## 2.6. Thermomechanical Cuttings Cleaner (TCC)

Drill cuttings transported onshore will normally undergo a thermal treatment for removal of oil. Stricter legislations and regulations concerning discharges and emissions during drilling operations, has heightened the focus towards a higher standard with respect to waste technology (Paulsen et al., 2003). There are many available treatment methods for drilling waste, such as the Thermomechanical Cuttings Cleaner (TCC). The TCC method is regarded as a suitable treatment method for drill cuttings and has been available on the drilling waste market for approximately 10 years (Thermtech, 2006e). The TCC method is of outmost importance for this thesis, and will therefore be further elaborated.

### 2.6.1. Principles of the TCC method

The TCC method is based on a thermal separation by generating heat from friction, with the purpose of converting a hazardous oily waste into a useful and safe product (Halliburton, 2012). A rotating hammer mill is set in motion inside the process chamber, creating friction in the waste and thus converting kinetic energy into thermal energy (Thermtech, 2006b). The end result from this thermal treatment is three distinct phases of recovered oil, water and dry solids, respectively.

Separation is achieved by generating a temperature high enough to evaporate the oil and water from the mineral solids (Thermtech, 2006d). In order to achieve this, the temperature needs to be higher than the evaporation point of the base oil in the OBM (Halliburton, 2007). A typical temperature range of products will normally lie between 240 °C and up to 300 °C (Halliburton, 2007). The liquid phase evaporates through a vapor outlet and are subsequently condensed back to oil and water in separate containers in later process steps (Thermtech, 2006d). The solids on the other hand is recovered through an auger system and discharged through a cell valve as dry powder, shown in Figure 2-6 (Thermtech, 2006b). The dry material is normally rehydrated with water in order to promote easier handling.

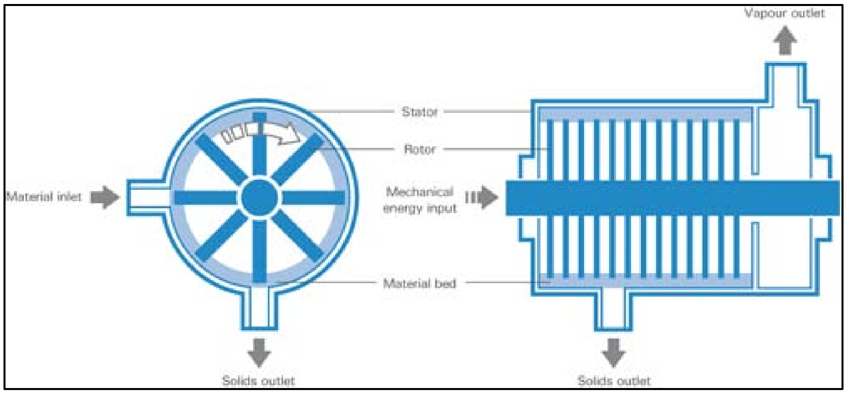

**Figure 2-6: Cut view of TCC process mill (Thermtech, 2006b)**

Figure 2-7 outlines the different process steps in a TCC treatment method. Before start-up the process chamber only consist of dry solids. When set in motion the mill forces the solids towards the inner wall and grinds them down into a very fine powder (Halliburton, 2007). This generates friction and starts to heat up the waste. When the process chamber reaches a pre set temperature, drilling waste will automatically be fed into the process chamber. Preheated solids will then warm up the incoming waste, and the separation process is eventually set in motion (Halliburton, 2012)

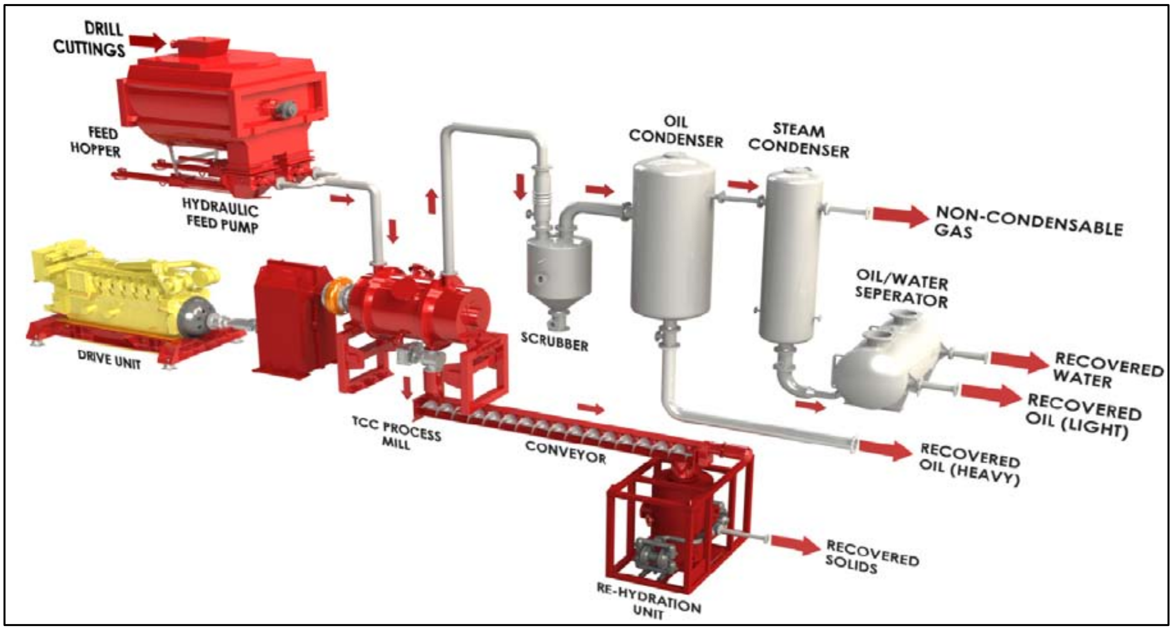

**Figure 2-7: TCC process flow diagram (Jensen and Halliburton, 2012)**

After treatment three different phases is recovered; oil, water and solids. Since the base oil is under influence of high temperatures for only a maximum of a few seconds, it will avoid cracking and thus sustain a high enough quality to be re-used as a component in OBM (Thermtech, 2006b, Svensen and Taugbol, 2011). In addition, the water and crushed cuttings are cleaned to levels well below the offshore requirements of 30 mg/l of oil in water and 1 % oil on cuttings by weight, respectively. According to TWMA (2010), the levels of retained hydrocarbons in the recovered solids and water are actually < 0.1 % and < 20 ppm, respectively. The recovered water is also said to typically contain 5 – 15 mg/l suspended solids.

## 2.6.2. Characteristics and field of application

According to Paulsen et al. (2003), implementation of waste volume reduction could potentially offer several HSE benefits. Therefore it is important to explore waste technologies that can aid the waste volume reduction process. Paulsen et al. (2003) feels that an introduction of an offshore based technology would help reduce the volume that needs to be discharged, or transported onshore. This would create lesser waste material, followed by fewer containers, less required storage space and fewer crane lift. Overall it would help reduce the safety risk with respect to loading and transportation. Paulsen et el. (2003) says that it is important that the unit can match offshore weight and footprint limits, otherwise such a technology cannot be implemented offshore. In addition he points out that it needs a sufficient processing capacity that does not compromise rig storage capacity and space.

The TCC unit could be a suitable option for waste volume reduction offshore. According to Paulsen et al. (2003), the clean base oil and water recovered in the process could be reused on site or discharged to sea, respectively. Due to an oil content of less than 1 % w/w as stated in the requirements, the dry powder generated could potentially be discharged to sea. However, due to the prevalent regulations concerning waste generated from drilling operations, transportation of waste onshore is thus of most relevance. Even after a thorough treatment of the waste where requirements are met, it is still considered a waste and needs to be disposed of in a proper way (Paulsen et al., 2003).

According to TWMA (2010), a TCC unit can be operated on a 24 – hour per day basis, with approximately 5 tons of drill cuttings treated per hour. However, the capacity of a TCC unit will depend on the energy input as well as the waste content (Thermtech, 2006a). Thermetch (2006b) points out that the capacity indication then will be based on the wastes composition. The amount of water in the waste will therefore affect the energy required to heat and evaporate the different compounds in the waste. Low water content will obviously yield a higher capacity compared to a waste with higher water content.

Thermtech (2006c,i) specifies that the TCC unit holds several advantages compared to other thermal desorption technologies, such as small footprint, high mobility and time efficient start up. In addition the process chamber has no oxygen sources and is protected by insulation and simple routines. Another important advantage is the absence of emissions to the atmosphere during the process (TWMA, 2010). Furthermore, the TCC unit is versatile when it comes to location of the actual processing. It is possible to process the drill cuttings and associated drilling wastes from a central processing facility, offshore rig or platform, supply vessel or on a land rig location (TWMA, 2010). This versatility opens the possibility for processing the cuttings directly near the source of waste. Due to this and other beneficial qualities such as inherent safety, the TCC unit is probably the only thermal technology that can be operated on board of a drilling rig (Thermtech, 2006c). The TCC unit has been successfully implemented on offshore rigs internationally (Halliburton, 2012). However, this method is only used onshore in Norway, but the objective is to eventually introduce it offshore Norway as well (Svensen and Taugbol, 2011). Experiences from offshore rigs operating with TCC units, indicate that having this procedure on the drilling rig would help reduce environmental impact, as well as lowering the costs affiliated with logistics and transportation of drilling waste (Svensen and Taugbol, 2011). Currently there are five operating TCC units in Norway, one located in Sandnessjøen, one in Mosjøen and three in Mongstad (Halliburton, 2012).

## 2.6.3. Study: TCC unit as Best Available Technique (BAT)

Chapter 2.6.3 is solely based on the article “Drill Cuttings Disposal, Balancing Zero Discharge and Use of Best Available Technique” published by Paulsen et al. in 2003. This article offers results and discussion regarding a study on how operators may comply with zero hazardous discharge in drilling operations, with reference to BAT. In this article they accentuate an investigation of the TCC unit conducted by Statoil, which included the possibility of implementing the TCC unit as an offshore treatment option for drilling waste. Different modeling tools were used in order to model the environmental impact factor (EIF) of drilling waste discharges. The test subjects included a TCC treated powder slurrified with condensed water from the TCC treatment and seawater, as well as WBM drill cuttings.

### 2.6.3.1. BAT review of TCC unit

The following issues were taken into consideration when balancing drill cuttings BAT solutions:

- ✓ Drilling technology
  - ✓ Well design (e.g.: hole diameter, and/or number of wells etc.)
  - ✓ Drilling fluid
  - ✓ Solids handling equipment on rig
- ✓ Drilling waste
  - ✓ Disposal options
  - ✓ Transport and logistics
  - ✓ Drilling waste disposal options

- ✓ Impacts of the different waste disposal options
  - ✓ Energy requirement, gas emissions
  - ✓ Environmental impact factor if discharged offshore
  - ✓ Risk of jeopardizing drilling progress
  - ✓ Human hazard
- ✓ Costs

An offshore treatment unit like the TCC unit could potentially reduce the waste volume significantly. The ideal prospective fate for the treated fractions was a direct discharge of the water faction into the sea, reuse of oil fraction on site, and direct discharge or transportation to land of the solid fraction. If the treated drill cuttings would require shipment to shore for disposal, then Paulsen et al. points out that current technology would allow the dried powder to be blown in bulk, avoiding numerous crane lift operations.

It was stated that a BAT review should entail an evaluation of the handling, processing, transportation and disposition of the material. Three disposal options were investigated and compared with respect to total disposal costs, constraints, environmental load (energy, $CO_2$, $NO_x$, $SO_2$) and waste minimization benefits:

1) Use of containers
2) TCC offshore and discharge of drilling waste
3) Use of bulk transfer system and large, closed pressurized containers.

Option number 2 had the lowest costs and environmental loads compared with the two remaining options. In addition it had high waste minimization benefits, even if the treated powder was shipped to shore. Constraints mentioned for option number 2, was the need for extra rig storage capacity of drill cuttings, as treatment capacity is limited. However, calculations showed that the storage capacity should be possible to match for a number of drilling rigs. It was clear that the TCC method had the potential to help reduce environmental load and risk associated with transfer of waste material.

### 2.6.3.2. Fate of chemicals during TCC processing

Even though the TCC method was viewed as the most favorable option, Paulsen et al. still raised the question; *"is it justifiable to discharge the treated waste material?"* This is a reasonable question since the waste volume and their final fate are important inputs in an environmental assessment. The environmental impact of discharging the treated material to the sea column was therefore also investigated.

In order to gain more knowledge about the fate of the chemicals during the TCC processing, a thermogravimetry (TG) analysis was performed. This is an area where the knowledge is limited and where only assumptions have been previously made. The oil-soluble drilling chemicals were assumed distilled together with the oil, while water-soluble chemicals would follow the water phase. Previously suggestions have also included the possibility of decomposition of the chemicals and transformation during the TCC process. By using a TG analysis, a simulation of the fate of the chemicals during heating would be conducted.

Simply summarized; three different OBM chemicals were heated up to 550°C in an inert atmosphere (helium), and their weight change was recorded as a function of temperature. Chemical 1 consisted of a polymer and did not show any weight changes until 250 °C. Even after that the changes was minimal, until around 350 °C. Chemical 2 and chemical 3 consisted of a polymer and two solvents each. The weight changes started relatively early for both chemicals, at 50 °C and 100 °C, respectively. At the cut-off point of 300 °C, chemical 2 and 3 had a weight loss of 35 % and 37 %, respectively. At 500 °C all the samples had more or less evaporated. In other words; chemical 1 only consisted of non-volatile components, while chemical 2 and 3 had a volatile part that constituted of 35 % and 37 %, respectively. The conclusion drawn from this, were that the polymers contained in every chemical was essentially non-volatile. Thus, they would most likely remain within the solid material after the TCC treatment.

### 2.6.3.3. Environmental Impact Factor (EIF) of treated powder discharge

Another important issue discussed in this article, is how the treated powder would behave in the water if it was to be discharged. This is an area which is relatively unknown, and therefore needs excessive testing and analyzing. DREAM and ParTrack are common modeling tools used to model impacts of water-dispersed chemicals. In this case, Statoil used these modeling tools for the purpose of modeling the EIF of drilling waste discharge. The discharge point of the simulated slurry was set at 50 m depth, with an particle diameter size range of 0,5 – 70 µm. Calculations made included dispersion and sedimentation patterns for both the powder particles and the weighting agent barite.

The results from a 12 ¼” drill section showed a spreading of the particles over a wide area. Smaller particles would float and quickly get drifted far away by currents. Thus, it was assumed that potential deposition layers would be extremely small, for both WBM drill cuttings and the TCC powder. Predicted influence area was modeled based on an estimated discharge of 856 ton particulate matter spread over 10 days. Based on these data, Paulsen et al. estimated that no accumulation or cutting piles should be expected. Only a thin layer of a few millimeters thickness could potentially form in the nearest area surrounding the rig.

The EIF was calculated for five different situations, where the chemical residues were assumed unaltered and attached to the cuttings. The following cases and results were listed:

1. OBM 2, 17 ½" section, EIF = 4
2. OBM 1, 12 ¼" section, EIF = 78
3. OBM 1, 8 ½" section, EIF = 223
4. WBM GP, 17 ½" section, EIF = 153
5. Cesium Formeate, 8 ½" section, EIF = 1527

Paulsen et al. explains the EIF number as follows: *"The EIF number is a quantification of a possible effect on marine organisms within a specific body of water. The reference water body is 100 000 $m^3$. Hence, EIF = 1 says that a body of 100 000 $m^3$ seawater is estimated to have a concentration of chemical(s) with a possible effect on marine species. The predicted effect is given with reference to the specific discharge point and the respective ambient conditions."*

The results showed a distinct difference between these cases, especially between the modeled EIF numbers for the TCC treated material and corresponding WBM cuttings with 17 ½" section. For instance, the predicted EIF number for the TCC treated material was much lower than for WBM cuttings of 4 and 153, respectively. Actually, discharge of TCC treated material was predicted at a relatively low EIF in all cases. Paulsen et al. points out that EIF = 78 is within the acceptable range calculated for produced water discharges at the Norwegian Sector of the North Sea.

### 2.6.3.4. Conclusion from study

Paulsen et al. states from the OSPAR Regulation and in the IOOC Directive, *"a "best technique" solution is justified by being the most effective in achieving a high general level of protection of the environment as a whole".* This case study shows several potential benefits by implementing a TCC unit offshore, both on aspects such as environmental budgets and HSE benefits. However, no definitive conclusion was given on the matter of viewing TCC unit as the best option for BAT. There are still some uncertainties left to investigate, such as to what extent the treated powder will form aggregates with corresponding unknown sedimentation rates. In addition, it is unknown if the remaining chemicals attached to the particles could pose negative effects on the environment. Nevertheless, a discharge of TCC treated material must be in compliance with the prevalent regulations.

## 2.7. Chemicals in the Petroleum Industry

In this context, chemicals are used as a generic term for all the chemical additives used in drilling operations, well operations and in production of oil and gas. According to the Norwegian Petroleum Directorate (2011), as much as 99 % of all chemicals used in Norwegian petroleum activities are either categorized as green or yellow chemicals[1]. These categories are not considered to be environmentally hazardous and will not pose a threat to the environment. Environmentally hazardous chemicals refers to specific chemicals or groups of chemicals with inherent properties  such as acute toxicity, persistence, bioaccumulation and/or low biodegradation (Norwegian Petroleum Directorate, 2011).

In order to drill a new well, the oil companies involved need to apply for a discharge permit. According to a technical report issued by Baroid Surface Solutions at Halliburton (2009), this application must contain detailed descriptions on intended plans for the well, as well as the intended discharge affiliated with this activity. The discharges must therefore comprise of amounts and types of chemicals that will be used during the drilling activities. Since chemicals and solids are classifies according to their inherent environmentally hazardous properties, all chemicals intended to be used in drilling activities needs to be tested for acute toxicity and potential for bioaccumulation and biodegradation (Halliburton (Baroid Surface Solutions), 2009).

### 2.7.1. Substitution of environmental hazardous chemicals

In an ongoing effort to reduce discharge of potential environmentally hazardous chemicals from petroleum activities and into the sea, a goal of zero hazardous discharge was established (Norwegian Petroleum Directorate, 2011). This was stated in a report to the Norwegian parliament nr. 58 (1996-1997) called Environmental policy for a sustainable development.  The goal of zero hazardous discharge has later been refined and specified in other reports to the Norwegian parliament. The basic principle of this report is to stop the discharge of oil and environmentally hazardous chemicals into the ocean (Norwegian Petroleum Directorate, 2011).  Great emphasis is put on the possibility of early identification of the main harmful components of the discharges and to assess their effects on the environment (Pinturier and Moltu, 2008). This includes both naturally occurring compounds as well as manufactured compounds added during the operations(Pinturier and Moltu, 2008).

According to the Norwegian Petroleum Directorate (2011), the total discharge of environmentally hazardous chemicals (red and black) was as high as 4160 tons in 1997. Implementing the zero hazardous discharge goal reduced the discharge of red and black chemicals to 17 tons by 2008, which is equal to a reduction of 99,6 %. Already in 2005 the

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[1] See Appendix 2 for additional information on categorization of chemicals.

goal of zero hazardous discharge was reached for both existing and new installations, according to a report to the Norwegian parliament nr 26 (2006-2007). However, in order to ensure a phasing – out of the remaining red and black chemicals there is still a high focus towards substitution of chemicals. (Norwegian Petroleum Directorate, 2011).

### 2.7.2. Environmental effects by discharging of drilling waste

The following section, 2.7.2, is solely based on a report issued by the Norwegian Petroleum Directorate in 2011, which consists of a survey of available environmental technology in the petroleum industry on the Norwegian Continental Shelf.

Environmental monitoring of discharge to sea affiliated with the petroleum industry was first introduced in 1973. In the beginning this activity was basically limited to monitoring sediments with regards to discharge of drill cuttings. However, when discharge of oil based drill cuttings was prohibited in 1993, environmental monitoring was eventually directed towards the water column. The increasing amount of discharged produced water in the 90s was also a major contributor to this change. According to HSE regulations the Petroleum Industry it is now required to conduct environmental monitoring of both sediments and water column[2].

These governmental demands have contributed to acquire vast information on the seabed surrounding Norwegian petroleum installations. However, since the water column is a dynamic system, it has been more difficult to acquire the right methodology in order to collect the most representative information. Thus, monitor of the water column has continuously developed along the way, and will still be subject to some changes in the near future. This is due to operators limited experiences with this type of surveillance, as well as the difficulty of establishing changes in the water column as oppose to the sediments.

On the other hand, the methodology for sampling and analysis for sediments has been unchanged since 1990. This surveillance program covers chemical analysis of hydrocarbons, heavy metals, radioactive substances and potentially changes in composition in benthic biota. The results from this monitor program actually led to great changes in discharge of drill cuttings. Drill cuttings with oil-on cuttings > 1 % in weight was prohibited to be discharged in the Norwegian shelf in 1993. In fact, this discharge prohibition was later applicable for the whole OSPAR area.

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[2] See Appendix 8.3, §§§§52, 53, 54 and 55 for further information about rules and regulations concerning monitoring of the external environment.

# 2.8. Rules and regulations

The laws and regulations concerning activities on the Norwegian Continental Shelf have changed allot since the first exploration well was drilled in 1966. Up until 1980, diesel was used as the continuous phase in oil based drilling mud. (Akvaplan-niva AS, 2010). After the ban of discharging of OBM-cuttings in 1993, all waste from drilling or production of hydrocarbons using OBM has been classified as hazardous waste.

Drilling activities conducted in the Northern Continental Shelf is mainly governed by The Activities Regulations, the Pollution Act and the Waste Regulations. The purpose of this chapter is to outline the most relevant information in these laws and regulations with regard to this thesis. Citations have been made from these ruled and regulations by emphasizing the text in italic.

## 2.8.1. The Activities Regulations

The following section, 2.8.1, is only based upon the regulation 2010-04-29 no 613: Regulations relating to conducting petroleum activities, from now on referred to as The Activities Regulations (Aktivitetsforskriften, 2010).

### 2.8.1.1. Chapter XI: Emissions and discharges to the external environment

Chapter XI in The Activities Regulations deals with emissions and discharges to the external environment. §§§ 60, 68, 70, 71 and their associated guidelines, are of most importance with regards to activities concerning drill cuttings.

According to §60, oily water needs to be cleaned prior to discharge to sea, except for displacement water. It is important to keep the oil content in water being discharged to sea as low as possible. It is further stated that the *"oil content shall not exceed 30 mg oil per liter of water as a weighted average for one calendar month".* The possibility of reducing the total discharged water volume should also be considered, which can be achieved by implementing measures such as water shut-off, downhole separation and injection.

§ 68 provide rules and guidelines for the discharge of cuttings, sand and solids particles. According to the guidelines provided for §68, cuttings is defined as both solid material from the formation and solid material added as part of the drilling fluid as well as other fluids used in drilling and well activities. § 68 states that if the formation oil, other oil or base fluid in organic drilling fluid exceed ten grams per kilo of dry mass, drill cuttings is not allowed discharged to sea. This also applies for sand and other solid particles. However if the requirement of ten grams of oil per kilo of dry mass is met, discharge to sea should only be last resort.

The operator should consider additional cleaning or other disposal methods as oppose to discharge to sea. Re injection into formation is considered a viable option. In addition the responsible party must conduct measurements of the amount of organic drilling fluid and oil discharged with the solids, where mineral oil-based and synthetic drilling fluid is included in organic drilling fluids.

§ 70 provide rules and guidelines related to measuring the discharged quantity of oil, other substances and water. It states that *"The content of oil and other substances in the discharge shall be measured."* In this context other substances means substances for which reporting requirements are set, cf. the Climate and Pollution Agency's *Guidelines for reporting from offshore petroleum activities.* The test results received from the measurements shall be used to verify the treatment plant's performance.

A measurement program needs to be established in order to ensure representative and comparable measurements. This measurement program should contain measurements frequency, discharge parameters and measurement methods.

§70 further states that *"The oil content of water shall be analyzed according to OSPAR's reference method for determining dispersed oil in water (OSPAR ref. No. 2005-15, which is a modification of ISO 9377-2) or analysis method calibrated towards this (…)."*

According to § 71 *"The responsible party shall measure the amounts of organic drilling fluid and oil discharged with solids".* In this context organic drilling fluid is referred to as mineral oil-bases and synthetic drilling fluids. The term solids include cuttings, produced sand and other solid materials from the well.

#### 2.8.1.2. Chapter XII: Waste

Chapter XII in The Activities Regulations deals with waste management.

In § 72, emphasis is put on avoiding generation of waste to the extent possible. In the matter of waste generation the operator must prepare a waste management plan where the waste will be handled in a prudent environmental and hygienic manner. Subjects such as source separation, reduction of waste volume, reuse, recycling and potential energy recovery should be included in the management plan. When handling the waste generated during drilling activities there are some additional regulations which applies to the given situation.

### 2.8.2. Pollution Control Act

The following section, 2.8.2, is based on Act 1981-03-13 no. 06: Concerning Protection against Pollution and Concerning Waste, from here on referred to as the Pollution Control Act (Norwegian Government, 2003). Other references used in this section, is clearly implied in the text.

The Pollution Control Act is an enabling act, which means that the discharge permits and regulations are issued by the pollution control authorities (Climate and Pollution Agency, 2004). Details in each case of The Pollution Control Act are outlined in these discharge permits and regulations (Climate and Pollution Agency, 2004).

The purpose of this Act, as it is stated in §1, is to[3]:
*"(…) protect the outdoor environment against pollution and to reduce existing pollution, to reduce the quantity of waste and to promote better waste management.*

*The Act shall ensure that the quality of the environment is satisfactory, so that pollution and waste do not result in damage to human health or adversely affect welfare, or damage the productivity of the natural environment and its capacity for self-renewal."*

The following guidelines are cited from § 2 of the Act:

1. *"Efforts shall be made to prevent any occurrence or increase of pollution, and to limit any pollution that does occur. Similarly, efforts shall be made to avoid waste problems. The Act shall be used to achieve a level of environmental quality that is satisfactory on the basis of an overall evaluation of human health and welfare, the natural environment, the costs associated with any measures implemented and economic considerations*
2. *The pollution control authorities shall coordinate their activities with the planning authorities in such a way that land-use planning legislation together with this Act is used to avoid and limit pollution and waste problems.*
3. *Efforts to avoid and limit pollution and waste problems shall be based on the technology that will give the best results in the light of an overall evaluation of current and future use of the environment and economic considerations.*
4. *Waste shall be managed in such a way as to minimize damage and nuisance. Waste shall be recovered when this is appropriate on the basis of an evaluation of environmental and natural resource considerations and economic factors.*
5. *The costs of preventing or limiting pollution and waste problems shall be met by the person responsible for the pollution of waste.*
6. *Pollution and waste problems resulting from activity in Norwegian territory shall be counteracted to the same extent irrespective of whether the damage or nuisance arises within or outside Norway."*

The Act, § 7, states that no one may possess, do or implement anything which may entail risk of pollution, unless this is permitted by law pursuant to §8 or §9, or unless it is permitted in accordance with decisions pursuant to §11 in the Act[4].

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[3] See Appendix 4, § 4, to view the appliance of the Act on the continental shelf.
[4] See Appendix 4 to view the content of §9.

According to § 11, the pollution control authority may upon application give permission for activities which may lead to pollution. § 12 state that the application shall entail any information necessary to evaluate whether a grant should be given for the permit.

According to §13, a notification to the pollution control authority is in order if someone is planning any activity that may involve major pollution problems. In addition they might need to perform an environmental impact assessment.

The following citation from § 13 state that this environmental impact assessment normally shall include a study of:

1. *"which types of pollution the activity will generate during normal operations and in the event of all conceivable types of accidents, and the likelihood of such accidents,*
2. *what short- and long-term effects the pollution may have. If necessary, studies shall be made of natural conditions in the areas that may be affected by pollution. In particular, it shall be ascertained how pollution will affect people's use of the environment and who will suffer particular nuisance as a result of pollution,*
3. *alternative locations, production processes, purification measures and ways of recovering waste that have been evaluated, and reasons for the solutions chosen by the applicant,*
4. *how the activity will be integrated into the general and local development plans for the area, and if relevant, how it will restrict future planning. "*

## 2.8.3. Waste Regulations

Regulation 2004-06-01 No. 930: Regulations relating to the recycling of waste (The Waste Regulations) only exist in Norwegian (Avfallsforskriften, 2004), thus the following section, 2.8.3, is based upon the Norwegian text as well as an unofficial translation of relevant sections of the Norwegian regulation by the Climate and Pollution Agency (Waste Regulations, 2012). Throughout the following section this regulation will be referred to as the Waste Regulations.

### 2.8.3.1. Chapter 9: Landfilling of waste

The purpose of the provision in chapter 9 of the Waste Regulations is to ensure that the waste in question is handled in a proper way, ensuring a controlled and sound landfilling procedure. This is important in order to prevent adverse effects on the environment and human health to the extent possible.

According to § 9-3; Definitions (letter g), inert waste is defined as *"(...) waste that does not undergo any significant physical, chemical or biological transformations. Inert waste will not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect* *other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm to human health. The total leachability and pollutant content of the waste and the ecotoxicity of the leachate must be insignificant and in particular not endanger the quality of the surface water and/or groundwater."*

According to § 9-5 *"each landfill should be classified into one of the following classes[5]:*

- ✓ *Class 1: landfill for hazardous waste,*
- ✓ *Class 2: landfills for non-hazardous waste,*
- ✓ *Class 3: landfills for inert waste."*

Appendix II in chapter 11 in Waste Regulations contains specific acceptance criteria for these three waste categories. Table 2-3 presents the leaching limit values given for hazardous waste. In order to be allowed to dump hazardous waste at landfills for hazardous waste, the waste may not exceed the limits given in Table 2-3. The two remarks appurtenant to Table 2-3 are direct citations from appendix II, section 2.4.1: Leaching limit values, in Waste Regulations.

**Table 2-3: Leaching limit values for hazardous waste (Waste Regulations, 2012)**

| **Parameter** | **L/S = 10 l/kg at standard leaching test with particle size < 4mm mg/kg dry matter** | **CO (L/S = 0.1 l/kg) at percolation test mg/l** |
|---|---|---|
| Arsenic (As) | 25 | 3 |
| Barium (Ba) | 300 | 60 |
| Cadmium (Cd) | 5 | 1.7 |
| Chromium ( Cr), total | 70 | 15 |
| Copper (Cu) | 100 | 60 |
| Mercury (Hg) | 2 | 0.3 |
| Molybdenum (Mo) | 30 | 10 |
| Nickel (Ni) | 40 | 12 |
| Lead (Pb) | 50 | 15 |
| Antimony (Sb) | 5 | 1 |
| Selenium (Se) | 7 | 3 |
| Zinc (Zn) | 50 | 60 |
| Chloride | 25 000 | 15 000 |
| Fluoride | 500 | 120 |
| Sulphate | 50 000 | 17 000 |
| Dissolved organic carbon (DOC)* | 1 000 | 320 |
| Total dissolved solids (TDS)** | 100 000 | - |

**"*If the waste exceeds the limit values for DOC at its own pH, it may alternatively be tested at L/S = 10 l/kg and a pH between 7.5 and 8.0. The waste may be considered as meeting the acceptance criteria for DOC if the result of this determination does not exceed 1 000 mg/kg.**

****The values for total dissolved solids (TDS) can be used as an alternative to the limit values for sulphate and chloride."**

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[5] See Appendix 5 to view § 9-6: Waste to be accepted in the different classes of landfill.

Additional limit values are given for hazardous waste in section 2.4.2, which states that the waste may not exceed one of the limit values for organic parameters given in Table 2-4. The remark appurtenant to Table 2-4 are direct citations from appendix II, section 2.4.2: Limit values for organic parameters, in Waste Regulations.

**Table 2-4: Limit values for organic parameters in hazardous waste (Waste Regulations, 2012)**

| Parameter | Value |
|---|---|
| Loss of ignition | 10 % |
| Total organic carbon (TOC) | 6 %* |

**"*If the value is not achieved, the relevant authority may allow a higher limit value, provided that the limit value for DOC, 1 000 mg/kg, is met at L/S = 10 l/kg, either at its own pH or at a pH value between 7.5 and 8.0."**

Appendix II, section 2.2: Acceptance criteria for landfills for non-hazardous waste, in Waste Regulations points out that waste permitted to be dumped at a landfill for non-hazardous waste, are the wastes which is not classified as hazardous waste pursuant to chapter 11, appendix 1 of the Waste Regulations (the European List of Wastes).
Table 2-5 illustrates the leaching limit values for slightly contaminated masses received at landfills for inert waste. In order to be categorized as inert waste, the waste may not exceed the leaching limit values given in Table 2-5. The three remarks appurtenant to Table 2-5 are direct citations from appendix II, section 2.1.1: Leaching limit values, in Waste Regulations.

**Table 2-5: Leaching limit values for inert waste (Waste Regulations, 2012)**

| Parameter | L/S = 10 l/kg from standard leaching test with particle size < 4mm mg/kg dry matter | CO (L/S = 0.1 l/kg) from percolation test mg/l |
|---|---|---|
| Arsenic (As) | 0.5 | 0.06 |
| Barium (Ba) | 20 | 4 |
| Cadmium (Cd) | 0.04 | 0.02 |
| Chromium ( Cr), total | 0.5 | 0.1 |
| Copper (Cu) | 2 | 0.6 |
| Mercury (Hg) | 0.01 | 0.002 |
| Molybdenum (Mo) | 0.5 | 0.2 |
| Nickel (Ni) | 0.4 | 0.12 |
| Lead (Pb) | 0.5 | 0.15 |
| Antimony (Sb) | 0.06 | 0.1 |
| Selenium (Se) | 0.1 | 0.04 |
| Zinc (Zn) | 4 | 1.2 |
| Chloride | 800 | 460 |
| Fluoride | 10 | 2.5 |
| Sulphate | 1 000* | 1 500 |
| Phenol index | 1 | 0.3 |
| Dissolved organic carbon (DOC)** | 500 | 160 |
| Total dissolved solids (TDS)*** | 4 000 | - |

**"*If the waste exceeds the limit values for sulphate, it may still be considered as meeting the acceptance criteria provided that leaching does not exceed any of the following value: 1 500 mg/l as CO at L/S = 0.1 l/kg and 6 000 mg/kg at L/S = 10 l/kg**
****If the waste exceeds the limit values for dissolved organic carbon (DOC) at its own pH value, it may alternatively be tested at L/S = 10 l/kg and at a pH between 7.5 and 8.0. The waste may be considered as meeting the acceptance criteria for DOC if the results of this test do not exceed 500 mg/l.**
*****The values for total dissolved solids can be used as an alternative to the values for sulphate and chloride."**

Additional requirements need to be met, in order for a waste to be landfilled as inert waste. Table 2-6 presents the limit values required for organic parameters. The waste cannot exceed these limits for the total content of organic parameters. The remark belonging to Table 2-6 is a direct citation from appendix II, section 2.1.2: Limit values for organic parameters, in Waste Regulations.

**Table 2-6: Limit values for organic parameters in inert waste (Waste Regulations, 2012)**

| Parameters | Value |
|---|---|
| Total organic carbon (TOC) | 3 %* |
| Benzene, toluene, ethyl benzene and xylenes (BTEX) | 6 mg/kg |
| Polychlorinated biphenyls (7 congeners of PCB) | 1 mg/kg |
| Mineral oil (C10 to C40) | 500 mg/kg |
| Polycyclic aromatic hydrocarbons (PAH 16) | 20 mg/kg |
| Benzo(a)pyrene | 2 mg/kg |

**"*In the case of soil, the competent authority may allow a higher limit value, provided that the limit value for dissolved organic carbon, 500 mg/kg, is met at L/S = 10 l/kg, either at the pH of the soil or at a pH value between 7.5 and 8.0."**

### 2.8.3.2. Chapter 11: Hazardous waste

Chapter 11 in Waste Regulations covers the different aspects regarding hazardous waste. According to §11-1, this provision is created in order to ensure that hazardous waste is dealt with in a proper way, eliminating the risk for pollution or damage to people or animals. In addition the purpose of this provision is to contribute to an appropriate and dependable system for the management of hazardous waste.

Hazardous waste is in accordance with § 11-3 defined as *"(…) waste that cannot be treated appropriately together with other household waste because it may cause serious pollution or involve risk of injury to people and animals".*

The types of hazardous waste that are covered by the provisions of this chapter is listed in § 11-4. These includes waste which is marked with a star * in the European Waste list (EWL) given in Appendix 1 appurtenant to chapter 11 in the Waste Regulations (no 1), as well as other waste where the content of hazardous substances exceeds the limit values specified in appendix 3 appurtenant to chapter 11 (no 2). The wastes listed in EWL are divided into different chapters according to source of origin. Chapter 01 covers waste from searching, extraction in mining, quarry and physical and chemical treatment of minerals.

Table 2-7 illustrates the different types of waste categories in chapter 1 which is relevant for this thesis.

**Table 2-7: Categorization of waste according to European Waste List (EWL)**

| **Subsection:** | **Waste category:** |
|---|---|
| **16 50** | Drilling fluids and other dill cuttings |
| *16 50 71 | Drilling fluid and drill cutting containing oil |
| *16 50 72 | Drilling fluid and other drill cuttings containing hazardous substances |

The following citation from § 11-4 states that: *"Types of waste that are included under subsection one, no 1, can be exempt from the provisions in this chapter if the holder of the waste can document that the waste is not hazardous in accordance with subsection one, no 2. The holder of the waste shall notify the Climate and Pollution Agency or the agency authorized by the Ministry of the Environment about such exemptions. The Climate and Pollution Agency or the agency authorized by Ministry of the Environment can determine more detailed requirements concerning documentation*

*Waste from processed, solid products may contain hazardous substances that exceed the limit values specified in appendix 3 of this chapter. These types of waste are covered by subsection one, no 2, if there is a possibility that the hazardous substances will leak out into the surroundings and thereby constitute a risk of pollution.*

*Holders of the waste are responsible for assessing whether the waste is covered by the provisions of this chapter. Climate and Pollution Agency or the agency authorized by the Ministry of the Environment, in case of doubt, may determine whether the waste is covered by the provisions in this chapter. "*

Appendix 1, EWL, associated with chapter 11, states that if presented documentations shows that a specific type of hazardous waste actually is not hazardous according to the criteria's in appendix 3, the waste can be handled as non-hazardous waste (Avfallsforskriften, 2004). If this is the case, The Pollution Authority needs to be oriented on the matter(Avfallsforskriften, 2004). Thus copies of the analytical evidence and other relevant documentation must be sent to The Climate and Pollution Agency(Avfallsforskriften, 2004).

### 2.8.4. Onshore discharge limitations for water phase

Table 2-8 outlines the discharge limitations issued by the Climate and Pollution Agency (KLIF) in Norway for recovered water after treatment of drilling waste appurtenant to treatment facility at Halliburton Mongstad. These discharge limitations is only valid at this treatment facility.

**Table 2-8: Discharge limitations for retrieved water phase at Halliburton Mongstad**

| Discharge component | Discharge limits | |
|---|---|---|
| | Discharge limits in concentration per day: [mg/l] | Long-term limits [kg/year] |
| Oil | 10 | 1 225 |
| TOC | 1 000 | 122 500 |
| Arsenic (As) | 0.05 | 6.1 |
| Barium (Ba) | 0.5 | 36.8 |
| Cadmium (Cd) | 0.01 | 12.3 |
| Chromium (Cr) | 0.05 | 61.3 |
| Copper (Cu) | 0.1 | 6.1 |
| Mercury (Hg) | 0.003 | 12.3 |
| Molybdenum (Mo) | 0.1 | 1.2 |
| Nickel (Ni) | 0.3 | 12.3 |
| Lead (Pb) | 0.025 | 61.3 |
| Zink (Zn) | 0.5 | 0.4 |
| Tin (Sn) | 0.1 | 3.1 |
| Vanadium (V) | 0.25 | 30.6 |
| pH | 5.7 – 8.5 | - |
| Discharge flow (maximal) | 672 $m^3$/diurnal | 245 000 $m^3$/year |

# 3. Materials and methods

The following chapter describes the sampling process, treatment facilities and outlines the different parameters which have been analyzed. This is a part of the suggested analytical program of untreated/treated solids and water phase from TCC processing, where this work is considered as a pre-study for potential upcoming OLF study.

## 3.1. The sampling process

Samples were taken from two different treatment facilities, TWMA and Halliburton Mongstad. The sampling process was personally conducted on Wednesday 16.05.2012 with some assistance from the personnel working at the facilities.

### 3.1.1. Packaging and packing material

The packing material was prepared and delivered at Halliburton Mongstad by the accredited laboratory Eurofins, located in Bergen. Instructions and amount of samples needed for the different analysis was specified ahead of the sampling process, and is outlined in Table 8-5 and 8-6 in Appendix 8.6. After retrieving the samples from both TWMA and Halliburton Mongstad, the samples were returned to Eurofins for further analysis.

### 3.1.2. TWMA

The first round of samples was gathered from TWMA Norway AS in Mongstad. The batch currently treated on this facility was drill cuttings derived from drilling 17 ½” section on the platform Snorre B. The mud type used during drilling activities consisted of Yellow Enviromul. This batch of drill cutting was treated in a TCC Rotomill, a process which has previously been described. The temperature inside the TCC unit was approximately 270 °C during the time of sampling. Samples were taken from drill cuttings before treatment, as well as samples from the three end-phases; solids, oil and water.

#### 3.1.2.1. Sample 1: Drill cuttings before treatment

The first step was to collect one sample from the untreated drill cuttings before it entered the TCC process. Approximately 5 kg of untreated drill cuttings was collected directly from an outlet, as illustrated in Figure 3-1.

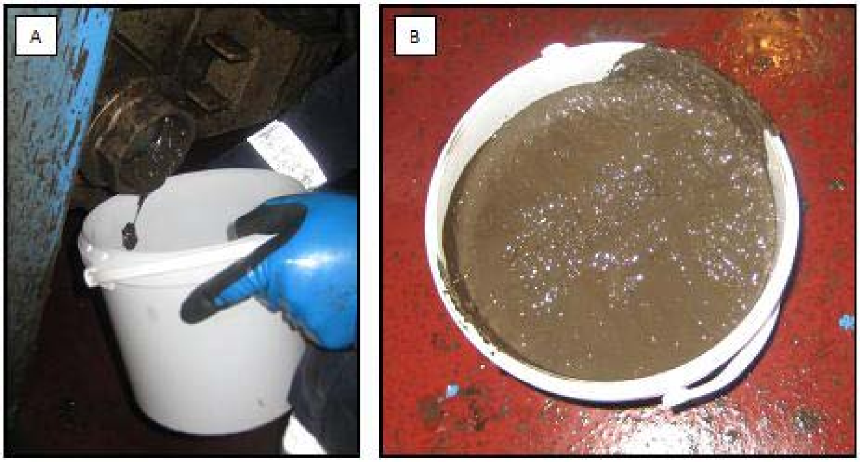

**Figure 3-1: A) Sampling of untreated drill cuttings B) Drill cuttings before treatment**

### 3.1.2.2. Sample 2 & 3: Drill cuttings after treatment

The first sample of treated drill cuttings was collected 5 minutes after sampling from the untreated drill cuttings. According to Erik Brohjem, Production Manager at TWMA Norway AS, this should in theory be sufficient time for the batch of sampled untreated drill cuttings to pass through the system. In order to ensure that the samples from the treated drill cuttings were representative, another sample of the retrieved solids were taken 50 minutes after the first sample. Both sample 2 and 3 consisted of approximately 5 kg each, as shown in Figure 3-2.

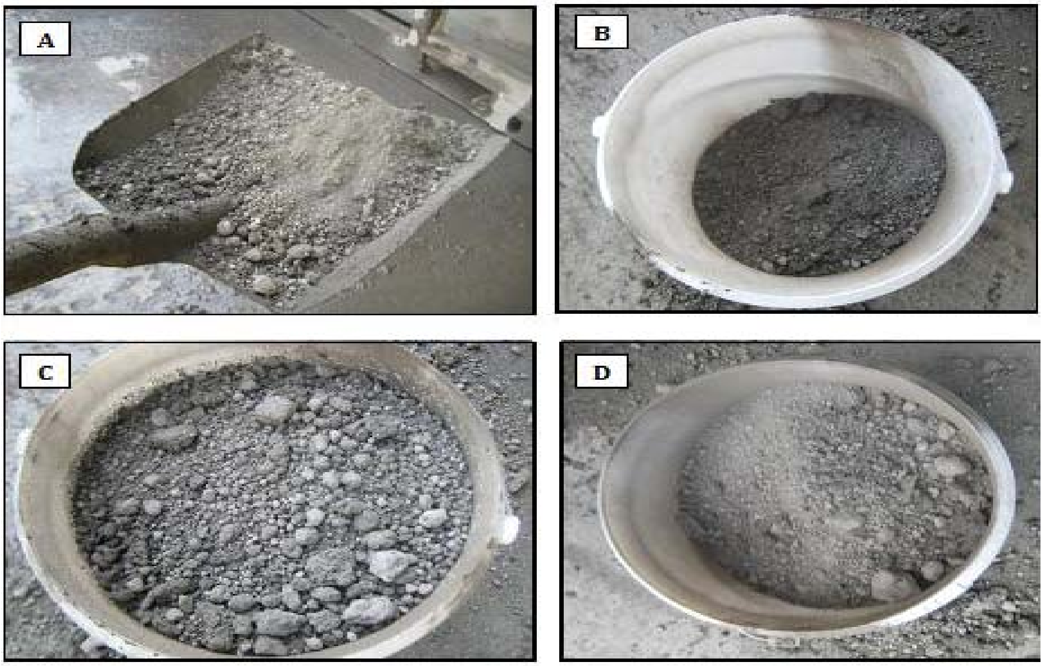

**Figure 3-2: A-C) First sample of treated drill cuttings D) Second sample of treated drill cuttings**

### 3.1.2.3. Sample 4: Water phase

Approximately 5 l of water was collected directly from the water outlet. This was approximately 20 minutes after sample 1 of the untreated drill cuttings was taken. The water sampled from this outlet was divided into separate containers, according to assigned future analysis. This is illustrated in Figure 3-3.

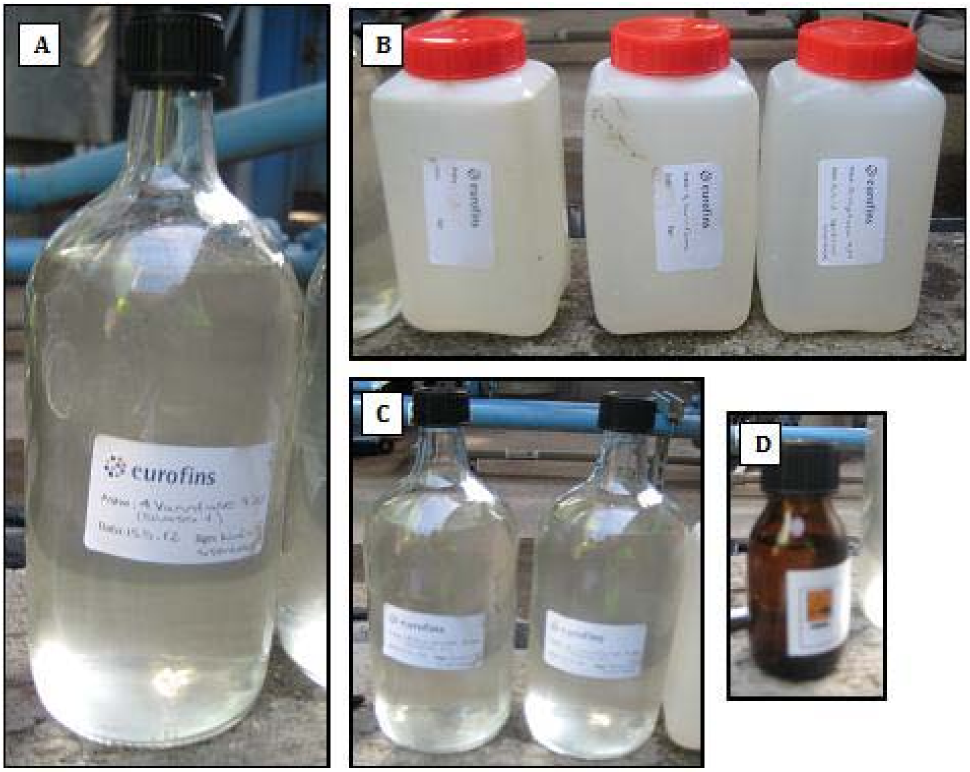

**Figure 3-3: A and C) Water assigned for test such as oil-in water, PAH and BTEX B) Additional water D) Water containing preserving agent for intended mercury test**

### 3.1.2.4. Sample 5: Oil phase

Approximately 1 l of recovered oil was sampled directly from the oil outlet, shown in Figure 3-4. This sample was taken around 30 minutes after the first sample of untreated drill cuttings was collected.

**Figure 3-4: Oil phase sample**

### 3.1.3. Halliburton Mongstad

The second round of samples was gathered from Halliburton Mongstad located on Mongstad. The batch treated on this facility was a mixture of heavy slop. The slop was treated in a TCC Rotomill at a temperature of around 260 °C. Samples were taken from the untreated slop, as well as samples from the three end-phases; solids, oil and water.

#### 3.1.3.1. Sample 6: Slop before treatment

The first step was to collect one sample from the untreated slop before it entered the TCC process. Approximately 5 kg of untreated slop was collected from the TCC feeding tank and into a sample bucket, as illustrated in Figure 3-5 D).

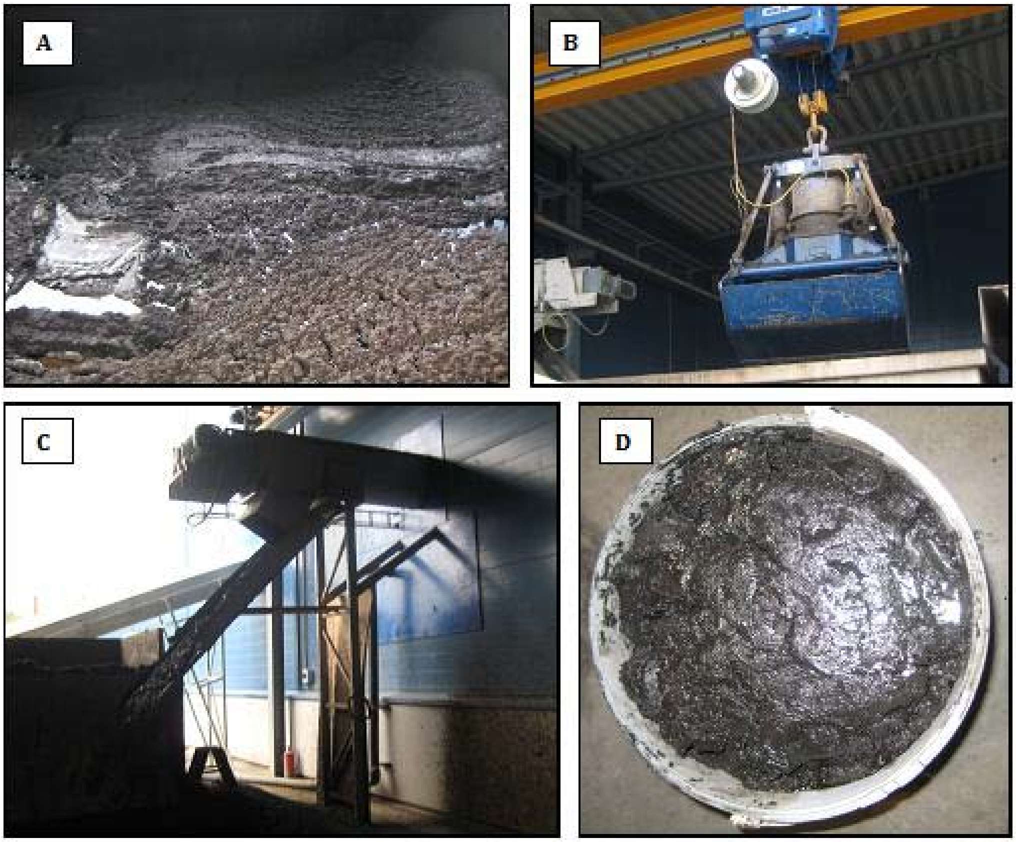

**Figure 3-5: A) Batch of untreated slop B) C) D) Sample of untreated slop**

#### 3.1.3.2. Sample 7 and 8: Slop after treatment

Due to high water content in the slop, the slop requires longer processing time in order to evaporate all the water as oppose to the batch of drill cuttings treated at TWMA. Thus, the first sample of treated slop was collected approximately 30 minutes after sampling from the untreated slop. In order to ensure representative samples from the processed solids, an additional sample was taken approximately 15 minutes after the first sample of dry solids.

Both sample 7 and sample 8 was collected directly from the recovered solids outlet and consisted of approximately 5 kg each as shown in Figure 3-6.

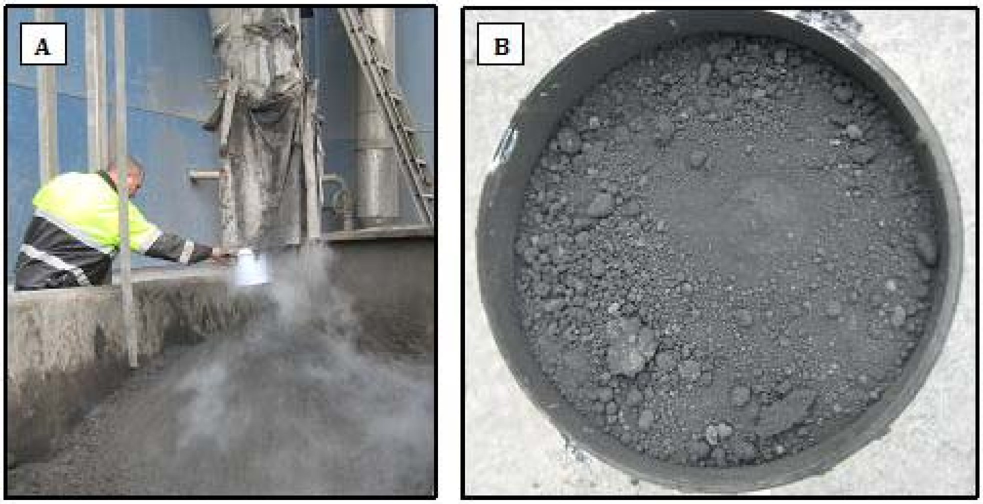

**Figure 3-6: A) Sampling directly from the recovered solids outlet B) One sample of treated slop**

### 3.1.3.3. Sample 9: Water phase

Approximately 5 l of water was collected directly from the water outlet. This was approximately 30-40 minutes after sample 6 of the untreated slop was taken. Similarly to the water samples taken from TWMA, the water collected at Halliburton Mongstad was divided into separate containers, according to assigned future analysis. Figure 3-7 illustrates the visual difference in water samples from TWMA and Halliburton Mongstad, however the samples from TWMA was sampled first and thus had longer cooling and settling time. The two bottles from the left represents samples collected from TWMA, while the two adjacent samples on the right are from Halliburton Mongstad.

**Figure 3-7: Comparison of water samples collected from TWMA and Halliburton Mongstad (H.M.)**

#### 3.1.3.4. Sample 10: Oil phase

Approximately 1 l of recovered oil was sampled directly from the oil outlet, as illustrated in Figure 3-8 A). This sample was collected around 15 minutes after the first sample of untreated slop was collected. Figure 3-8 B) illustrates the visual difference in oil samples collected from TWMA and Halliburton Mongstad respectively.

**Figure 3-8: A) Sampling of oil B) Visual comparison of oil samples from TWMA and Halliburton Mongstad (H.M.)**

## 3.2. Parameters analyzed

The following chapter outlines the different parameters that were analyzed on drill cuttings/slop before treatment, drill cuttings/slop after treatment as well as the prevailing water- and oil phases after treatment. All tests were conducted by personnel at Eurofins.

### 3.2.1. Analysis conducted on drill cuttings and slop

The following tests listed in Table 3-1 and 3-2 were conducted on both treated and untreated slop/drill cuttings. Table 3-1 is affiliated with the leaching test conducted on the slop/drill cuttings samples, consisting of a leaching test with a liquid-solid ratio of 10 l/kg and a column test with a liquid-solid ratio of 0.1 l/kg. Table 3-2 contains the remaining tests on slop/drill cuttings independent of the leaching test.

**Table 3-1: Leaching test (L/S = 10 l/kg) and column test (L/S = 0.1 l/kg)**

| **Analysis:** | **Content/Parameters *(LOQ):** |
|---|---|
| **Leaching test,<br>L/S=10 l/kg, 4mm** | pH of leaching discharge<br>Conductivity of leaching discharge<br>Temperature of leaching discharge<br>Water content |
| **Leaching test analysis,<br>L/S=10 l/kg, 4mm** | Total Solids (TS) (800.0 mg/kg TS)<br>Arsenic (As) (0.05 mg/kg TS)<br>Barium (Ba) (2.0 mg/kg TS)<br>Cadmium  (0.004 mg/kg TS)<br>Chromium (Cr) (0.2 mg/kg TS)<br>Copper (Cu)<br>Mercury (Hg) (0.001 mg/kg TS)<br>Molybdenum (Mo) (0.05 mg/kg TS)<br>Nickel (Ni) (0.01 mg/kg TS)<br>Lead (Pb) (0.05 mg/kg TS)<br>Antimony (Sb) (0.006 mg/kg TS)<br>Selenium (Se) (0.01 mg/kg TS)<br>Zink (Zn) (0.4 mg/kg TS)<br>Chloride (10.0 mg/kg TS)<br>Fluoride (1.0 mg/kg TS)<br>Sulphate (10.0 mg/kg TS)<br>Phenol index (0.1 mg/kg TS)<br>LOC (20.0 mg/kg TS) |
| **Column test (incl. analysis),<br>1 eluate,<br>L/S = 0.1 l/kg** | Water content<br>pH<br>Temperature<br>Conductivity<br>Arsenic (As) (0.01 mg/l)<br>Barium (Ba) (0.1 mg/l)<br>Cadmium  (0.002 mg/l)<br>Chromium (Cu) (0.05 mg/l)<br>Mercury (Hg) (0.001 mg/l)<br>Molybdenum (Mo) (0.05 mg/l)<br>Nickel (Ni) (0.1 mg/l)<br>Lead (Pb) (0.05 mg/l)<br>Antimony (Sb) (0.02 mg/l)<br>Selenium (Se) (0.04 mg/l)<br>Zink (Zn) (0.5 mg/l)<br>Chloride (1.0 mg/l)<br>Fluoride (0.1 mg/l)<br>Sulphate (1.0 mg/l)<br>Phenol index (0.005 mg/l)<br>LOC (2.0 mg/l)<br>Total Solids (TS) (80.0 mg/l) |

***Level of quantification = LOQ**

**Table 3-2: Remaining test on slop/drill cuttings**

| **Analysis:** | **Method:** | **Parameters/ Content (LOQ):** | **Reference method:** |
|---|---|---|---|
| pH | pH – meter | | EN 12176 |
| Ignition loss | Gravimetric | Total ignition loss | EN 12879 |
| TOC | | Water content<br>Total carbon (TC)<br>Total inorganic carbon (TIC)<br>Total organic carbon (TOC) | |
| Organic parameters according to Waste Regulations | | Total solids<br>Water content<br>PCB 7<br>Total organic carbon (TOC)<br>Total inorganic carbon (TIC)<br>Total carbon (TC) | |
| PAH 16 EPA | GC-MS | Napthalene<br>Acenaphthylene<br>Acenaphthene<br>Fluorene<br>Phenanthene<br>Anthracene<br>Fluoranthene<br>Pyrene<br>Benzo(a)anthracene<br>Chrysene/Triphenylene<br>Benzo(b)fluoranthene<br>Benzo(k)fluoranthene<br>Benzo(a) pyrene<br>Indeno(1,2,3-cd)pyrene<br>Dibenz(a,h)anthracene<br>Benzo(g,h,i)perylene<br>Sum PAH(16) EPA | ISO/DIS 16703-Mod |
| BTEX | GC-MS | Benzene<br>Toluene<br>Ethylbenzene<br>m,p–Xylene<br>o-Xylene | ISO/DIS 16703-Mod |
| Total hydrocarbons (THC) | GC-FID | THC > C5-C8<br>THC>C8-C10<br>THC>C10-C12<br>THC>C12-C16<br>THC>C16-C35<br>SUM THC (>C5-C35) | ISO/DIS 16703-Mod |
| Metals | | Total solids (TS)<br>Arsenic (As) (0.5 mg/kg TS)<br>Lead (Pb) (0.3 mg/kg TS)<br>Cadmium (Cd) (0.01 mg/kg TS)<br>Copper (Cu) (0.05 mg/kg TS)<br>Chromium (Cr) (0.05 mg/kg TS)<br>Mercury (Hg) (0.001 mg/kg TS)<br>Nickel (Ni) (0.2 mg/kg TS)<br>Zink (Zn) (0.05 mg/kg TS)<br>+ 4 additional metals | |

| | | | |
|---|---|---|---|
| Sulphate | Ion-chromatography | Sulphate | NS EN ISO 10304-1 |
| Nitrate ($NO_3$-N) | Ion-chromatography | Nitrate ($NO_3$-N) | NS EN ISO 10304-1 |
| Chloride | Ion-chromatography | Chloride | NS EN ISO 10304-1 |
| Fluoride | Ion-chromatography | Fluoride (F) | NS EN ISO 10304-1 |
| Total solids | Gravimetric | Total solids (TS) | NS 4764 |

### 3.2.2. Analysis conducted on water and oil samples

Table 3-3 consist the different test conducted on the water samples from both TWMA and Halliburton Mongstad.

**Table 3-3: Tests conducted on the water phase**

| **Analysis:** | **Method:** | **Parameters/ Content (LOQ):** | **Reference method:** |
|---|---|---|---|
| Oil in water C10-C40 | GC-FID | Oil in water C10-C40 | ISO 9377-2 |
| PAH 16 EPA | GC-MS | Napthalene<br>Acenaphthylene<br>Acenaphthene<br>Fluorene<br>Phenanthene<br>Anthracene<br>Fluoranthene<br>Pyrene<br>Benzo(a)anthracene<br>Chrysene/Triphenylene<br>Benzo(b)fluoranthene<br>Benzo(k)fluoranthene<br>Benzo(a) pyrene<br>Indeno(1,2,3-cd)pyrene<br>Dibenz(a,h)anthracene<br>Benzo(g,h,i)perylene<br>Sum PAH(16) EPA | Internal method |
| BTEX | GC-MS | Benzene<br>Toluene<br>Ethylbenzene<br>m,p–Xylene<br>o-Xylene | Internal method |
| Metalls | ICP-MS | Mercury (Hg) (0.005 µg/l)<br>Arsenic (As) (0.2 µg/l)<br>Lead (Pb) (0.2 µg/l)<br>Cadmium (Cd) (0.01 µg/l)<br>Copper (Cu) (1.0 µg/l)<br>Chromium (Cr) (0.5 µg/l)<br>Nickel (Ni) (0.5 µg/l)<br>Zink (Zn) (2.0 µg/l) | |
| Nitrate | Discrete, selective photometric analyzer | Nitrate ($NO_3$-N) | NS EN ISO 13395 |
| Nitrate + Nitrite | Discrete, selective photometric analyzer | Nitrate + Nitrite ($\sum(NO_3+NO_2)$-N) | NS EN ISO 13395 |

| | | | |
|---|---|---|---|
| Nitrite | Discrete, selective photometric analyzer | Nitrite ($NO_2$-N)<br>LOQ: 2.0 µg/l | NS EN ISO 13395 |
| Sulphate | Discrete, selective photometric analyzer | Sulphate ($SO_4$) | EPA Method 375.4 |
| Suspended solids (SS) | Gravimetric | Suspended solids (SS) | Internal method |
| Total organic carbon | Combustion/IR | Total organic carbon (TOC/NPOC) | |

A flash point test was conducted on the oil phases, using the method ASTMD 6450.

# 4. Results

The following chapter presents the different results retrieved from Eurofins. Results from leaching tests on drill cuttings and slop are first presented, followed by results from testing of main chemical groups such as PAH, BTEX, PCB, THC and heavy metals. Remaining results from testing of retrieved water and oil phases are subsequently presented. Finally, comparable test results from drill cuttings and slop are then compared with limit values according to Waste Regulations and onshore discharge requirements.

## 4.1. Leaching tests

Leaching tests were conducted on drill cuttings and slop, samples of both untreated and treated drilling waste. Table 4-1 and 4-2 lists the different values retrieved from the leaching test on sample 1, 2 and 3 taken from TWMA. Table 4-1 illustrates the results from a leaching test with a liquid-solid ratio of 10 l/kg, while Table 4-2 illustrates the results from a column test (percolating test) with a liquid-solid ratio of 0.1 l/kg.

**Table 4-1: Leaching test conducted on drill cuttings from TWMA (L/S = 10 l/kg)**

| Analysis (L/S = 10 l/kg) | Sample 1: Drill cuttings before treatment [mg/kg TS] | Sample 2: Drill cuttings after treatment [mg/kg TS] | Sample 3: Drill cuttings after treatment [mg/kg TS] | Uncertainty of measurements (MU) |
|---|---|---|---|---|
| Total solids (TS) | 21 000 ± 6 300 | 20 000 ± 6 000 | 21 000 ± 6 300 | 30 % |
| Arsenic (As) | 0.19 ± 0.057 | 0.27 ± 0.081 | 0.21 ± 0.063 | 30 % |
| Barium (Ba) | 2.5 ± 0.75 | 3.2 ± 0.96 | 2.7 ± 0.81 | 30 % |
| Cadmium (Cd) | <0.0040 ± 0.0012 | <0.0040 ± 0.0012 | <0.0040 ± 0.0012 | 30 % |
| Chromium (Cr) | 0.26 ± 0.078 | 0.24 ± 0.072 | 0.22 ± 0.066 | 30 % |
| Copper (Cu) | <0.20 ± 0.060 | <0.20 ± 0.060 | <0.20 ± 0.060 | 30 % |
| Mercury (Hg) | <0.0010 ± 0.00030 | <0.0010 ± 0.00030 | <0.0010 ± 0.00030 | 30 % |
| Molybdenum (Mo) | 0.81 ± 0.24 | 1.9 ± 0.57 | 1.8 ± 0.54 | 30 % |
| Nickel (Ni) | 0.18 ± 0.054 | 0.62 ± 0.19 | 0.62 ± 0.19 | 30 % |
| Lead (Pb) | <0.050 ± 0.015 | <0.050 ± 0.015 | <0.050 ± 0.015 | 30 % |
| Antimony (Sb) | 0.048 ± 0.014 | 0.11 ± 0.033 | 0.10 ± 0.030 | 30 % |
| Selenium (Se) | 0.21 ± 0.063 | 0.12 ± 0.036 | 0.13 ± 0.039 | 30 % |
| Zink (Zn) | <0.40 ± 0.12 | <0.40 ± 0.12 | <0.40 ± 0.12 | 30 % |
| Chloride | 8 700 ± 870 | 8 300 ± 830 | 8 700 ± 870 | 10 % |
| Fluoride | <10 ± 1.5 | <75 ± 11 | <50 ± 7.5 | 15 % |
| Sulphate | 750 ± 112 | 780 ± 117 | 920 ± 138 | 15 % |
| Phenol index | 0.32 ± 0.032 | 0.66 ± 0.066 | 0.59 ± 0.059 | 10 % |
| DOC | 1 400 ± 140 | 1 400 ± 140 | 1 300 ± 130 | 10 % |
| **Additional information from leaching test:** | | | | |
| Conductivity of leaching discharge | 330 mS/m | 320 mS/m | 320 mS/m | - |
| pH of leaching discharge | 10.6 | 9.7 | 9.6 | 0 % |
| Temperature of leaching discharge | 22.9 °C | 23.9 °C | 23.9 °C | - |

***Remarks: Elevated Level of Quantification (LOQ) for Fluoride due to complicated matrix.**

There were some problems associated with conducting a column test on the untreated sample of drill cuttings (sample 1). The drill cuttings in this sample acted as a plug in the column, thereby making it impossible to get any water through. No results from the column test on sample 1 were received from Eurofins, thus Table 4-2 only consists of results from the treated drill cuttings (sample 2 and 3).

**Table 4-2: Column test conducted on drill cuttings from TWMA (L/S = 0.1 l/kg)**

| **Analysis (L/S = 0.1 l/kg)** | **Sample 2: Drill cuttings after treatment [mg/l]** | **Sample 3: Drill cuttings after treatment [mg/l]** | **Uncertainty of measurements (MU)** |
|---|---|---|---|
| Total solids (TS) | 360 000 ± 144 000 | 150 000 ± 60 000 | 40 % |
| Arsenic (As) | <0.090 ± 0.036 | <0.070 ± 0.028 | 40 % |
| Barium (Ba) | 0.82 ± 0.33 | 0.83 ±0.33 | 40 % |
| Cadmium (Cd) | 0.0043 ± 0.0017 | 0.0047 ±0.0019 | 40 % |
| Chromium (Cr) | <0.050 ± 0.020 | 0.095 ± 0.038 | 40 % |
| Copper (Cu) | 0.43 ± 0.17 | 0.43 ± 0.17 | 40 % |
| Mercury (Hg) | <0.0010 ± 0.00040 | <0.0010 ± 0.00040 | 40 % |
| Molybdenum (Mo) | 10 ± 4 | 8.7 ± 3.5 | 40 % |
| Nickel (Ni) | 0.86 ± 0.34 | 0.88 ± 0.35 | 40 % |
| Lead (Pb) | <0.050 ± 0.020 | <0.050 ± 0.020 | 40 % |
| Antimony (Sb) | <0.20 ± 0.080 | <0.20 ± 0.080 | 40 % |
| Selenium (Se) | 0.25 ± 0.10 | 0.21 ± 0.084 | 40 % |
| Zink (Zn) | 0.50 ± 0.20 | <0.50 ± 0.20 | 40 % |
| Chloride | 75 000 ± 30 000 | 83 000 ± 33 200 | 40 % |
| Fluoride | 240 ± 96 | <15 ± 6 | 40 % |
| Sulphate | 1 900 ± 760 | 1 900 ± 760 | 40 % |
| Phenol index | 4.9 ± 2.0 | 4.1 ± 1.6 | 40 % |
| DOC | 5 300 ± 2 120 | 3 500 ± 1400 | 40 % |
| **Additional information from leaching test:** | | | |
| Conductivity of leaching discharge | 15 000 ± 1500 mS/m | 14 000 ± 1400 mS/m | 10 % |
| pH of leaching discharge | 8.2 | 8.3 | 0 % |
| Temperature of leaching discharge | 22.5 ± 2.25 °C | 22.3 ± 2.23 °C | 10 % |

Table 4-3 and 4-4 lists the different values retrieved from the leaching test on sample 6, 7 and 8 taken from Halliburton Mongstad (H.M.). Table 4-3 illustrates the results from a leaching test with a liquid-solid ratio of 10 l/kg.

**Table 4-3: Leaching test conducted on slop from H.M. (L/S = 10 l/kg)**

| Analysis (L/S = 10 l/kg) | * Sample 6: Slop before treatment [mg/kg TS] | Sample 7: Slop after treatment [mg/kg TS] | Sample 8: Slop after treatment [mg/kg TS] | Uncertainty of measurements (MU) |
|---|---|---|---|---|
| Total solids (TS) | 24 000 ± 7 200 | 23 000 ± 6 900 | 26 000 ± 7 800 | 30 % |
| Arsenic (As) | 0.064 ± 0.019 | 0.055 ± 0.016 | 0.055 ± 0.016 | 30 % |
| Barium (Ba) | 2.4 ± 0.72 | <2.0 ± 0.60 | 3.0 ± 0.90 | 30 % |
| Cadmium (Cd) | <0.0040 ± 0.0012 | <0.0040 ± 0.0012 | <0.0040 ± 0.0012 | 30 % |
| Chromium (Cr) | <0.050 ± 0.015 | <0.050 ± 0.015 | <0.050 ± 0.015 | 30 % |
| Copper (Cu) | <0.20 ± 0.060 | 0.53 ± 0.16 | <0.20 ± 0.060 | 30 % |
| Mercury (Hg) | <0.0010 ± 0.00030 | <0.0010 ± 0.00030 | <0.0010 ± 0.00030 | 30 % |
| Molybdenum (Mo) | 1.5 ± 0.45 | 1.6 ± 0.48 | 1.5 ± 0.45 | 30 % |
| Nickel (Ni) | 0.64 ± 0.19 | 1.4 ± 0.42 | 1.4 ± 0.42 | 30 % |
| Lead (Pb) | <0.050 ± 0.015 | <0.050 ± 0.015 | <0.050 ± 0.015 | 30 % |
| Antimony (Sb) | 0.041 ± 0.012 | 0.040 ± 0.012 | 0.038 ± 0.011 | 30 % |
| Selenium (Se) | 0.056 ± 0.017 | 0.043 ± 0.013 | 0.046 ± 0.014 | 30 % |
| Zink (Zn) | <0.40 ± 0.12 | <0.40 ± 0.12 | <0.40 ± 0.12 | 30 % |
| Chloride | 6 300 ± 630 | 6 100 ± 610 | 6 100 ± 610 | 10 % |
| Fluoride | 4.0 ± 0.60 | ** <50 ± 7.5 | ** <30 ± 4.5 | 15 % |
| Sulphate | 1 200 ± 180 | 530 ± 79.5 | 600 ± 90 | 15 % |
| Phenol index | 0.93 ± 0.093 | 0.89 ± 0.089 | 1.2 ± 0.12 | 10 % |
| DOC | 870 ± 87 | 2 400 ± 240 | 1 900 ± 190 | 10 % |
| **Additional information from leaching test:** | | | | |
| Conductivity of leaching discharge | 350 mS/m | 310 mS/m | 340 mS/m | - |
| pH of leaching discharge | 8.5 | 9.1 | 8.3 | 0 % |
| Temperature of leaching discharge | 23.7 °C | 23.6 °C | 23.9 °C | - |

***Remarks sample 6: Uncertain values due to complicated matrix.**

****Remarks sample 7 & 8: Elevated LOQ for Fluoride due to complicated matrix.**

Table 4-4 illustrates the results from a column test (percolating test) with a liquid-solid ratio of 0.1 l/kg.

**Table 4-4: Column test conducted on slop from H.M. (L/S = 0.1 l/kg)**

| **Analysis (L/S = 0.1 l/kg)** | **Sample 6: Slop before treatment [mg/l]** | **Sample 7: Slop after treatment [mg/l]** | **Sample 8: Slop after treatment [mg/l]** | **Uncertainty of measurements (MU)** |
|---|---|---|---|---|
| Total solids (TS) | 380 000 ± 152 000 | 140 000 ± 56 000 | 140 000 ± 56 000 | 40 % |
| Arsenic (As) | < 0.020 ± 0.0080 | < 0.040 ± 0.016 | < 0.040 ±0.016 | 40 % |
| Barium (Ba) | 0.31 ± 0.12 | 0.90 ± 0.36 | 0.72 ± 0.29 | 40 % |
| Cadmium (Cd) | < 0.0020 ± 0.00080 | < 0.0040 ± 0.0016 | < 0.0040 ± 0.0016 | 40 % |
| Chromium (Cr) | < 0.050 ± 0.020 | < 0.050 ± 0.020 | < 0.050 ± 0.020 | 40 % |
| Copper (Cu) | < 0.10 ± 0.040 | 0.31 ± 0.12 | 0.74 ± 0.30 | 40 % |
| Mercury (Hg) | < 0.0010 ± 0.00010 | < 0.0010 ± 0.00010 | < 0.0010 ± 0.00010 | 40 % |
| Molybdenum (Mo) | 1.5 ± 0.60 | 3.9 ± 1.6 | 3.5 ± 1.4 | 40 % |
| Nickel (Ni) | 0.67 ± 0.27 | 2.6 ± 1.0 | 2.7 ± 1.1 | 40 % |
| Lead (Pb) | < 0.050 ± 0.020 | < 0.050 ± 0.020 | < 0.050 ± 0.020 | 40 % |
| Antimony (Sb) | < 0.10 ± 0.040 | < 0.20 ± 0.080 | < 0.20 ± 0.080 | 40 % |
| Selenium (Se) | 0.11 ± 0.044 | 0.28 ± 0.11 | 0.23 ± 0.092 | 40 % |
| Zink (Zn) | < 0.50 ± 0.20 | < 0.50 ± 0.20 | < 0.50 ± 0.20 | 40 % |
| Chloride | 13 000 ± 5 200 | 54 000 ± 21 600 | 33 000 ± 13 200 | 40 % |
| Fluoride | < 100 ± 40 | 74 ± 30 | 76 ± 30 | 40 % |
| Sulphate | 1 700 ± 680 | 1 400 ± 560 | 1 300 ± 520 | 40 % |
| Phenol index | 1.1 ± 0.44 | 2.1 ± 0.64 | 3.1 ± 1.2 | 40 % |
| DOC | 1 400 ± 560 | 8 000 ± 3 200 | 8 200 ± 3 280 | 40 % |
| **Additional information from leaching test:** | | | | |
| Conductivity of leaching discharge | 5 300 ± 530 mS/m | 13 000 ± 130 mS/m | 11 000 ± 110 | 10 % |
| pH of leaching discharge | 7.4 | 7.8 | 7.5 | 0 % |
| Temperature of leaching discharge | 22.3 ± 2.23 °C | 21.1 ± 2.11 °C | 22.5 ± 2.25 | 10 % |

## 4.2. PAH

Table 4-5 outlines the different PAH values found in untreated drill cuttings, treated drill cuttings and in the retrieved water phase.

**Table 4-5: PAH values detected in drill cuttings and retrieved water phase from TWMA**

| **PAH 16 EPA** | *** Sample 1: Drill cuttings before treatment [mg/kg TS]** | **Sample 2: Drill cuttings after treatment [mg/kg TS]** | **Sample 3: Drill cuttings after treatment [mg/kg TS]** | ****Sample 4: Retrieved water phase [mg/kg]** |
|---|---|---|---|---|
| Napthalene | 0.94 ± 0.23 | 0.033 ± 0.0082 | 0.031 ± 0.0077 | 0.067 ± 0.020 |
| Acenaphthylene | <0.1 ± 0.04 | <0.01 ± 0.004 | 0.010 ± 0.0041 | 0.00059 ± 0.00018 |
| Acenaphthene | <0.1 ± 0.02 | 0.024 ± 0.0060 | 0.028 ± 0.0070 | 0.0084 ± 0.0025 |
| Fluorene | <0.1 ± 0.02 | 0.060 ± 0.015 | 0.058 ± 0.014 | 0.0013 ± 0.00039 |
| Phenanthrene | 0.82 ± 0.20 | 0.26 ± 0.065 | 0.25 ± 0.062 | 0.00041 ± 0.00012 |
| Anthracene | <0.1 ± 0.02 | 0.018 ± 0.0045 | 0.016 ± 0.0040 | $4.4*10^{-5} \pm 1.3*10^{-5}$ |
| Fluoranthene | 0.28 ± 0.070 | 0.073 ± 0.018 | 0.074 ± 0.018 | $1.3*10^{-5} \pm 5.2*10^{-6}$ |
| Pyrene | 0.51 ± 0.13 | 0.40 ± 0.10 | 0.37 ± 0.092 | $1.2*10^{-5} \pm 4.8*10^{-6}$ |
| Benzo(a)anthracene | <0.1 ± 0.02 | 0.026 ± 0.0065 | 0.042 ± 0.010 | $8*10^{-6} \pm 3*10^{-6}$ |
| Chrysene/Triphenylene | 0.13 ± 0.045 | 0.032 ± 0.011 | 0.045 ± 0.016 | $8*10^{-6} \pm 3*10^{-6}$ |
| Benzo(b)Fluoranthene | <0.1 ± 0.02 | <0.01 ± 0.002 | <0.01 ± 0.002 | $8*10^{-6} \pm 3*10^{-6}$ |
| Benzo(k)Fluoranthene | <0.1 ± 0.02 | <0.01 ± 0.002 | <0.01 ± 0.002 | $8*10^{-6} \pm 3*10^{-6}$ |
| Benzo(a) pyrene | <0.1 ± 0.02 | <0.01 ± 0.002 | <0.01 ± 0.002 | $7*10^{-6} \pm 3*10^{-6}$ |
| Indeno(1,2,3-cd)pyrene | <0.1 ± 0.03 | <0.01 ± 0.003 | <0.01 ± 0.003 | $7*10^{-6} \pm 3*10^{-6}$ |
| Dibenz(a,h)anthracene | <0.1 ± 0.04 | <0.01 ± 0.004 | <0.01 ± 0.004 | $8*10^{-6} \pm 3*10^{-6}$ |
| Benzo(g,h,i)perylene | <0.1 ± 0.04 | <0.01 ± 0.004 | 0.010 ± 0.004 | $7*10^{-6} \pm 3*10^{-6}$ |
| **Sum PAH(16) EPA** | **2.7** | **0.93** | **0.93** | **0.078** |

***Remarks sample 1: Elevated LOQ due to dilution.**

****Values for sample 4 was initially reported in µg/l, see Appendix 8 for the conversions.**

Table 4-6 outlines the different PAH values found in untreated slop, treated slop and in the retrieved water phase. The MU in percentage for values in both Table 4-5 and 4-6 are given in Appendix 8.

**Table 4-6: PAH values detected in slop and retrieved water phase from H.M.**

| PAH 16 EPA | * Sample 6: Slop before treatment [mg/kg TS] | Sample 7: Slop after treatment [mg/kg TS] | Sample 8: Slop after treatment [mg/kg TS] | **Sample 9: Retrieved water phase [mg/kg] |
|---|---|---|---|---|
| Napthalene | 10 ± 2.5 | 0.023 ± 0.0057 | 0.026 ± 0.0065 | 0.219 ± 0.0657 |
| Acenaphthylene | <0.1 ± 0.04 | <0.01 ± 0.004 | <0.01 ± 0.004 | 0.0068 ± 0.0020 |
| Acenaphthene | 1.6 ± 0.40 | <0.01 ± 0.002 | <0.01 ± 0.002 | 0.105 ± 0.315 |
| Fluorene | 3.2 ± 0.80 | 0.035 ± 0.0087 | 0.037 ± 0.0092 | 0.018 ± 0.0054 |
| Phenanthrene | 5.5 ± 1.4 | 0.15 ± 0.037 | 0.15 ± 0.0037 | 0.014 ±0.0042 |
| Anthracene | 0.48 ± 0.12 | 0.010 ± 0.0025 | 0.013 ± 0.0032 | 0.0014 ± 0.00042 |
| Fluoranthene | 0.28 ± 0.070 | 0.031 ± 0.0077 | 0.025 ± 0.0062 | 0.00047 ± 0.00014 |
| Pyrene | 1.3 ± 0.32 | 0.24 ± 0.060 | 0.24 ± 0.060 | 0.0020 ± 0.00060 |
| Benzo(a)anthracene | 0.12 ± 0.030 | 0.14 ± 0.035 | 0.13 ± 0.032 | 0.00046 ± 0.00014 |
| Chrysene/Triphenylene | 0.45 ± 0.16 | 0.12 ± 0.042 | 0.11 ± 0.038 | $2.5*10^{-4} \pm 7.5*10^{-5}$ |
| Benzo(b)Fluoranthene | <0.1 ± 0.02 | 0.14 ± 0.035 | 0.13 ± 0.032 | $2.3*10^{-5} \pm 9.2*10^{-6}$ |
| Benzo(k)Fluoranthene | <0.1 ± 0.02 | 0.030 ± 0.0075 | 0.019 ± 0.0047 | $1.7*10^{-5} \pm 6.8*10^{-6}$ |
| Benzo(a) pyrene | <0.1 ± 0.02 | 0.071 ± 0.018 | 0.077 ± 0.019 | $7*10^{-6} \pm 2.8*10^{-6}$ |
| Indeno(1,2,3-cd)pyrene | <0.1 ± 0.03 | 0.026 ± 0.0078 | 0.028 ± 0.0084 | $2.6*10^{-6} \pm 1.0*10^{-6}$ |
| Dibenz(a,h)anthracene | <0.1 ± 0.04 | 0.021 ± 0.0084 | 0.023 ± 0.0092 | $8*10^{-6} \pm 3.2*10^{-6}$ |
| Benzo(g,h,i)perylene | <0.1 ± 0.04 | 0.12 ± 0.048 | 0.12 ± 0.048 | $4.1*10^{-6} \pm 1.6*10^{-6}$ |
| **Sum PAH(16) EPA** | **23** | **1.2** | **1.1** | **0.37** |

***Remarks sample 6: Elevated LOQ due to dilution.**

****Values for sample 9 was initially reported in µg/l, see Appendix 8 for the conversions.**

## 4.3. BTEX

Table 4-7 shows the BTEX values detected in untreated and treated drill cuttings, as well as the retrieved water phase.

**Table 4-7: BTEX values detected in drill cuttings and retrieved water phase from TWMA**

| BTEX | * Sample 1: Drill cuttings before treatment [mg/kg TS] | Sample 2: Drill cuttings after treatment [mg/kg TS] | Sample 3: Drill cuttings after treatment [mg/kg TS] | **Sample 4: Retrieved water phase [mg/kg] |
|---|---|---|---|---|
| Benzene | <0.1 ± 0.03 | <0.01 ± 0.004 | <0.01 ± 0.004 | 0.183 ± 0.0549 |
| Toluene | 0.31 ± 0.062 | 0.048 ± 0.0096 | 0.048 ± 0.0096 | 0.636 ±0.191 |
| Ethylbenzene | 0.17 ± 0.034 | <0.01 ± 0.004 | <0.01 ± 0.004 | 0.030 ± 0.0090 |
| m,p–Xylene | 0.76 ± 0.15 | 0.024 ± 0.0096 | 0.024 ± 0.0096 | 0.10 ± 0.035 |
| o-Xylene | 0.38 ± 0.076 | 0.014 ± 0.0056 | 0.013 ± 0.0052 | 0.068 ± 0.020 |

***Remarks sample 1: Elevated LOQ due to dilution.**

****Values for sample 4 was initially reported in µg/l, see Appendix 8 for the conversions.**

Table 4-8 shows the BTEX values detected in untreated and treated slop, as well as the retrieved water after treatment. The MU in percentage for values in both Table 4-7 and 4-8 are given in Appendix 8.

**Table 4-8: BTEX values detected in slop and retrieved water phase from H.M.**

| BTEX | Sample 6: Slop before treatment [mg/kg TS] | Sample 7: Slop after treatment [mg/kg TS] | Sample 8: Slop after treatment [mg/kg TS] | *Sample 9: Retrieved water phase [mg/kg] |
|---|---|---|---|---|
| Benzene | 0.60 ± 0.18 | <0.01 ± 0.004 | <0.01 ± 0.004 | 0.320 ± 0.096 |
| Toluene | 6.5 ± 1.3 | 0.65 ± 0.13 | 0.63 ± 0.13 | 6.474 ± 1.942 |
| Ethylbenzene | 2.4 ± 0.48 | 0.017 ± 0.0068 | 0.016 ± 0.0064 | 0.196 ± 0.0588 |
| m,p–Xylene | 11 ± 2.2 | 0.079 ± 0.016 | 0.045 ± 0.018 | 0.953 ± 0.333 |
| o-Xylene | 5.1 ± 1.0 | <0.01 ± 0.004 | <0.01 ± 0.004 | 0.356 ± 0.107 |

***Values for sample 9 was initially reported in μg/l, see Appendix 8 for the conversions.**

## 4.4. PCB

Table 4-9 list the values of different PCB compounds found in treated and untreated drill cuttings.

**Table 4-9: PCB 7 values detected in drill cuttings from TWMA**

| PCB 7 | * Sample 1: Drill cuttings before treatment | | Sample 2: Drill cuttings after treatment | | Sample 3: Drill cuttings after treatment | |
|---|---|---|---|---|---|---|
| | [mg/kg TS] | MU | [mg/kg TS] | MU | [mg/kg TS] | MU |
| PCB 28 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 52 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 101 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 118 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 138 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 153 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 180 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| **Sum 7 PCB** | **Not detected** | | **Not detected** | | **Not detected** | |

***Remarks sample 1: Elevated LOQ due to dilution.**

Table 4-10 list the values of different PCB compounds found in treated and untreated slop.

**Table 4-10: PCB 7 values detected in slop from H.M.**

| PCB 7 | * Sample 6: Slop before treatment | | Sample 7: Slop after treatment | | Sample 8: Slop after treatment | |
|---|---|---|---|---|---|---|
| | [mg/kg TS] | MU | [mg/kg TS] | MU | [mg/kg TS] | MU |
| PCB 28 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 52 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 101 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 118 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 138 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 153 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| PCB 180 | <0.005 ± 0.001 | 25 % | <0.005 ± 0.001 | 40 % | <0.005 ± 0.001 | 40 % |
| **Sum 7 PCB** | **Not detected** | | **Not detected** | | **Not detected** | |

***Remarks: Elevated LOQ due to dilution.**

## 4.5. Total hydrocarbons (THC)

Table 4-11 outlines the THC values found in untreated and treated drill cuttings, while Table4-12 outlines the THC values found in untreated and treated slop.

**Table 4-11: THC values detected in drill cuttings from TWMA**

| Total hydrocarbons (THC) | Sample 1: Drill cuttings before treatment | | Sample 2: Drill cuttings after treatment | | Sample 3: Drill cuttings after treatment | |
|---|---|---|---|---|---|---|
| | [mg/kg TS] | MU | [mg/kg TS] | MU | [mg/kg TS] | MU |
| THC > C5-C8 | <50 ± 15 | 30 % | <5 ± 1.5 | 30 % | <5 ± 1 | 30 % |
| THC>C8-C10 | 210 ± 52.5 | 25 % | 16 ± 4.8 | 30 % | 13 ± 3.9 | 30 % |
| THC>C10-C12 | 2 300 ± 575 | 25 % | 20 ± 6 | 30 % | 17 ± 5.1 | 30 % |
| THC>C12-C16 | 46 000 ± 11 500 | 25 % | 610 ± 152 | 25 % | 500 ± 125 | 25 % |
| THC>C16-C35 | 57 000 ± 14 250 | 25 % | 2 600 ± 650 | 25 % | 2 300 ± 575 | 25 % |
| **SUM THC (>C5-C35)** | **110 000** | **-** | **3 300** | **-** | **2 800** | **-** |

**Table 4-12 THC values detected in slop from H.M.**

| Total hydrocarbons (THC) | Sample 6: Slop before treatment | | Sample 7: Slop after treatment | | Sample 8: Slop after treatment | |
|---|---|---|---|---|---|---|
| | [mg/kg TS] | MU | [mg/kg TS] | MU | [mg/kg TS] | MU |
| THC > C5-C8 | <50 ± 15 | 30 % | <5 ± 1 | 30 % | <5 ± 1 | 30 % |
| THC>C8-C10 | 1 000 ± 250 | 25 % | <5 ± 1 | 30 % | <5 ± 1 | 30 % |
| THC>C10-C12 | 16 000 ± 4 000 | 25 % | 14 ± 4.2 | 30 % | 17 ± 5.1 | 30 % |
| THC>C12-C16 | 100 000 ± 25 000 | 25 % | 240 ± 60 | 25 % | 270 ± 67.5 | 25 % |
| THC>C16-C35 | 67 000 ± 16 750 | 25 % | 1 800 ± 450 | 25 % | 1 700 ± 425 | 25 % |
| **SUM THC (>C5-C35)** | **190 000** | **-** | **2 100** | **-** | **2 000** | **-** |

## 4.6. Heavy metals

Table 4-13 shows the amount of heavy metals found in untreated and treated drill cuttings.

**Table 4-13: Heavy metal values detected in drill cuttings from TWMA**

| Heavy metals | Sample 1: Drill cuttings before treatment [mg/kg TS] | Sample 2: Drill cuttings after treatment [mg/kg TS] | Sample 3: Drill cuttings after treatment [mg/kg TS] | Uncertainty of measurements (MU) |
|---|---|---|---|---|
| Arsenic (As) | 18 ± 5.4 | 17 ± 5.1 | 16 ± 4.8 | 30 % |
| Barium (Ba) | 310 ± 62 | 9 200 ± 1 840 | 8 600 ± 1 720 | 20 % |
| Cadmium (Cd) | 0.25 ± 0.075 | <1.2 ± 0.36 | <1.2 ± 0.36 | 30 % |
| Chromium (Cr) | 32 ± 9.6 | 40 ± 12 | 41 ± 12 | 30 % |
| Copper (Cu) | 81 ± 24 | 83 ± 25 | 80 ± 24 | 30 % |
| Mercury (Hg) | 0.12 ± 0.024 | <0.057 ± 0.011 | <0.056 ± 0.011 | 20 % |
| Molybdenum (Mo) | 3.1 ± 0.46 | 3.9 ± 0.58 | 4.1 ± 0.61 | 15 % |
| Nickel (Ni) | 54 ± 16 | 60 ± 18 | 61 ± 18 | 30 % |
| Lead (Pb) | 25 ± 7.5 | 35 ± 10 | 33 ± 9.9 | 30 % |
| Antimony (Sb) | <2.3 ± 0.34 | <1.9 ± 0.28 | <1.9 ± 0.28 | 15 % |
| Selenium (Se) | 1.7 ± 0.51 | 2.3 ± 0.69 | 2.2 ± 0.66 | 30 % |
| Zink (Zn) | 170 ± 42 | 110 ± 27.5 | 120 ± 30 | 25 % |

Table 4-14 shows the amount of heavy metals found in samples of untreated and treated slop.

**Table 4-14: Heavy metal values detected in slop from H.M.**

| Heavy metals | Sample 6: Slop before treatment [mg/kg TS] | Sample 7: Slop after treatment [mg/kg TS] | Sample 8: Slop after treatment [mg/kg TS] | Uncertainty of measurements (MU) |
|---|---|---|---|---|
| Arsenic (As) | 10 ± 3 | 8.8 ± 2.6 | 9.6 ± 2.9 | 30 % |
| Barium (Ba) | 310 ± 62 | 93 ± 19 | 94 ± 19 | 20 % |
| Cadmium (Cd) | <0.32 ± 0.096 | <0.22 ± 0.066 | <0.22 ± 0.066 | 30 % |
| Chromium (Cr) | 40 ± 12 | 35 ± 10 | 35 ± 10 | 30 % |
| Copper (Cu) | 67 ± 20 | 64 ± 19 | 65 ± 19 | 30 % |
| Mercury (Hg) | 0.085 ± 0.017 | 0.032 ± 0.0064 | <0.032 ± 0.0064 | 20 % |
| Molybdenum (Mo) | 4.6 ± 0.69 | 6.4 ± 0.96 | 6.5 ± 0.97 | 15 % |
| Nickel (Ni) | 32 ± 9.6 | 27 ± 8.1 | 27 ± 8.1 | 30 % |
| Lead (Pb) | 23 ± 6.9 | 18 ± 5.4 | 17 ± 5.1 | 30 % |
| Antimony (Sb) | <2.1 ± 0.31 | <1.9 ± 0.28 | <1.9 ± 0.28 | 15 % |
| Selenium (Se) | <1.6 ± 0.48 | <1.1 ± 0.33 | <1.1 ± 0.33 | 30 % |
| Zink (Zn) | 100 ± 25 | 87 ± 22 | 91 ± 23 | 25 % |

## 4.7. Additional test results of drilling wastes

Table 4-15 shows the remaining parameters tested in untreated and treated drill cuttings.

**Table 4-15: Additional test results of drill cuttings from TWMA**

| Analysis | Sample 1: Drill cuttings before treatment | Sample 2: Drill cuttings after treatment | Sample 3: Drill cuttings after treatment | Uncertainty of measurements (MU) |
|---|---|---|---|---|
| Solids | 73.8 ± 3.69 % | 80.3 ± 4.01 % | 81.4 ± 4.07 % | 5 % |
| Total solids | 72 ± 8.6 % | 80 ± 9.6 % | 81 ± 9.7 % | 12 % |
| Total carbon (TC) | 17.9 ± 0.895 % tv | 5.5 ± 0.27 % tv | 5.7 ± 0.28 % tv | 5 % |
| Total inorganic carbon (TIC) | 0.8 ± 0.04 % tv | 1.1 ± 0.055 % tv | 1.1 ± 0.055 % tv | 5 % |
| Total organic carbon (TOC) | 17.1 ± 1.71 % tv | 4.4 ± 0.44 % tv | 4.6 ± 0.46 % tv | 10 % |
| Total ignition loss | 12. 8 ± 1.28 % tv | 9.5 ± 0.95 % tv | 9.7 ± 0.97 % tv | 10 % |
| pH | 8.4 | 11 | >10 | 0 % |

Tale 4-16 shows the remaining parameters tested in untreated and treated slop.

**Table 4-16: Additional test results of slop from H.M.**

| Analysis | Sample 6: Slop before treatment | Sample 7: Slop after treatment | Sample 8: Slop after treatment | Uncertainty of measurements (MU) |
|---|---|---|---|---|
| Solids | 56.5 ± 2.82 % | 84.1 ± 4.20 % | 84.2 ± 4.21 % | 5 % |
| Total solids | 52 ± 6.2 % | 85 ± 10 % | 84 ± 10 % | 12 % |
| Total carbon (TC) | 19.6 ± 0.980 % tv | 5.7 ± 0.28 % tv | 5.6 ± 0.28 % tv | 5 % |
| Total inorganic carbon (TIC) | 1.6 ± 0.080 % tv | 1.5 ± 0.075 % tv | 1.5 ± 0.075 % tv | 5 % |
| Total organic carbon (TOC) | 18.0 ± 1.8 % tv | 4.2 ± 0.42 % tv | 4.1 ± 0.41 % tv | 10 % |
| Total ignition loss | 12.1 ± 1.21 % tv | 11.1 ± 1.11 % tv | 11.1 ± 1.11 % tv | 10 % |
| pH | 9.0 | 9.2 | 8.6 | 0 % |

## 4.8. Additional test results of water and oil phases

Table 4-17 outlines the additional test results of the water phases after treatment of drilling wastes at TWMA and Halliburton Mongstad, indicated with sample 4 and 9 respectively.

**Table 4-17: Additional tests results of water phase from TWMA and H.M.**

| Parameters: | Sample 4: Retrieved water phase [mg/l] | Sample 9: Retrieved water phase [mg/l] | Uncertainty of measurements (MU): |
|---|---|---|---|
| Arsenic (As) | 0.019 ± 0.0028 | 0.017 ± 0.0025 | 15 % |
| Lead (Pb) | 0.001 ± 0.0005 | 0.00039 ± 0.00019 | 50 % |
| Cadmium (Cd) | 0.00001 ± 0.000001 | 0.00001 ± 0.000001 | 50 % |
| Copper (Cu) | 0.066 ± 0.0099 | 0.0083 ± 0.0041 | 15 % and 50 % |
| Chromium (Cr) | 0.0011 ± 0.00055 | 0.0046 ± 0.0023 | 50 % |
| Nickel (Ni) | 0.0047 ± 0.0023 | 0.0036 ± 0.0018 | 50 % |
| Zink (Zn) | 0.18 ± 0.027 | 0.011 ± 0.0055 | 15 % and 50 % |
| Mercury (Hg) | 0.00541 ± 0.000541 | 0.000452 ± $4.52*10^{-5}$ | 10 % |
| Sulphate ($SO_4$) | 5.0 ± 0.5 | 1.4 ± 0.14 | 10 % |
| Nitrate ($NO_3$-N) | 0.8 ± 0.16 | <0.005 ± 0.001 | 20 % and 30 % |
| Nitrate + Nitrite ($\sum(NO_3+NO_2)$-N) | 1.9 ± 0.38 | 0.049 ± 0.015 | 20 % and 30 % |
| Nitrite ($NO_2$-N) | 1.1 ± 0.11 | 0.046 ± 0.0046 | 10 % |
| Chloride | 51.5 | 14.7 | - |
| Oil in water C10-C40 | 14.8 ± 2.96 | 1 050 ± 262.5 | 25 % |
| Suspended solids (SS) | - | - | SS could not be estimated due to disturbance from oil film |
| Total organic carbon | 2 170 | 2 510 | - |

Table 4-18 shows the flash point of the retrieved oil phase after treatment of drill cuttings and slop, respectively.

**Table 4-18: Tests conducted on the oil phase from TWMA and H.M.**

| Analysis: | Sample 5: Oil phase after treatment | Sample 10: Oil phase after treatment |
|---|---|---|
| Flash point | 112 °C | 104 °C |
| Dynamic viscosity at 40 °C | 3.290 mPa*s | 2.998 mPa*s |

# 4.9. Comparison of results against limit values given in Waste Regulations

Table 4-19 shows a comparison of the different parameters detected in treated drill cuttings and slop compared to the leaching limit values for hazardous waste given in Waste Regulations. The liquid-solid ratio is 10 l/kg.

**Table 4-19: Comparison of leaching limit values for hazardous waste given in Waste Regulations and leaching values detected in treated drill cuttings (L/S = 10 l/kg)**

| Analysis (L/S = 10 l/kg): | Leaching limit values for hazardous waste [mg/kg TS] | Sample 2: Drill cuttings after treatment [mg/kg TS] | Sample 3: Drill cuttings after treatment [mg/kg TS] |
|---|---|---|---|
| Total solids (TS) | 100 000 | 20 000 ± 6 000 | 21 000 ± 6 300 |
| Arsenic (As) | 25 | 0.27 ± 0.081 | 0.21 ± 0.063 |
| Barium (Ba) | 300 | 3.2 ± 0.96 | 2.7 ± 0.81 |
| Cadmium (Cd) | 5 | <0.0040 ± 0.0012 | <0.0040 ± 0.0012 |
| Chromium (Cr) | 70 | 0.24 ± 0.072 | 0.22 ± 0.066 |
| Copper (Cu) | 100 | <0.20 ± 0.060 | <0.20 ± 0.060 |
| Mercury (Hg) | 2 | <0.0010 ± 0.00030 | <0.0010 ± 0.00030 |
| Molybdenum (Mo) | 30 | 1.9 ± 0.57 | 1.8 ± 0.54 |
| Nickel (Ni) | 40 | 0.62 ± 0.19 | 0.62 ± 0.19 |
| Lead (Pb) | 50 | <0.050 ± 0.015 | <0.050 ± 0.015 |
| Antimony (Sb) | 5 | 0.11 ± 0.033 | 0.10 ± 0.030 |
| Selenium (Se) | 7 | 0.12 ± 0.036 | 0.13 ± 0.039 |
| Zink (Zn) | 50 | <0.40 ± 0.12 | <0.40 ± 0.12 |
| Chloride | 25 000 | 8 300 ± 830 | 8 700 ± 870 |
| Fluoride | 500 | <75 ± 11 | <50 ± 7.5 |
| Sulphate | 50 000 | 780 ± 117 | 920 ± 138 |
| DOC | 1 000 | 1 400 ± 140 | 1 300 ± 130 |

Table 4-20 shows a comparison of the different parameters detected in treated drill cuttings and slop during a column test against the leaching limit values for hazardous waste given in Waste Regulations. The liquid-solid ratio is 0.1 l/kg.

**Table 4-20: Comparison of leaching limit values for hazardous waste given in Waste Regulations and leaching values detected in treated drill cuttings (L/S = 0.1 l/kg)**

| **Analysis (L/S = 0.1 l/kg):** | **Leaching limit values for hazardous waste [mg/kg TS]** | **Sample 2: Drill cuttings after treatment [mg/kg TS]** | **Sample 3: Drill cuttings after treatment [mg/kg TS]** |
|---|---|---|---|
| Arsenic (As) | 0.3 | <0.090 ± 0.036 | <0.070 ± 0.028 |
| Barium (Ba) | 20 | 0.82 ± 0.33 | 0.83 ± 0.33 |
| Cadmium (Cd) | 0.3 | 0.0043 ± 0.0017 | 0.0047 ±0.0019 |
| Chromium (Cr) | 2.5 | <0.050 ± 0.020 | 0.095 ± 0.038 |
| Copper (Cu) | 30 | 0.43 ± 0.17 | 0.43 ± 0.17 |
| Mercury (Hg) | 0.03 | <0.0010 ± 0.00040 | <0.0010 ± 0.00040 |
| Molybdenum (Mo) | 3.5 | 10 ± 4 | 8.7 ± 3.5 |
| Nickel (Ni) | 3 | 0.86 ± 0.34 | 0.88 ± 0.35 |
| Lead (Pb) | 3 | <0.050 ± 0.020 | <0.050 ± 0.020 |
| Antimony (Sb) | 0.15 | <0.20 ± 0.080 | <0.20 ± 0.080 |
| Selenium (Se) | 0.2 | 0.25 ± 0.10 | 0.21 ± 0.084 |
| Zink (Zn) | 15 | 0.50 ± 0.20 | <0.50 ± 0.20 |
| Chloride | 8 500 | 75 000 ± 30 000 | 83 000 ± 33 200 |
| Fluoride | 40 | 240 ± 96 | <15 ± 6 |
| Sulphate | 7 000 | 1 900 ± 760 | 1 900 ± 760 |
| DOC | 250 | 5 300 ± 2 120 | 3 500 ± 1 400 |

Table 4-21 compares the limit values for organic parameters in hazardous waste according to Waste Regulations against the different values for organic parameters detected in treated drill cuttings.

**Table 4-21: Comparison of limit values for organic parameters in hazardous waste according to Waste Regulations with results from treated drill cuttings.**

| **Parameter** | **Limit value** | **Sample 2: Drill cuttings after treatment** | **Sample 3: Drill cuttings after treatment** |
|---|---|---|---|
| Loss of ignition | 10 % | 9.5 ± 0.95 % tv | 9.7 ± 0.97 % tv |
| Total organic carbon (TOC) | 6 % | 4.4 ± 0.44 % tv | 4.6 ± 0.46 % tv |

Table 4-22 shows a comparison of the different parameters detected in treated drill cuttings compared to the leaching limit values for inert waste given in Waste Regulations. The liquid-solid ratio is L/S = 10 l/kg.

**Table 4-22: Comparison of leaching limit values for inert waste given in Waste Regulations and leaching values detected in treated drill cuttings (L/S = 10 l/kg)**

| Analysis (L/S = 10 l/kg): | Leaching limit values for inert waste [mg/kg TS] | Sample 2: Drill cuttings after treatment [mg/kg TS] | Sample 3: Drill cuttings after treatment [mg/kg TS] |
|---|---|---|---|
| Total solids (TS) | 4000 | 20 000 ± 6 000 | 21 000 ± 6 300 |
| Arsenic (As) | 0.5 | 0.27 ± 0.081 | 0.21 ± 0.063 |
| Barium (Ba) | 20 | 3.2 ± 0.96 | 2.7 ± 0.81 |
| Cadmium (Cd) | 0.04 | <0.0040 ± 0.0012 | <0.0040 ± 0.0012 |
| Chromium (Cr) | 0.5 | 0.24 ± 0.072 | 0.22 ± 0.066 |
| Copper (Cu) | 2 | <0.20 ± 0.060 | <0.20 ± 0.060 |
| Mercury (Hg) | 0.01 | <0.0010 ± 0.00030 | <0.0010 ± 0.00030 |
| Molybdenum (Mo) | 0.5 | 1.9 ± 0.57 | 1.8 ± 0.54 |
| Nickel (Ni) | 0.4 | 0.62 ± 0.19 | 0.62 ± 0.19 |
| Lead (Pb) | 0.5 | <0.050 ± 0.015 | <0.050 ± 0.015 |
| Antimony (Sb) | 0.06 | 0.11 ± 0.033 | 0.10 ± 0.030 |
| Selenium (Se) | 0.1 | 0.12 ± 0.036 | 0.13 ± 0.039 |
| Zink (Zn) | 4 | <0.40 ± 0.12 | <0.40 ± 0.12 |
| Chloride | 800 | 8 300 ± 830 | 8 700 ± 870 |
| Fluoride | 10 | <75 ± 11 | <50 ± 7.5 |
| Sulphate | 1 000 | 780 ± 117 | 920 ± 138 |
| Phenol index | 1 | 0.66 ± 0.066 | 0.59 ± 0.059 |
| DOC | 500 | 2 400 ± 240 | 1 900 ± 190 |

Table 4-23 shows a comparison of the different parameters detected in treated drill cuttings after a column test against the leaching limit values for inert waste given in Waste Regulations. The liquid-solid ratio is 0.1 l/kg.

**Table 4-23: Comparison of leaching limit values for inert waste given in Waste Regulations and leaching values detected in treated drill cuttings (L/S = 0.1 l/kg)**

| Analysis (L/S = 0.1 l/kg): | Leaching limit values for hazardous waste [mg/kg TS] | Sample 2: Drill cuttings after treatment [mg/kg TS] | Sample 3: Drill cuttings after treatment [mg/kg TS] |
|---|---|---|---|
| Arsenic (As) | 0.06 | <0.090 ± 0.036 | <0.070 ± 0.028 |
| Barium (Ba) | 4 | 0.82 ± 0.33 | 0.83 ± 0.33 |
| Cadmium (Cd) | 0.02 | 0.0043 ± 0.0017 | 0.0047 ± 0.0019 |
| Chromium (Cr) | 0.1 | <0.050 ± 0.020 | 0.095 ± 0.038 |
| Copper (Cu) | 0.6 | 0.43 ± 0.17 | 0.43 ± 0.17 |
| Mercury (Hg) | 0.002 | <0.0010 ± 0.00040 | <0.0010 ± 0.00040 |
| Molybdenum (Mo) | 0.2 | 10 ± 4 | 8.7 ± 3.5 |
| Nickel (Ni) | 0.12 | 0.86 ± 0.34 | 0.88 ± 0.35 |
| Lead (Pb) | 0.15 | <0.050 ± 0.020 | <0.050 ± 0.020 |
| Antimony (Sb) | 0.1 | <0.20 ± 0.080 | <0.20 ± 0.080 |
| Selenium (Se) | 0.04 | 0.25 ± 0.10 | 0.21 ± 0.084 |
| Zink (Zn) | 1.2 | 0.50 ± 0.20 | <0.50 ± 0.20 |
| Chloride | 460 | 75 000 ± 30 000 | 83 000 ± 33 200 |
| Fluoride | 2.5 | 240 ± 96 | <15 ± 6 |
| Sulphate | 1 500 | 1 900 ± 760 | 1 900 ± 760 |
| DOC | 160 | 5 300 ± 2 120 | 3 500 ± 1 400 |

Table 4-24 compares the limit values for organic parameters in inert waste according to Waste Regulations against the different values for organic parameters detected in treated drill cutting.

**Table 4-24: Comparison of limit values for organic parameters in inert waste according to Waste Regulations with results from treated drill cuttings**

| Parameters | Limit value for organic parameters | Sample 2: Drill cuttings after treatment | Sample 3: Drill cuttings after treatment |
|---|---|---|---|
| Total organic carbon (TOC) | 3 % | 4.4 ± 0.44 % tv | 4.6 ± 0.46 % tv |
| BTEX | 6 mg/kg | <0.106 mg/kg | <0.105 mg/kg |
| PCB 7 | 1 mg/kg | Not detected | Not detected |
| Mineral oil (C10-C40) | 500 mg/kg | 3 300 mg/kg | 2 800 mg/kg |
| PAH 16 | 20 mg/kg | 0.93 mg/kg | 0.93 mg/kg |
| Benzo(a)pyrene | 2 mg/kg | <0.01 mg/kg | <0.01 mg/kg |

## 4.10. Comparison of results against onshore discharge limitations

Table 4-25 compares the discharge limitations given at Halliburton Mongstad treatment facility against samples for retrieved water phase after treatment of drill cuttings and heavy slop as sample 4 and 5, respectively.

**Table 4-25: Comparison of discharge limitations against samples for water phases.**

| Discharge component | Discharge limit, daily mean concentration: [mg/l] | Sample 4: Retrieved water phase [mg/l] | Sample 9: Retrieved water phase [mg/l] |
|---|---|---|---|
| Oil in water | 10 | 14.8 ± 3.7 | 1 050 ± 262.5 |
| TOC | 1 000 | 2 170 | 2 510 |
| Arsenic (As) | 0.05 | 0.019 ± 0.0028 | 0.017 ± 0.0025 |
| Barium (Ba) | 0.5 | - | - |
| Cadmium (Cd) | 0.01 | $1*10^{-5} \pm 5*10^{-6}$ | $1*10^{-5} \pm 5*10^{-6}$ |
| Chromium (Cr) | 0.05 | 0.0011 ± 0.00055 | 0.0046 ± 0.0023 |
| Copper (Cu) | 0.1 | 0.066 ± 0.0099 | 0.0083 ± 0.0041 |
| Mercury (Hg) | 0.003 | 0.00541 ± 0.000541 | $4.52*10^{-4} \pm 4.52*10^{-5}$ |
| Molybdenum (Mo) | 0.1 | - | - |
| Nickel (Ni) | 0.3 | 0.0047 ± 0.0023 | 0.0036 ± 0.0018 |
| Lead (Pb) | 0.025 | 0.001 ± 0.0005 | 0.00039 ± 0.00019 |
| Zink (Zn) | 0.5 | 0.18 ± 0.027 | 0.011 ± 0.0055 |
| Tin (Sn) | 0.1 | - | - |
| Vanadium (V) | 0.25 | - | - |
| pH | 5.7 – 8.5 | 7.8 | 7.4 |

# 5. Discussion

This chapter starts with a discussion of the results retrieved from leaching tests of both drill cuttings and slop, and then moves onto specific test parameters such as PAH, BTEX, PCB, heavy metals and TOC. Results gained from leaching tests and organic parameters in drill cuttings are then compared against leaching limit values according to Waste Regulations. This is followed by a comparison of the results on retrieved water phases against prevailing discharge limits. Weaknesses in the experiment and corresponding results are then discussed, before suggestions for further research are revealed.

## 5.1. Leaching tests

At first glance it seems as untreated and treated drill cuttings have relatively similar results from the leaching test with a liquid-solid ratio of 10 l/kg, illustrated in Table 4-1. Parameters such as chromium, copper, lead, chloride and DOC are relatively similar for the three different samples. For instance, the DOC level in untreated drill cuttings is 1 400 mg/kg TS, while treated drill cuttings has the values 1 400 and 1 300 mg/kg TS in sample 2 and 3, respectively. Even though the difference between the results is small, some values are actually higher for treated drill cuttings as oppose to untreated. Sulphate is one example, where the value in untreated drill cuttings is at 750 mg/kg TS. In treated drill cuttings the values are 780 and 920 mg/kg TS in sample 2 and 3, respectively. However, by taking the uncertainty of measurements into account this slight difference between the samples are evened out.

Similar observation can be drawn from the results from the same leaching test conducted on heavy slop, shown in Table 4-3. The different parameters detected in slop have small differences when comparing the samples against each other. Unlike Table 4-2, the DOC in Table 4-3 differs somewhat in values from untreated to treated slop. Untreated slop has a DOC value at 870 mg/kg TS, while treated slop has a DOC value at 2 400 and 1 900 mg/kg TS in sample 2 and 3, respectively.

Since the column test did not work on untreated drill cuttings, it is not possible to compare the results from treated drill cuttings against untreated drill cuttings. However, when comparing the two samples of treated drill cuttings in Table 4-2, there is a lot of resemblance in the results. Most of the parameters have more or less similar detection values in both samples. The ones that stands out from the rest is mainly total solids, chloride, fluoride and DOC. The values detected of these parameters in sample 2 are relatively higher than for those in sample 3, except for chloride. However, this difference in results is not that great when taking into account the uncertainty of measurements listed in the table.

The results from the column test conducted on slop also indicate a lot a resemblance between the three samples, shown in Table 4-4. Further observation shows a slightly higher overall values for the treated slop in sample 7 and 8 as oppose to untreated slop. Sulphate and fluoride are the only examples where the value detected in untreated slop is higher than for those detected in treated slop. For instance, detected value of sulphate in untreated slop amounts up to 1 700 mg/kg TS, while sample 7 and 8 amounts up to 1 400 and 1 300 mg/kg TS, respectively.

## 5.2. PAH

The traces of different PAH detected in drill cuttings and slop were relatively low even before treatment.  Even though the values were initially low, Table 4-5 and 4-6 illustrates a marked decrease in the PAH values after treatment. The highest PAH value detected in untreated drill cuttings and untreated slop was in both cases napthalene constituted of 0.94 and 10 mg/kg TS, respectively. The two samples of treated drill cuttings constituted of 0.033 and 0.031 mg/kg TS, which equals a percentage of decrease of 96.5 % and 96.7 %, respectively, shown in Table 4-5. Treated slop also shows a distinct decrease in detected napthalene values when compared against untreated slop. The two samples of treated slop constituted of 0.023 and 0.026 mg/kg TS, which equals a percentage of decrease of 99.8 % and 99.7 %, shown in Table 4-6. The latter example illustrates the highest percentage of decrease in PAH values achieved during the treatment process. More than 84 % of the results in Table 4-5 indicate a removal efficiency of PAH above 60 %. Out of these, another 56 % has removal efficiency above 80 %. The lowest removal efficiency in Table 4-5 is of pyrene which initially has a value of 0.51 mg/kg TS in untreated drill cuttings. After treatment the pyrene values was detected at 0.40 and 0.37 mg/kg TS, which equals a removal percentage of approximately 22 and 27 %, respectively. The same tendency is found in Table 4-6, where approximately 65 % of the PAH values has a removal percentage above 60 %. Out of these, another 71 % has removal efficiency above 80 %. The total sum of PAH (16) EPA, shown in Table 4-5 and 4-6, also indicates an efficient removal of PAH. Even though there are some variations in percentage removal of PAH before and after treatment, it seems as the TCC unit functions well with respect to removing PAH from both drill cuttings and slop.

One reasonable question when observing this high removal efficiency of PAH from treated waste during TCC processing is; where does the removed PAH concentrations end up? Is the PAH parameters altered during processing or do they end up in another phase; namely oil or water phase? Samples collected from retrieved water phase from both processing of drill cuttings and heavy slop, show relatively small detected concentrations illustrated in Table 4-5 and 4-6, respectively. The highest level detected in both water phases is napthalene, which is also the case for treated drill cuttings and slop. Sample 4 and 9 of the water phases constituted of 0.067 mg/kg and 0.219 mg/kg napthalene, respectively. This number just indicates where some of the PAH concentrations might end up, while approximately 0.84 and 9.76 mg/kg napthalene detected in sample 1 and 6, respectively, are still uncounted for. This is after subtracting napthalene concentration found in both sample 3 and 7 of drill cuttings and slop, respectively. However, there are some uncertainties related to concentrations detected in retrieved water phase since it is difficult to predict if these water phases are representative enough. This will be elaborated in more details under sub-chapter 5-3 and 5-11.

The low levels of PAH in treated drill cuttings and slop, indicates that a high degree of PAH are removed from the solids during treatment. However, Table 4-6 shows some inconsistencies in the PAH values with regards to treated slop. Certain results actually show a slightly increase in PAH levels. This is the case for benzo(a)anthracene, benzo(b)fluoranthene and benzon(g,h,i)perylene, illustrated in Table 4-6. Before treatment the PAH concentrations was 0.12, <0.1 and <0.1 mg/kg TS, respectively. However, after treatment the PAH concentrations in sample 7 has increased to 0.14, 0.14 and 0.12 mg/kg TS, respectively, while sample 8 has PAH levels of 0.13, 0.13 and 0.12 mg/kg TS, respectively. Since the increase after treatment is relatively small, one possible explanation could lie within the estimated uncertainties with regards to the results, which have been implied in Table 4-6 and Appendix 8. When employing these uncertainties intervals to the results, the values is more as expected; namely a decrease in the PAH concentrations.

A comparison of the different PAH values detected in sample 2 and sample 3 of treated drill cuttings in Table 4-5, shows a great similarity. This is also the case for sample 7 and 8 in Table 4-6. These similarities could indicate that these samples originate from the same batch as sample 1 and 6, respectively.

## 5.3. BTEX

The initial values of BTEX detected in untreated slop, is higher compared to untreated drill cuttings. However, the remaining BTEX in both drilling wastes is relatively similar. The results indicate a high removal efficiency of more than 90 % for all parameters in slop, shown in Table 4-8, and for 80 % of the parameters in drill cuttings, shown in Table 4-7. The remaining parameters in Table 4-7 have a removal percentage of approximately 85 %. M-p-Xylene in slop has a removal percentage of 99.3 and 99.6 % for sample 7 and 8, respectively. The initial value is 11 mg/kg TS, while after treatment the values has decreased to 0.079 and 0.045 mg/kg TS for sample 7 and 8, respectively.

Detected BTEX values in sample 2 and 3 of drill cuttings, is actually the same for every parameter, as shown in Table 4-7. The only exemption is for o-xylene, which only distinguish 0.0004 mg/kg TS between these two samples. The same applies for the parameters in Table 4-8 as well, where the similarities between sample 7 and 8 are highly noticeable. This observation could indicate that the samples collected of drill cuttings and slop consist of two individual representative batches.

As previously discussed under chapter 5.2, though related to PAH, it is interesting to try to evaluate where the removed BTEX end up after treatment. Table 4-7 and 4-8 gives a good indication that some of the BTEX possibly evaporates together with the water phase. The remaining BTEX which neither ends up in treated solids and water phase could then possibly follow the oil phase. According to Table 4-7 it seems as the values of benzene and toluene are actually higher in the retrieved water phase as oppose to the values in untreated drill cuttings. Less than 0.1 mg/kg benzene and 0.31 mg/kg toluene was detected in untreated drill cuttings, while the water phase constituted of 0.183 mg/kg benzene and 0.636 mg/kg toluene. This increase could possibly be explained by considering uncertainties related to collecting representative samples. The water phase is stored in a storage tank after TCC treatment and could possibly contain a mixture of retrieved water originated from different batches of drill cuttings. Thus, the results from the tests conducted on the retrieved water phases might not be 100 % reliable.

## 5.4. PCB

The level of PCB 7 detected in both slop and drill cuttings are relatively low, illustrated in Table 4-9 and 4-10. Less than 0.005 mg/kg TS was detected for all the different PCB compounds, both in untreated and treated drilling wastes. No detection of the the sum of PCB along with the need to dilute in order to elevate the level of quantification is a good indication that the PCB levels in drill cuttings and slop are extremely low.

## 5.5. Total hydrocarbons (THC)

As expected, the levels of hydrocarbons in untreated drill cuttings and slop are relatively high, illustrated in Table 4-11 and 4-12. This is most likely due to the oil particles adhered to the solids, mainly from drilling fluid used during drilling activities. It seems as the smaller carbon chains such as C5-C8 and C8-C10 is present in very small amounts in drilling wastes, while the total hydrocarbons present in drilling waste mainly consists of larger carbon chains such as C12-C16 and C16-C35. The latter groups constitute of 103 000 mg/kg TS out of a total of 110 000 mg/kg TS hydrocarbons in drill cuttings. In slop the total hydrocarbons with larger chains constitute of 167 000 mg/kg TS out of a total of 190 000 mg/kg TS hydrocarbons.

The sum of THC (>C5-C35) given in Table 4-11 and 4-12 indicates a high removal rate of hydrocarbons. In untreated drill cuttings the sum of THC amounts up to 110 000 mg/kg TS, while the treated drill cuttings only consists of 3 300 mg THC/kg TS and 2 800 mg THC/kg TS. This equals a removal percentage of 97 % and 97.5 %, respectively. The removal efficiency is even higher for treated slop. Total amount of THC in untreated slop is 190 000 mg THC/kg TS. However, after treatment the sum THC has decreased to 2 100 mg THC/mg TS and 2 000 mg THC/kg TS which equals a removal percentage of approximately 98.9 % in both cases.

These results indicate that the TCC treatment will remove the oil-on-cuttings to a level well below the general requirements on the NCS of 10 grams of oil per kg of dry material. Samples of treated drill cuttings constitute of 3.3 and 2.8 g oil per kg of dry material in sample 2 and 3, respectively. While treated slop consist of 2.1 and 2.0 g of oil per kg of dry material in sample 7 and 8, respectively.

## 5.6. Heavy metals

One general observation from Table 4-13 and 4-14 is that the removal efficiency of heavy metals in drill cuttings and slop during processing seems relatively low. In addition there are a lot of inconsistencies in Table 4-13 with regards to amount of heavy metals in the waste before and after treatment. Before treatment barium is present in the waste with the total amount of 310 mg/kg TS. However, after treatment the level of barium has increased to 9 200 and 8 600 mg/kg TS in sample 2 and 3, respectively. As a matter of fact, this trend can be observed in almost every heavy metal tested for in drill cuttings, thus not as high an increase as for barium. The only exemptions from this are arsenic, mercury, antimony and zinc, which have a varying degree of decrease in amount after treatment. Mercury has the highest removal percentage of approximately 52.5 % and 53.5 % in sample 2 and 3, respectively. With a starting concentration of 0.12 mg Hg/kg TS and an end result of less than 0.057 and 0.056 mg Hg/kg TS, respectively.

The increasing level of heavy metals in treated drill cuttings can possibly be explained by uncertainties in measurements. When taking the uncertainties into account when studying the results, it is possible to retrieve a result which indicates a small decrease in the heavy metals in treated drill cuttings. However, this is not applicable for barium and cadmium. Implementing the uncertainty intervals to these results still reveals an increase in amount of heavy metal in untreated drill cuttings, and the end result is still relatively high.

It is normal to get a high content of barium, though not as high as the results indicates. However, the increase of barium from untreated to treated drill cuttings seems unreasonable since TCC processing only applies friction and heat, thus not producing barium in the process. Due to this it was determined to conduct a re-test of the barium concentration in untreated and treated drill cuttings in order to establish if there are some errors involved. Unfortunately these results were not due in time to be included in this work. However, one possible explanation for this increase in barium could be related to the decrease in bulk density of the waste after TCC treatment. Specific gravity for untreated and treated drill cuttings are 2 and 1, respectively. Higher specific gravity in untreated drill cuttings is a result of high content of water and oil around the particles. During TCC processing these liquids will evaporate and then be replaced by air particles. Water is heavier than air and the volume will therefore not change. Thus the specific gravity for treated drill cuttings will be less than for untreated, meaning that the concentration of barium in mg/kg will double, while the amount of waste and barium particles will still be the same. The decrease in bulk density might only explain some of the increase, since the barium level increase with approximately 30 and 28 times in treated drill cuttings.

The situation is somewhat different for untreated and treated slop in Table 4-14. Untreated slop has a higher level of heavy metals compared with treated slop, with the exception of molybdenum. Here there is a slightly increase in total amount of molybdenum in treated slop as oppose to untreated. However, the removal efficiency is extremely varying for each heavy metal, ranging from the highest removal percentage of 70 % for barium to the lowest of approximately 3 % for copper. The concentration of some of the heavy metals is still relatively high even after treatment, such as for barium, chromium, copper, nickel, lead and zinc. For instance, barium is present in treated slop with a concentration of 93 mg/kg TS and 94 mg/kg TS in sample 7 and 8, respectively. The fact that there have been some problems associated with too high levels of nickel in treated slop for a short period of time, corresponds whit the nickel results in sample 7 and 8.

The low removal rate of heavy metals during TCC processing could indicate that the heavy metals are not as successfully removed from the solids as previously assumed.

## 5.7. Additional test results of drilling wastes

The total amount of carbon before treatment was estimated to be 17.9 % in drill cuttings and 19.6 % in slop. After treatment the total amount of carbon was 5.5 % and 5.7 % for drill cuttings and 5.7 % for slop. This equals a percentage removal of approximately 69 %, 68 % and 71 %, respectively. Oil is the largest source of carbon in both drill cuttings and heavy slop. During TCC processing the oil is evaporated of the solids, leaving behind a smaller total amount of carbon. Thus, this process is illustrated through the yielded results of total carbon before and after treatment.

The total inorganic carbon was much lower than the total organic carbon in both drill cuttings and slop, as illustrated in Table 4-15 and 4-16.

The pH in drill cuttings was 8.4 before treatment with an increase to 11 and 10.6 after treatment. Starting pH in untreated slop was 9.0, in sample 7 of the treated slop the pH had a slightly increase to 9.2 while it decreased to 8.6 in sample 8.

Decrease in ignition loss is higher for drill cuttings as oppose to treated slop, shown in Table 4-15 and 4-16. Total ignition loss after treatment of drill cuttings has a average of 9.5 % for sample 2 and 3, while treated slop had a detected ignition loss of 11.1 for both samples.

## 5.8. Additional test results of water and oil phases

Table 4-17 shows that the oil in water content in retrieved water phase after treatment of drill cuttings was estimated to be 14.8 ± 2.96 mg/l in sample 4. As mentioned previously, the discharge requirements for oily water shall not exceed 30 mg oil per liter of water as a weighted average for one calendar month. Even after taking the uncertainties of measurements into account the concentration of oil in water is still below the requirements, namely 17.8 mg/l. This result would then indicate that the retrieved water phase after TCC processing is cleaned to a level well below the prevalent requirement. Thus, discharge of the retrieved water phase into the sea could be a possible outcome, assumed that the TCC unit is implementation as a treatment option for drill cuttings offshore. Nevertheless, the concentration of oil in water could possibly be lowered even further, just by implementing simple measures. Additional treatment measures after TCC processing could potentially include an oil absorbing filter to lower the hydrocarbon content to an even greater extent. However, since there was not conducted any parallel tests for this value, it is still suggested to do some more test in order to verify the result.

The oil in water content in the water phase retrieved after slop treatment is much higher. Sample 9 shows a concentration of oil in water at 1 050 mg/l, which is further discussed in chapter 5.10. Chloride and TOC level in both drill cuttings and slop are also relatively high. The chloride concentration yielded in sample 4 and 9 was 51.5 and 14.7 mg/l, respectively, while TOC was estimated at 2 170 and 2 510 mg/l, respectively.

The results from the water phase from both drill cuttings and slop yields very low concentrations of heavy metals, sulphate, nitrate and nitrite. Compared against the heavy metals found in untreated drill cuttings and slop, the numbers in Table 4-17 could indicate that the heavy metals does not principally follow the water phase. This coincides with the principle of solubility, which says that heavy metals are insoluble or have low solubility in water.

## 5.9. Comparison of limit values given in Waste Regulations

When comparing the leaching limit values for hazardous waste against the leaching values retrieved from treated drill cuttings, Table 4-19 indicates that the levels for the different parameters are well below the requirements. The only exception is for dissolved organic carbon (DOC), which has a leaching limit value of 1 000 mg/kg TS. This is not the case for treated drill cuttings, where the DOC amounts up to 1 400 mg/kg TS and 1 300 mg/kg TS. These concentrations are more than what is accepted for a hazardous waste according to the Waste Regulations. As stated in Waste Regulations and the remark appurtenant to Table 2-3, if the DOC level exceeds 1 000 mg /kg dry matter at its own pH, it is possible to test the waste at L/S = 10 l/kg and a pH between 7.5 and 8.0. If the DOC does not exceed 1000 mg/kg in this test, then it can be consider meeting the acceptance criteria for DOC. Thus, this could be an option in this case.

Table 4-20 indicates some inconsistencies between leaching limit values for hazardous waste and results retrieved from treated drill cuttings. Most of the results from the samples are well below the limits given in Waste Regulations. A total of 11 out of 16 parameters are detected below the requirements, including copper, cadmium, mercury, nickel and sulphate. However, the remaining five parameters are thus above the limits. This is the case for molybdenum, selenium, chloride, fluoride and DOC. Even when taking the uncertainties of measurements into account, the levels are still too high for these parameters, except for selenium. One interesting observation is that the concentration of fluoride detected in sample 2 is much higher than for sample 3, which constituted of 240 and 15 mg/kg TS, respectively. This equals a difference of 225 mg/kg TS, in other words 16 times higher for sample 2. The difference in levels of chloride and DOC in untreated and treated drill cuttings is also noticeable. Sample 2 and sample 3 of treated drill cuttings are assumed to originate from the same batch. Differences in values such as for fluoride could suggest otherwise.

According to the results retrieved on ignition loss and TOC it seems as the treated drill cuttings upholds the limit values for organic parameters in hazardous wastes, shown in Table 4-21. The limit value for loss of ignition was set at 10 %, while the detected ignition loss in sample 2 and 3 of treated drill cuttings was 9.5 and 9.7 %, respectively. Limit value for TOC in hazardous waste is 6 %, while the detected TOC level in treated drill cuttings was 4.4 and 4.6 % in sample 2 and 3, respectively. A decrease in TOC values is as expected, mainly due to evaporation of water. Even though some of the parameters will remain in the solids, an essential part of the parameters will evaporated together with the water.

One general observation from Table 4-22 and 4-23, is too high levels of molybdenum, nickel, chloride, fluoride and DOC compared to the leaching limit values for inert waste. Table 4-22 also shows an elevated total solid number and phenol index, while Table 4-23 has high numbers for copper, antimony and selenium. The remaining parameters in both tables have values below the limits given in Waste Regulations, such as arsenic, cadmium and mercury. Values for total solids, chloride, fluoride and DOC are very high compared to the limits, shown in Table 4-22 and 4-23. This difference cannot be explained by applying uncertainties of measurements, since the difference between limit values and detected values still are too high. Too high levels of molybdenum and nickel can neither be explained by MU, even though the difference from leaching limits is very small.

One unexpected observation in all of these four tables, is that despite of the high level of barium present in treated drill cuttings in Table 4-13 and 14 the amount of barium detected in the eluate is actually well below the requirements. For instance, leaching limit values for inert waste is 20 and 4 mg/kg TS for leaching tests with a liquid-solid ratio of 10 l/kg and 0.1 l/kg, respectively. The results from these tests were 3.2 and 2.7 mg/kg TS with L/S = 10 l/kg, while the column test with L/S = 0.1 l/kg detected 0.82 and 0.83 mg/kg TS.

Results from Table 4-24 shows that the amount of organic parameters such as BTEX, PCB 7, PAH 16 and benzo(a)pyrene presents in treated drill cuttings are well below the limits set for inert waste. PAH 16 are for instances listed with a limit of 20 mg/kg, while the detection value found in treated drill cuttings was 0.93 mg/kg. The level of TOC and mineral oil (THC) found in treated drill cuttings are on the other hand high above the given limits. Percentage TOC found in treated drill cuttings was 4.4 and 4.6 %, while the TOC limit is set at 3 %. The limit for THC in inert waste is set at 500 mg/kg, while the content found in treated drill cuttings was estimated at 3 300 and 2 800 mg/kg.

According to the results observed when comparing treated drill cuttings against limit values given in Waste Regulations, it illustrates that drill cuttings is within the category of hazardous waste. Results show too many inconsistencies within the limit values given for inert waste, making it difficult to consider disposal of drill cuttings to inert waste landfills. This is partly due to too high concentrations of TOC and mineral oil in drill cuttings compared with the limits set for organic parameters in inert waste. However, upholding prevalent requirements for almost all parameters and the absence of discharge limits for mineral oil in hazardous waste, makes drill cuttings more suitable for disposal at hazardous landfilling. If disposal of drill cuttings at inert waste landfills is a desirable objective in the near future, it might be an option to consider process optimization of the TCC unit. This could possibly include an evaluation of the removal efficiency of the TCC unit to see if it is possible to achieve better cleaning results, without damaging the oil phase for the purpose of re-usage. Too high temperatures have the potential to degrade the oil, thus making it unfit for reuse.

## 5.10. Comparison of results against onshore discharge limitations

Table 4.25 shows that a lot of the tested parameters in both retrieved water phases was detected well below the discharge limits set by KLIF for Halliburton Mongstad treatment facility. This includes parameters such as arsenic, cadmium, chromium, copper, nickel, lead, zinc and pH. The only exceptions were for oil-in-water, TOC and mercury.

The discharge limit set for oil-in-water concentration in the retrieved water phase is set at a concentration of 10 mg/l, shown in Table 4.25. The detected oil level in the retrieved water phase from treatment of heavy slop (sample 9) was at 1 050 mg/l, which is 105 times higher as indicated in the discharge limits. Accounting for uncertainties of measurement will still give a too high concentration of oil-in-water. However, detected oil-in-water concentrations in retrieved water phase after treatment of drill cuttings (sample 4) was only 14.8 mg/l, upholding the discharge limit set in Table 4-25.

Both retrieved water phases contained a TOC concentration above the discharge limit set in Table 4-25 at 1000 mg/l. TOC found in sample 4 and 9 consisted of 2 170 and 2 510 mg/l, respectively. This is more than twice as high as for the discharge limit. Eurofins did not list any uncertainty of measurement for this parameter in the analytical report.

The detected mercury concentration in sample 4 was also too high, namely at 0.00541 mg/l. Comparison against the discharge limit set for mercury at 0.003 mg/l indicates that the mercury concentration in retrieved water phase after treatment of drill cuttings is too high. Accounting for the given uncertainty of measurements still gives a value above the discharge limit. However, the mercury concentration found in sample 9 is below the discharge limit, namely at 0.000453 mg/l.

Results given in Table 4-25 illustrates that 13 out of 15 parameters in both samples were below the discharge limit set for discharge of treated wastewater. This indicates that the retrieved water phase would require some additional cleaning before discharging. Such a measure could include bio-processing, which would remove the oil-in-water and TOC detected in the samples. However, this is under the assumption that all detected heavy metals concentrations in the water are below the discharge limits. Thus, additional tests would be required in order to determine if the mercury concentration in water phase from treated drill cuttings is acceptable or not.

Barium, molybdenum, tin and vanadium are also listed as parameters requiring discharge limits at Halliburton Mongstad. Unfortunately these parameters were not included in the test round up front. Thus it would be required to include these parameters in a prospective similar comparison in the future.

## 5.11. Weaknesses

One explanation for the increase in some of the concentrations from untreated to treated drill cuttings and slop, could potentially be affiliated with the uncertainties from the sampling procedure. During the sampling process, sample 6 of the untreated slop was first collected before it entered the TCC unit. In order to get a representative sample of the treated slop; meaning a sample of treated slop which originated from the same batch of slop as sample 6, the TCC unit was given sufficient time to process the slop. A time gap of 30 minutes was estimated to be sufficient time to give a representative sample, thus sample 7 was collected 30 minutes after sample 6. Another 15 minutes passed before sample 8 was collected. It is somewhat difficult to predict how long processing time a batch of untreated slop/drill cuttings will take from the time it enters the TCC unit until it leaves the unit as a treated powder. Several factors will affect this, such as water content in the drilling waste. The higher the water content, the higher processing time is required in order to evaporate all the water from the solids. Since drill cuttings contain less water than slop, the first sample (sample 2) of treated cuttings was taken 5 minutes after the untreated sample (sample 1) was collected. Another 50 minutes passed before the second sample (sample 3) of treated drill cuttings was collected. The examples of inconsistencies between the two samples of treated drill cuttings as well as for treated slop, might also point towards this explanation. It could be possible that these two estimated time frame for slop and drill cuttings, respectively, was not accurate enough. However, to determine the precise moment to collect the samples is something that is quite difficult. The same uncertainties might also apply for the samples of retrieved water phase, as previously discussed in chapter 5.3.

As mentioned, some of the deviations or unexpected results can possibly be explained when accounting for the given uncertainties of measurements in the results. The measuring uncertainty affiliated with each result should, according to (Eurofins, 2012), include two standard deviations as well as some corrections values for sampling, storage and shipment of samples, homogeneity, contribution from instruments and methods. This uncertainty, MU, will increase when dealing with very small detection levels of the different substances.

## 5.12. Future research

The increased abundance of drilling waste on landfill seen the last few years brings focus towards even further development of a sustainable drilling waste management as well as establishing a BAT for drilling waste. As mentioned in section 2.6.3, the TCC methods have several benefits as a possible BAT. However, even further analysis and evaluations are required in an attempt to minimize the current knowledge gap on subjects such as fate of chemicals during TCC processing and possible effects on the environment. Thus it would be beneficial to further characterize the composition of untreated drill cuttings, followed by a comparison of the composition of treated solids after TCC processing and subsequently the water and oil phase. This would assist in determining the fate of the chemicals during the TCC processing, and thereby making it easier to model and monitor a possible discharge of drill cuttings to sea.

In order to get a representative and complete study, it is recommended to add additional test parameters such as different mud types/systems as well as drill cuttings originated from different drill sections. This method only included the mud type Yellow Enviromul which consists of both yellow and green chemicals. It could be interesting to see how different chemical composition in mud will affect the drill cuttings as well as the composition of treated solids after TCC. It could for instance be beneficial to test mud types such as Red Enviromul, XP-07 and low solids oil based mud (LSOBM), which all have different chemical compositions. The drill section relevant for drill cuttings tested in this thesis was 17 ½". Implementing other drill sections would give a better range of the study, and better options for comparison. This could for instance include testing of drill cuttings derived from drilling sections such as 8 ½" and 12 ¾".

The test parameters utilized on solid and water phases in this thesis, could be suitable as test parameters for further research when assessing TCC treatment of drilling waste. This could be related to potential offshore disposal of the treated drill cuttings, thus evaluating possible effects on the environment. Additional test parameters should then include the particle size of treated drill cuttings as well as the particles fate when discharged. As mentioned in section 2.6.3.3, this is a field where the knowledge is limited. Thus it is of high importance and relevance to acquire more information on this subject, especially in the process of evaluating the TCC unit as best available technique.

The process of assessing the TCC method as an offshore treatment method requires a vast amount of acquired information on different subjects such as costs, transport, logistics, risks and environment. Due to the prevalent rules and regulations associated with discharge of drill cuttings offshore, an onshore disposal method might be the most suitable outcome after treatment. Then it might be beneficial to evaluate the practicality of treating the drill cuttings offshore and subsequently transport the treated waste onshore for disposal. This could include an assessment of proposed practice against current practice of transporting drill cuttings onshore for both treatment and disposal. Results from this thesis indicate that the recovered water phase after TCC treatment could potentially be discharged offshore, since the oil in water content is well below the prevalent requirements. This, as well as a re-use of recovered oil, could potentially reduce the volume of waste sent onshore for disposal.

Due to the low removal rate and inconsistencies in the results from test on heavy metals in drill cuttings and slop, it could be beneficial to conduct more tests on this subject. This could assist in determining if the removal rate of heavy metals corresponds with the results from this study.

# 6. Conclusions

The results acquired from the analysis on drill cuttings and heavy slop indicate a high removal efficiency of the test parameters such as hydrocarbons, PAH and BTEX. Concentrations of PAH and BTEX are relatively low in the drilling wastes even before treatment. Nevertheless, results show a high removal percentage for both parameters. PAH concentrations in the water phase are relatively low, while BTEX concentration in the water phase is high. This observation could possibly indicate that it is more likely that BTEX evaporates together with the water, while only some of the PAH will follow the water phase.

There were some difficulties associated with detection of PCB concentrations in treated drill cuttings and heavy slop, mainly due to initially low content of PCB in the wastes. In addition, the results indicate a varying and low removal efficiency of heavy metals as well as some inconsistencies affiliated with the results from drill cuttings. In some cases the samples of treated drill cuttings contained a higher concentration of the heavy metals as oppose to untreated drill cuttings. This increase was most pronounced in detected barium concentrations. Before treatment the barium concentration was 310 mg/kg TS, while after treatment it was detected at 9 200 and 8 600 mg/kg TS in sample 2 and 3, respectively. Possible explanation for some of the increase could be related to the decrease in bulk density of the waste after treatment as well as non homogeneity in the samples.

Results from leaching tests conducted on treated drill cuttings shows that the treated solids upholds most of the leaching limits and organic parameters set for hazardous waste. There are some exceptions such as DOC in both leaching test and column test, as well as chloride, molybdenum and fluoride in the column test. Nevertheless, drill cuttings are still suitable for disposal at hazardous waste landfills. However, comparing treated drill cuttings against leaching limits and organic parameters for inert waste shows even more inconsistencies. For instance, the TOC and mineral oil concentrations in treated drill cuttings were too high compared with the limits set for inert waste. Which indicates that treated drill cuttings is unsuitable for possible disposal at inert waste landfills.

Results from tests conducted on the retrieved water phases after treatment of drilling wastes, indicates a TOC concentration above the discharge limit of 1000 mg/l. The oil-in-water concentration was also too high for retrieved water phase after treatment of heavy slop. Due to this, the retrieved water phase is not clean enough to be directly discharged onshore after TCC treatment. Thus it would require additional treatment in order to decrease the TOC and oil-in-water concentrations below the discharge limits set for Halliburton Mongstad. This could possibly include a bio-processing treatment, assuming that the concentrations of heavy metals are below the discharge limits. Since this is not the case for retrieved water phase after treatment of drill cuttings, it is recommended to perform parallel tests to determine if the mercury concentration in water phase after treatment of drill cuttings is acceptable or not. Additional tests should also include detection of barium, molybdenum, tin and vanadium in both water phases, since these were not included in this test round.

The oil in water content detected in recovered water phase after TCC processing indicates that the treatment method cleans the water to concentrations well below the prevalent requirements. Detected oil in water concentration was 14.8 mg/l, while the offshore discharge requirements are set at 30 mg oil per liter of water as a weighted average for one calendar month. Discharge of the recovered water phase could therefore be a potential outcome if the TCC unit were to be implemented offshore. The oil-on-cuttings concentration in treated drill cuttings and slop was also below the discharge requirements set for the NCS. Samples of treated drill cuttings constitute of 3.3 and 2.8 g oil per kg of dry material in sample 2 and 3, respectively. While treated slop consist of 2.1 and 2.0 g of oil per kg of dry material in sample 7 and 8, respectively. This upholds the requirements of 10 grams of oil per kg of dry material.

Previously studies have shown that TCC process has several benefits as best available technique offshore. However, the prevalent rules and regulations eliminate the possibility for discharge of the treated drill cuttings to the sea. Thus, the treated waste would still be disposed of onshore. Even further studies are required in order to assess the possibility of direct discharge of the treated drill cuttings offshore. This could include a further assessment of the chemical composition of treated drilling waste, chemical fate during TCC processing, particle fate and potential effect to the environment if discharged. Even if the treated solids are found not suitable for direct discharge, an offshore TCC treatment could still be a suitable waste management measure due to the potential of re-use of recovered oil and direct discharge of treated water. It is also suggested to include additional parameters in a future study, such as different mud types/systems and drill sections. This could give a better range of the study as well as better options for comparison.

Weaknesses in the experimental method used in this work include uncertainties affiliated with the sampling procedure. This is due to difficulties associated with estimation of how long processing time a batch of untreated heavy slop or drill cuttings requires, from the time it enters the TCC unit until it leaves the unit as a treated powder. If this estimation is not accurate enough, it could possibly lead to unrepresentative samples of treated powder compared with untreated waste. In addition there is the possibility of retrieving samples which are not homogenous, rendering inconsistencies in the results. Since no parallel tests were performed of the analysis's it is difficult to compare and evaluate if the values retrieved are correct or too influenced by uncertainties. Thus, it is suggested to perform parallel tests in order to verify the results.

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# 8. Appendix

The following chapter first presents an overview of disposal methods for drill cuttings. It then outlines the classification of chemicals according to possible environmental effect. Then it presents extractions from the Activities Regulations, Pollution Control Act and Waste Regulations not covered in chapter 4. This is followed by an overview of the packing material used during the sampling procedure. It then outlines the MU affiliated with values retrieved of PAH and BTEX, given in percentage. At last it outlines conversions affiliated with different values found in the water phase.

## 8.1. Appendix 1: Overview of disposal methods for drill cuttings

Table 8-1 gives an overview over the types of disposal methods that have been used for drill cuttings over the past years when using OBM.

**Table 8-1: Disposal methods of drill cuttings when using OBM, tons (The Norwegian Oil Industry Association (OLF), 2011)**

| Reporting year | Drill cuttings exported to other fields | Drill cuttings discharged to sea | Mass drill cuttings injected | Drill cuttings sent onshore | Total amount drill cuttings generated |
|---|---|---|---|---|---|
| **2003** | 5 612 | 0 | 110 231 | 49 676 | 176 598 |
| **2004** | 0 | 0 | 51 691 | 20 329 | 148 071 |
| **2005** | 0 | 0 | 60 242 | 20 287 | 246 018 |
| **2006** | 0 | 0 | 54 433 | 22 679 | 211 942 |
| **2007** | 467 | 0 | 50 321 | 28 875 | 191 191 |
| **2008** | 0 | 0 | 49 108 | 24 275 | 228 743 |
| **2009** | 424 | 0 | 47 640 | 39 072 | 252 562 |
| **2010** | 0 | 0 | 26 938 | 81 188 | 125 123 |

Table 8-2 gives an overview over the types of disposal methods that have been used for drill cuttings over the past years when using WBM.

**Table 8-2: Disposal methods of drill cuttings when using WBM, tons (The Norwegian Oil Industry Association (OLF), 2011)**

| Reporting year | Drill cuttings exported to other fields | Drill cuttings discharged to sea | Mass drill cuttings injected | Drill cuttings sent onshore |
|---|---|---|---|---|
| **2004** | | 86 061 | 1 726 | 58 |
| **2005** | | 72 684 | 895 | 893 |
| **2006** | 325 | 80 757 | 1 423 | 2 226 |
| **2007** | 0 | 86 405 | 1 191 | 722 |
| **2008** | 651 | 70 199 | 2 717 | 2 501 |
| **2009** | 0 | 132 003 | 1 624 | 251 |
| **2010** | 0 | 207 655 | 664 | 9 896 |

Table 8-3 gives an overview over the types of disposal methods that have been used for drill cuttings over the past years when using SBM.

**Table 8-3: Disposal methods of drill cuttings when using SBM, tons (The Norwegian Oil Industry Association (OLF), 2011)**

| Reporting year | Drill cuttings exported to other fields | Drill cuttings discharged to sea | Mass drill cuttings injected | Drill cuttings sent onshore |
|---|---|---|---|---|
| **2003** | 0 | 5 108 | 276 | 1 197 |
| **2004** | 0 | 2 451 | 0 | 0 |
| **2005** | 0 | 0 | 0 | 930 |
| **2006** | 0 | 0 | 0 | 0 |
| **2007** | 0 | 0 | 0 | 0 |
| **2008** | 0 | 0 | 0 | 0 |
| **2009** | 0 | 0 | 0 | 0 |
| **2010** | 0 | 0 | 0 | 0 |

Table 8-4 illustrates the chemical discharges according to KLIFs (former STF) categorization, going back until 1997 and up to 2010.

**Table 8-4: Overview of chemical discharge according to STFs categorization, tons (Norwegian Petroleum Directorate, 2011)**

| SFTs categorization | Green | Yellow | Red | Black |
|---|---|---|---|---|
| **1997** | 114 778 | 39 684 | 3 933 | 228 |
| **1998** | 142 646 | 10 971 | 2 441 | 34 |
| **1999** | 162 603 | 9 495 | 1 839 | 21 |
| **2000** | 187 323 | 14 184 | 1 337 | 18 |
| **2001** | 167 365 | 11 834 | 1 117 | 45 |
| **2002** | 164 450 | 10 898 | 1 022 | 35 |
| **2003** | 118 388 | 10 977 | 626 | 5 |
| **2004** | 91 044 | 10 599 | 299 | 2 |
| **2005** | 80 105 | 10 240 | 93 | 3 |
| **2006** | 93 141 | 11 078 | 39 | 3 |
| **2007** | 109 778 | 11 796 | 23 | 1 |
| **2008** | 114 403 | 12 819 | 15 | 2 |
| **2009** | 159 569 | 14 701 | 21 | 1 |
| **2010** | 127 249 | 11 727 | 16 | 1 |

## 8.2. Appendix 2: Categorization of chemicals

KLIF categorizes the different chemicals used in the Petroleum Industry according to their possible environmental effect. According to chapter XI, §62 in The Activities Regulations the chemicals can be divided into following categories:

1) *"Black category:*
   *The black category include substances that appear on the following lists:*
   *- The priority list from Storting White Paper No. 21 (2004-2005)*
   *- The OSPAR List of Chemicals for Priority Action, cf. OSPAR Strategy with regard to Hazardous Substances.*

   *In addition, substances with the following ecotoxicological properties are classified as black:*
   *- Substances with both a biodegradability of BOD28 < 20% and bioaccumulation potential of Log Pow ≥ 5).*
   *- Substances with both a biodegradability of BOD28 < 20% and that are toxic ($LC_{50}$ or $EC_{50}$ ≤ 10 mg/l).*
   *- Substances that are harmful in a mutagenic or reproductive manner."*

   Chemicals belonging in this category are considered hazardous for the environment, thus they are not normally allowed discharged. However, according to a report from Halliburton (2009), such a discharge can be granted under special circumstances. If this is the case, then the permit will only be valid for a type of chemical and specific amount. The operator needs to apply for a new permit if changes in amount and type of chemical are desirable. The application needs to be approved by KLIF and an environmental documentation, called HOCNF, must be delivered along with the application (Halliburton (Baroid Surface Solutions), 2009).

2) *"Red category:*
   *The red category includes substances with the following ecotoxicological properties:*
   *- Non-organic substances that are acutely toxic ($EC_{50}$ or $LC_{50}$ ≤ 1 mg/l)*
   *- Organic substances with biodegradability BOD28 < 20%*
   *- Organic substances or compound substances that meet two of the three following criteria:*
      *- Biodegradability, BOD28 < 60% or*
      *- Bioaccumulation potential. Log Pow ≥ 3 and molecular weight < 700 or*
      *- Acute toxicity, $LC_{50}$ or $EC_{50}$ ≤ 10 mg/l"*

   Chemicals belonging in this category is considered to be potentially harmful to the environment, and needs to be substituted with more environmental friendly chemicals. According to a report from Halliburton (2009), it is possible to get a permit for discharge of a total amount of environmentally hazardous substance within a preferred field of application. However, the operator is in charge of making sure that the discharge of red chemicals does not exceed the total amount permitted.

3) *"Yellow category:*
   *The yellow category includes substances that, based on their innate properties, are not defined as red or black, and which do not appear on OSPAR's PLONOR list."*

   Even though yellow chemicals do not pose an immediate threat to the environment, the goal is still to reduce the discharge and utilization of them. According to a report from Halliburton (2009), the operator must apply to KLIF for a discharge permit of yellow chemicals. The application needs to contain both type and amount of chemicals planned discharged.

4) *"Green category:*
   *The green category includes substances on OSPAR's PLONOR list, and are presumed not to have a significant impact on the environment. "*

   Chemicals in this category are considered to be environmentally friendly chemicals due to the lack of inherent environmentally hazardous properties. Even though the goal of minimizing the amount of discharged chemicals is applicable for this group as well, there is no need for a specific permit (Halliburton (Baroid Surface Solutions), 2009). However, in certain environmentally vulnerable areas, KLIF might require restrictions in amount and type of PLONOR-chemicals allowed used (Halliburton (Baroid Surface Solutions), 2009).

## 8.3. Appendix 3: The Activities Regulations

The following section is a direct extraction from the Activities Regulations.

### CHAPTER X
### MONITORING THE EXTERNAL ENVIRONMENT

### §52
### Cooperation on and planning of environmental monitoring

*The operators shall cooperate on monitoring the external environment in regions as defined in Guidelines for environmental monitoring of the petroleum activities on the Norwegian continental shelf (in Norwegian only).*

*The monitoring shall be adapted to the existing pollution risk, be able to prove and map pollution of the external environment, and indicate development trends in the environmental condition.*

*The environmental monitoring of pollution from regular emissions and discharges shall include both benthic habitats (the sediments, molluscs and benthic fauna) and the water column.*

*Personnel with monitoring functions shall at all times be able to efficiently gather and process information on such conditions.*

*The operators shall contribute to further development of the guidelines and relevant monitoring tools.*

*The Climate and Pollution Agency can in, special cases, set additional requirements for monitoring beyond the prevailing guidelines.*

### § 53
### Baseline surveys

*To map the environmental status, the operator shall carry out baseline surveys*

*a) before exploration drilling in new and previously unsurveyed exploration areas,*
*b) before exploration drilling in areas where there are proven particularly vulnerable environmental resources (species and habitats), or where their existence is probable,*
*c) before production drilling.*

*Baseline surveys of the sediments and relevant fauna elements on the seabed shall be performed in accordance with the Guidelines for environmental monitoring of the petroleum activities on the Norwegian continental shelf (in Norwegian only). A baseline survey shall be valid for six years.*

### § 54
### Environmental monitoring of seabed habitats

*Plans for environmental monitoring of benthic habitats (sediments, molluscs and benthic fauna) shall be prepared in accordance with the Guidelines for environmental monitoring of the petroleum activities on the Norwegian continental shelf (in Norwegian only) and shall be* *submitted to the Climate and Pollution Agency within 1 February of the year the monitoring will be carried out.*

*Studies in the individual region shall, as a rule, be carried out every three years. The surveys alternate between regions. The scope of monitoring shall be related to the shelf activity in the individual regions. Monitoring of new activity is in addition to, and shall be adapted to, existing monitoring.*

*The samples from the regional and field-specific stations shall be collected on the same trip. The regional stations shall describe the general background levels in the area for the examined components, and function as references to an expected normal condition. The field-specific stations shall provide information on the condition surrounding the individual facilities in the regions.*

*The operators shall, as part of the environmental monitoring, themselves contribute to developing new methods for monitoring sediments and benthic fauna.*

*Studies shall provide information on both the vertical and horizontal spread of relevant parameters.*

*The Climate and Pollution Agency can, in special cases, order other types of environmental surveys, and studies in other parts of the influence area, than those described in the Guidelines for environmental monitoring of the petroleum activities on the Norwegian continental shelf (in Norwegian only).*

## § 55

## Environmental monitoring of the water column

*Plans for environmental monitoring of the water column shall be prepared in accordance with the Guidelines for environmental monitoring of the petroleum activities on the Norwegian continental shelf (in Norwegian only), and shall be submitted to the Climate and Pollution Agency by 1 April of the year the monitoring will be carried out.*

*The water column monitoring shall consist of two main elements; condition monitoring and impact monitoring. The scope of the monitoring shall be in proportion to the expected risk.*

*The condition monitoring shall include fish, and shall be carried out every three years. The monitoring shall document whether fish from Norwegian waters are affected by pollution from the petroleum activities.*

*The impact monitoring shall be carried out in one region per year, and shall as a minimum include fish and mussels.*

*The operators shall, as part of the environmental monitoring, themselves contribute to developing methods of impact monitoring in the water column. As suitable methods for monitoring impacts and long-term impacts of the emissions and discharges are established, a selection of these shall be used in a more standardised programme.*

*The Climate and Pollution Agency can, in special cases, order other types of environmental surveys, and studies in other parts of the influence area, than those described in the Guidelines for environmental monitoring of the petroleum activities on the Norwegian continental shelf (in Norwegian only).*

## 8.4. Appendix 4: The Pollution Control Act

The Pollution Control Act only exists in Norwegian. The following section is thus a direct outline from a governmental translation which is based on the Norwegian text with latest amendments of 20 June 2003.

### CHAPTER 1
### INTRODCTORY PROVISIONS

#### §4
#### Application of the Act to activity on the continental shelf

*"The provisions of this Act also apply, subject to any restrictions deriving from international law and from the Act itself (cf. Chapter 8), to exploration for and production and utilization of natural subsea resources on the Norwegian part of the continental shelf, including decommissioning of facilities. The provisions of section 7, first paragraph, cf. Chapter 3, on the duty to obtain a permit and of section 9 on regulations nevertheless apply only to those aspects of such activity that regularly result in pollution. Nor do the provisions of section 7, second paragraph, cf. fourth paragraph, apply to measures to prevent or stop acute pollution.*

*The pollution control authority may issue further regulations relating to waste from such activity on the continental shelf as is mentioned in the first paragraph. As regards measures to clean up waste, the provisions of section 74, cf. section 7, apply correspondingly instead of section 37.*

*The pollution control authority may by regulations or individual decisions determine in cases of doubt what is to be regarded as aspects of an activity that regularly result in pollution, and may grant exemptions from the first paragraph."*

### CHAPTER 2
### GENERAL PROVISIONS RELATING TO POLLUTION

#### §6
#### What is meant by pollution

*"For the purpose of this Act, pollution means:*

1. *the introduction of solids, liquids or gases to air, water or ground,*
2. *noise and vibrations,*
3. *light and other radiation to the extent decided by the pollution control authority,*
4. *effects on temperature*

*which cause or may cause damage or nuisance to the environment.*

*The term pollution also means anything that may aggravate the damage or nuisance caused by earlier pollution, or that together with environmental impacts such as are mentioned in items 1 to 4 causes or may cause damage or nuisance to the environment."*

### §9

### Regulations relating to pollution

*"The pollution control authority may issue regulations laying down:*

1. *emission limit values for types of pollution that shall be permitted or laying down that pollution shall be prohibited completely or at certain times,*
2. *threshold limit values for the occurrence of certain substances, noise, vibrations, light and other radiation in the environment, and the measures that shall be taken if these values are exceeded,*
3. *how permanent and temporary installations shall be set up and how an enterprise shall be managed to prevent pollution,*
4. *quality requirements for pollution control equipment and a requirement that such equipment must not be sold without being approved by the pollution control authority,*
5. *that personnel operating an enterprise that may involve pollution shall have specific qualifications.*

*Regulations issued pursuant to items 1-3 may lay down that the said regulations shall apply wholly or partly and on further conditions instead of permits granted pursuant to section 11. If it is necessary to apply for a permit pursuant to the regulations, the provisions of Chapter 3 apply. The conditions that may be laid down in individual permits, cf. section 16, may instead be laid down in regulations pursuant to this section.*

*The pollution control authority may in individual cases grant exemptions from regulations that permit pollution if the conditions mentioned in section 18, first paragraph, are fulfilled or if the regulations provide the authority for this.*

*The scope of regulations issued pursuant to this section may be restricted to specific geographical areas."*

## 8.5. Appendix 5: Waste Regulations

### CHAPTER 9
### LANDFILLING OF WASTE

#### § 9-6 Waste to be accepted in the different classes of landfill

*"All waste shall be treated before it is landfilled, cf. section 9-3 letter i, unless treatment cannot promote economically viable recovery measures and reduce the health and environmental risks related to the waste.*

*Only hazardous waste and waste that fulfils the criteria laid down by the competent authority for the landfilling of hazardous waste is permitted to be landfilled at landfills for hazardous waste.*

*Landfills for non-hazardous waste may be used for*

*a) non-hazardous waste that fulfils the criteria of the competent authority for the acceptance of waste at landfills for non-hazardous waste,*
*b) stable, none-reactive hazardous waste with leaching behavior equivalent to that of the non-hazardous types of waste specified under letter a. This hazardous waste shall not be landfilled together with biodegradable waste.*

*Inert waste landfills shall be used only for inert waste and slightly contaminated masses, cf. section 2.1 of appendix II."*

### APPENDIX II
### WASTE CHARACTERISATION AND ACCEPTANCE CRITERIA

#### 3. Sampling and test methods for waste

*"Sampling and testing of waste shall be carried out by independent and qualified persons at institutions with the necessary competence. The laboratories shall have a documented efficient quality assurance system through accreditation or similar.*

*Alternatively, sampling may be carried out by producer of waste or the operators, provided that the sampling routines are quality assured by independent and competent institutions.*

*The testing of waste may also be carried out by the producer of waste or the operators if they have implemented an adequate quality assurance system including periodic independent checking, e.g. through accreditation or a system of similar quality.*

*CEN standards shall apply to sampling and testing. If a CEN standard is not available in the form of a formal European Standard (EN), a Norwegian standard or the draft CEN standard may be used when it has reached the prEN stage. If such standards are not available, adapted methods relevant to the problem at hand may be developed. Such methods must be scientifically documented, and shall as far as possible be based on applicable standards.*

*Sampling shall be based on a sampling strategy which takes the composition and characteristics of the waste into account, based on applicable standards for sampling of waste. The sampling strategy shall ensure that representative samples are taken, and that the extent of characterization and testing is sufficient for the waste in question."*

## CHAPTER 11
## HAZARDOUS WASTE

### § 11-5
### Responsible storage, etc., of hazardous waste

*"Hazardous waste shall be managed responsibly. All entities that store, transport or handle hazardous waste shall take the necessary measures to prevent risks of pollution or damage to people or animals.*

*Hazardous waste shall not be mixed together with other waste. Different types of hazardous waste shall not be mixed together if this may entail a risk of pollution or create problems for the further management of the waste."*

### § 11-6
### Permit for handling of hazardous waste

*"Any entity that handles hazardous waste must hold a permit issued by the Climate and Pollution Agency, the county governor or the agency authorized by the Ministry of the Environment."*

### § 11-7
### Exceptions from the requirement for a permit

*"The requirement to hold a permit under section 11-6 does not apply to*
*a) enterprises that hold a permit pursuant to section 11 of the Pollution Control Act for the management of hazardous waste from their own activities,*
*b) recovery of an enterprise's own hazardous waste that take place within the scope of the business unit if the recovery process does not involve a risk of pollution, cf. section 7 of the Pollution Control Act,*

*c) service offered by the individual retailer to the consumer to take back hazardous waste from corresponding products that the retailer sells,*
*d) acceptance of hazardous waste from ships that is established pursuant to chapter 20 on the delivery and acceptance of waste and cargo remnants from ships of Regulations no. 931 of 1 June 2004 relating to the restrictions of pollution,*
*e) municipal arrangements for the acceptance of hazardous waste, cf. the duty in section 11-10, that are operated by the individual municipality or through inter-municipal co-operation. Acceptance schemes are covered by this exemption are permitted to accept up to 1,000 kg of hazardous waste per year per waste holder and shall be operated in accordance with the requirements contained in appendix 2 to this chapter,*
*f) manufacturers and importers who receive or collect batteries under the terms of sections 3-3, 3-5 and 3-6 of chapter 3."*

### § 11-8
### Delivery duty

*"An enterprise where hazardous waste is generated shall deliver this waste to an entity that can handle it under the terms of sections 11-6 and 11-7. The hazardous waste shall be delivered at least once a year. The delivery duty does not arise until the total quantity of hazardous waste exceeds 1 kg.*

*When an activity is shut down or operations are suspended for more than three months, the delivery duty becomes effective immediately.*

*The delivery duty does not apply to enterprises that, with a permit under the terms of section 11 of the Pollution Control Act, treat or dispose of their own hazardous waste. The exemption from the delivery duty only applies to the waste that the permit under section 11 of the Pollution Control Act applies to."*

### § 11-12
### Duty of enterprises to file a declaration on the content of waste

*"An enterprise that delivers hazardous waste shall provide sufficient information on the origin, content and properties of the waste, such that the waste can be further handled in a responsible manner. When the waste is delivered, the enterprise shall complete a declaration form approved by the Climate and Pollution Agency. The packaging shall be labeled clearly with the serial number of the declaration form. The labeling must be able to tolerate physical and climatic influences. "*

### § 11-13
### Duties of the entity that handles hazardous waste

*“An entity that handles hazardous waste has the responsibility to ensure that the waste that is accepted from enterprises is declared and shall ensure that the declaration from accompanies all delivers when the waste is passed on.*

*The entity that firsts accepts hazardous waste that is subject to a declaration duty shall at the latest by the 15th of the following month transfer a copy of the completed declaration form to the Climate and Pollution Agency or the agency indicated by the Climate and Pollution Agency.*

*Climate and Pollution Agency or the agency authorized by the Ministry of the Environment may set fees for the declaration of hazardous waste. Payment of the fee shall be collected from the entity that first accepts the hazardous waste subject to a declaration duty and shall cover the costs associated with the operation of a declaration system that shall provide the necessary oversight and control of hazardous waste.”*

## 8.6. Appendix 6: Overview of packaging material

The following scheme was forwarded by Eurofins to indicate the volume needed for the different test planned on the samples taken from the treatment process of drill cuttings and slop. Table 8-5 indicated the packaging material needed for sampling of slop/drill cuttings.

**Table 8-5: Packaging material for leaching test and TOC**

| Analysis | Packaging material |
|---|---|
| Leaching test and analysis (minimum 200 g)<br>Column test (minimum 5 kg)<br>pH (10 g)<br>Ignition loss (50 g)<br>TOC (100 g)<br>Organic parameters (250 g)<br>Metals (10 g)<br>Sulphate ( 25 g)<br>Nitrate (25 g)<br>Chloride (25 g)<br>Fluoride (25 g)<br>Dry matter, ignition loss (50 g) | Bucket with lid, available sizes 5 l and 10 l |

Table 8-6 indicates the packaging material needed for the water samples. Packaging material needed for the oil samples were 1 L plastic bottle.

**Table 8-6 Packaging material for water**

| Analysis | Packaging material |
|---|---|
| Oil in water (C10-C40) | 1 l glass bottle |
| PAH, BTEX | 1 l glass bottle |
| Metals (except mercury) (50 ml) | Plastic bottle |
| Mercury (Hg) | 50 ml glass with added preserving agent |
| Chloride<br>Nitrate<br>Nitrate + Nitrite<br>Nitrite<br>Sulphate<br>TOC | 0-5 – 1 l plastic bottle |
| SS | 1 l plastic bottle |

# 8.7. Appendix 7: Uncertainty of Measurements

The following chapter presents the different uncertainty of measurement (MU) affiliated with the results given by Eurofins. These MUs have been used in order to calculate uncertainty intervals for the different results, which is presented in the Tables in Chapter 4.

## 8.7.1. PAH

Table 8-7 illustrates the different MU affiliated with PAH values found in untreated drill cuttings, treated drill cuttings and in the retrieved water phase (from TWMA).

**Table 8-7: MU associated with different PAH values detected in drill cuttings and retrieved water phase (TWMA)**

| PAH 16 EPA | * Sample 1: Drill cuttings before treatment | Sample 2: Drill cuttings after treatment | Sample 3: Drill cuttings after treatment | | Sample 4: Retrieved water phase | |
|---|---|---|---|---|---|---|
| | [mg/kg TS] | [mg/kg TS] | [mg/kg TS] | **MU | [µg/l] | MU |
| Napthalene | 0.94 | 0.033 | 0.031 | 25 % | 76 | 30 % |
| Acenaphthylene | <0.1 | <0.01 | 0.010 | 41 % | 0.53 | 30 % |
| Acenaphthene | <0.1 | 0.024 | 0.028 | 25 % | 8.8 | 30 % |
| Fluorene | <0.1 | 0.060 | 0.058 | 25 % | 1.5 | 30 % |
| Phenanthrene | 0.82 | 0.26 | 0.25 | 25 % | 0.48 | 30 % |
| Anthracene | <0.1 | 0.018 | 0.016 | 25 % | 0.055 | 30 % |
| Fluoranthene | 0.28 | 0.073 | 0.074 | 25 % | 0.015 | 40 % |
| Pyrene | 0.51 | 0.40 | 0.37 | 25 % | 0.015 | 40 % |
| Benzo(a)anthracene | <0.1 | 0.026 | 0.042 | 25 % | <0.01 | 40 % |
| Chrysene/Triphenylene | 0.13 | 0.032 | 0.045 | 35 % | <0.01 | 40 % |
| Benzo(b)Fluoranthene | <0.1 | <0.01 | <0.01 | 25 % | <0.01 | 40 % |
| Benzo(k)Fluoranthene | <0.1 | <0.01 | <0.01 | 25 % | <0.01 | 40 % |
| Benzo(a) pyrene | <0.1 | <0.01 | <0.01 | 25 % | <0.01 | 40 % |
| Indeno(1,2,3-cd)pyrene | <0.1 | <0.01 | <0.01 | 30 % | <0.002 | 40 % |
| Dibenz(a,h)anthracene | <0.1 | <0.01 | <0.01 | 40 % | <0.01 | 40 % |
| Benzo(g,h,i)perylene | <0.1 | <0.01 | 0.010 | 40 % | <0.002 | 40 % |
| **Sum PAH(16) EPA** | **2.7** | **0.93** | **0.93** | **-** | **87** | **-** |

***Remarks sample 1: Elevated LOQ due to dilution.**

**** Shows the Uncertainty of Measurements for sample 1, 2 and 3.**

Table 8-8 illustrates the different MU affiliated with PAH values found in untreated slop, treated slop and in the retrieved water phase (from Halliburton Mongstad).

**Table 8-8: MU associated with PAH values detected in slop and retrieved water phase (H.M.)**

| PAH 16 EPA | * Sample 6: Slop before treatment | Sample 7: Slop after treatment | Sample 8: Slop after treatment | | Sample 9: Retrieved water phase | |
|---|---|---|---|---|---|---|
| | [mg/kg TS] | [mg/kg TS] | [mg/kg TS] | **MU | [µg/l] | MU |
| Napthalene | 10 | 0.023 | 0.026 | 25 % | 250 | 30 % |
| Acenaphthylene | <0.1 | <0.01 | <0.01 | 41 % | 6.1 | 30 % |
| Acenaphthene | 1.6 | <0.01 | <0.01 | 25 % | 110 | 30 % |
| Fluorene | 3.2 | 0.035 | 0.037 | 25 % | 20 | 30 % |
| Phenanthrene | 5.5 | 0.15 | 0.15 | 25 % | 17 | 30 % |
| Anthracene | 0.48 | 0.010 | 0.013 | 25 % | 1.8 | 30% |
| Fluoranthene | 0.28 | 0.031 | 0.025 | 25 % | 0.53 | 30% |
| Pyrene | 1.3 | 0.24 | 0.24 | 25 % | 2.6 | 30 % |
| Benzo(a)anthracene | 0.12 | 0.14 | 0.13 | 25 % | 0.58 | 30 % |
| Chrysene/Triphenylene | 0.45 | 0.12 | 0.11 | 35 % | 0.32 | 30% |
| Benzo(b)Fluoranthene | <0.1 | 0.14 | 0.13 | 25 % | 0.030 | 40 % |
| Benzo(k)Fluoranthene | <0.1 | 0.030 | 0.019 | 25 % | 0.022 | 40 % |
| Benzo(a) pyrene | <0.1 | 0.071 | 0.077 | 25 % | <0.01 | 40 % |
| Indeno(1,2,3-cd)pyrene | <0.1 | 0.026 | 0.028 | 30 % | 0.0036 | 40 % |
| Dibenz(a,h)anthracene | <0.1 | 0.021 | 0.023 | 40 % | <0.01 | 40 % |
| Benzo(g,h,i)perylene | <0.1 | 0.12 | 0.12 | 40 % | 0.0057 | 40 % |
| **Sum PAH(16) EPA** | **23** | **1.2** | **1.1** | **-** | **410** | **-** |

***Remarks sample 6: Elevated LOQ due to dilution.**

**** Shows the Uncertainty of Measurements for sample 1, 2 and 3.**

## 8.7.2. BTEX

Table 8-9 presents the MU associated with BTEX values detected in untreated and treated drill cuttings, as well as the retrieved water phase.

**Table 8-9: MU associated with BTEX values detected in drill cuttings and retrieved water phase (TWMA)**

| BTEX | * Sample 1: Drill cuttings before treatment | | Sample 2: Drill cuttings after treatment | | Sample 3: Drill cuttings after treatment | | Sample 4: Retrieved water phase | |
|---|---|---|---|---|---|---|---|---|
| | [mg/kg TS] | MU | [mg/kg TS] | MU | [mg/kg TS] | MU | [µg/l] | MU |
| Benzene | <0.1 | 30 % | <0.01 | 40 % | <0.01 | 40 % | 160 | 30 % |
| Toluene | 0.31 | 20 % | 0.048 | 20 % | 0.048 | 20 % | 550 | 30 % |
| Ethylbenzene | 0.17 | 20 % | <0.01 | 40 % | <0.01 | 40 % | 26 | 30 % |
| m,p–Xylene | 0.76 | 20 % | 0.024 | 40 % | 0.024 | 40 % | 89 | 35 % |
| o-Xylene | 0.38 | 20 % | 0.014 | 40 % | 0.013 | 40 % | 59 | 30 % |

***Remarks sample 1: Elevated LOQ due to dilution.**

Table 8-10 presents the MU associated with BTEX values detected in untreated and treated slop, as well as the retrieved water after treatment.

**Table 8-10: MU associated with BTEX values detected in slop and retrieved water phase (H.M.)**

| BTEX | Sample 6: Slop before treatment | | Sample 7: Slop after treatment | | Sample 8: Slop after treatment | | Sample 9: Retrieved water phase | |
|---|---|---|---|---|---|---|---|---|
| | [mg/kg TS] | MU | [mg/kg TS] | MU | [mg/kg TS] | MU | [µg/l] | MU |
| Benzene | 0.60 | 30 % | <0.01 | 40 % | <0.01 | 40 % | 280 | 30 % |
| Toluene | 6.5 | 20 % | 0.65 | 20 % | 0.63 | 20 % | 5 600 | 30 % |
| Ethylbenzene | 2.4 | 20 % | 0.017 | 40 % | 0.016 | 40 % | 170 | 30 % |
| m,p–Xylene | 11 | 20 % | 0.079 | 20 % | 0.045 | 40 % | 820 | 35 % |
| o-Xylene | 5.1 | 20 % | <0.01 | 40 % | <0.01 | 40 % | 310 | 30 % |

## 8.8. Appendix 8: Conversions

The following formula was used to convert concentrations in retrieved water phase from µg/l to mg/kg.

mg/kg = $10^{-3}$ * µg/l * ρ

Example: From Table 4-5
Density of napthalene used was 1.14 g/cm$^3$

76 µg/l = 76/(1000*1*1.14)mg/kg = 0.067 mg/kg

The same approach was used for all similar calculations. The following densities were used in the calculations for the different parameters in retrieved water phase sample 4 and 9, shown in Table 8-11 and 8-12, respectively:

**Table 8-11: Conversion of denomination in retrieved water phase from treated drill cuttings, sample 4.**

| Parameter | Density used [g/cm$^3$] | Concentration [µg/l] | Concentration [mg/kg] |
|---|---|---|---|
| Napthalene | 1.14 | 76 | 0.067 |
| Acenaphthylene | 0.899 | 0.53 | 0.00059 |
| Acenaphthene | 1.043 | 8.8 | 0.0084 |
| Fluorene | 1.12 | 1.5 | 0.0013 |
| Phenanthrene | 1.18 | 0.48 | 0.00041 |
| Anthracene | 1.25 | 0.055 | $4.4*10^{-5}$ |
| Fluoranthene | 1.128 | 0.015 | $1.3*10^{-5}$ |
| Pyrene | 1.27 | 0.015 | $1.2*10^{-5}$ |
| Benzo(a)anthracene | 1.245 | <0.01 | $8*10^{-6}$ |
| Chrysene/Triphenylene | *1.288 | <0.01 | $8*10^{-6}$ |
| Benzo(b)fluoranthene | 1.287 | <0.01 | $8*10^{-6}$ |
| Benzo(k)fluoranthene | 1.286 | <0.01 | $8*10^{-6}$ |
| Benzo(a) pyrene | 1.351 | <0.01 | $7*10^{-6}$ |
| Indeno(1,2,3-cd)pyrene | 1.378 | <0.002 | $7*10^{-6}$ |
| Dibenz(a,h)anthracene | 1.232 | <0.01 | $8*10^{-6}$ |
| Benzo(g,h,i)perylene | 1.378 | <0.002 | $7*10^{-6}$ |

| | | | |
|---|---|---|---|
| Benzene | 0.874 | 160 | 0.183 |
| Toluene | 0.865 | 550 | 0.636 |
| Ethylbenzene | 0.867 | 26 | 0.030 |
| m,p-Xylene | 0.860 | 89 | 0.10 |
| o-Xylene | 0.870 | 59 | 0.068 |

*** Amount chrysene and triphenylene detected in the different samples was reported together in one value, thus the average of the two densities of 1.274 and 1.302 g/cm$^3$ was used instead. This also applies for Table 8-12.**

****Unable to determine the density for nitrite and nitrate, thus these values are given in µg/l in the tables in chapter 4. This also applies for Table 8-12.**

**Table 8-12: Conversion of denomination in retrieved water phase from treated slop, sample 9.**

| Parameter | Density used [g/cm$^3$] | Concentration [µg/l] | Concentration [mg/kg] |
|---|---|---|---|
| Napthalene | 1.14 | 250 | 0.219 |
| Acenaphthylene | 0.899 | 6.1 | 0.0068 |
| Acenaphthene | 1.043 | 110 | 0.105 |
| Fluorene | 1.12 | 20 | 0.018 |
| Phenanthrene | 1.18 | 17 | 0.014 |
| Anthracene | 1.25 | 1.8 | 0.0014 |
| Fluoranthene | 1.128 | 0.53 | 0.00047 |
| Pyrene | 1.27 | 2.6 | 0.0020 |
| Benzo(a)anthracene | 1.245 | 0.58 | 0.00046 |
| Chrysene/Triphenylene | 1.288 | 0.32 | 0.00025 |
| Benzo(b)fluoranthene | 1.287 | 0.030 | $2.3*10^{-5}$ |
| Benzo(k)fluoranthene | 1.286 | 0.022 | $1.7*10^{-5}$ |
| Benzo(a) pyrene | 1.351 | <0.01 | $7*10^{-6}$ |
| Indeno(1,2,3-cd)pyrene | 1.378 | 0.0036 | $2.6*10^{-6}$ |
| Dibenz(a,h)anthracene | 1.232 | <0.01 | $8*10^{-6}$ |
| Benzo(g,h,i)perylene | 1.378 | 0.0057 | $4.1*10^{-6}$ |
| Benzene | 0.874 | 280 | 0.320 |
| Toluene | 0.865 | 5 600 | 6.474 |
| Ethylbenzene | 0.867 | 170 | 0.196 |
| m,p-Xylene | 0.860 | 820 | 0.953 |
| o-Xylene | 0.870 | 310 | 0.356 |