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Abstract

Thermomechanical Cuttings Cleaner – Qualification for Offshore Treatment of Oil Contaminated Cuttings on the Norwegian Continental Shelf and Martin Linge Case Study

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The aim of this thesis is to introduce and qualify the Thermomechanical Cuttings Cleaner (TCC) technology for treatment of oil contaminated cuttings on the Norwegian Continental Shelf (NCS) with particular reference to the Martin Linge field development.

In the first part, a summary of drilling waste, related regulation and waste management techniques is given to present the possible treatment and disposal options of oil contaminated cuttings.

The thesis then informs about the TCC technology in detail. In the next section the TCC's treatment capacity and efficiency is verified by means of field data analysis. Both environmental considerations and TCC field experience are taken into account to qualify the TCC technology for use. In the last section the TCC cuttings treatment is compared to cuttings re-injection and skip & ship solution with the aim to find and implement the best cuttings treatment solution at the Martin Linge field.

In Conclusion, the thesis argues that the TCC technology qualifies for use on NCS and outlines it to be the best cuttings handling solution for the Martin Linge field development with regards to HSE-, cost and operation reliability considerations. The author recommends the implementation of the TCC technology as presented in the thesis.

Table of Contents

List of Tables

List of Figures

Nomenclature

- BAT - Best Available Technique
- BEP - Best Environmental Practices
- BTEX - Benzene, Toluene, Ethylbenzene and Xylenes
- CRI - Cuttings Re-Injection
- CST - Cutting Storage Tank
- DCR - Dispersion by Chemical Reaction
- DECC - Department of Energy & Climate Change
- DNV- Det Norske Veritas
- GC/MS - Gas Chromatography / Mass Spectrometry
- HC – Hydrocarbones
- HPHT- High Pressure High Temperature
- HPWBM - High Performance Water Based Mud
- HSE - Health, Safety and Environment
- NCS - Norwegian Continental Shelf
- NOROG - Norwegian Oil and Gas Association
- NPD - Norwegian Petroleum Directorate
- OBM - Oil Based Mud
- OPF - Organic-phase drilling fluid
- OSPAR Commision - Oslo and Paris Commision
- PAH - Polycyclic Aromatic Hydrocarbon
- PLC - Programmable Logic Controller
- PWRI - Produced Water Re-Injection
- ROP - Rate of Penetration

- TCC - Thermomechanical Cuttings Cleaner
- TDU - Thermal Desorption Unit
- UKCS - United Kingdom Continental Shelf
- WBM - Water Based Mud

Chapter 1: Introduction

The aim of this thesis is to introduce and qualify the Thermomechanical Cuttings Cleaner (TCC) technology for treatment of oil contaminated cuttings on the Norwegian Continental Shelf (NCS) with particular reference to the Martin Linge field development.

1.1 Background of the Thesis and Problem Formulation

Oil and gas wells are drilled with rotating drill bits (Skaugen, 1997). The drill bit is situated at the bottom of the drill stem which consists of several hollow pipes. The main functions of the drill stem are a) to provide weight to press the bit against the formation and b) to enable mud circulation. If weight and rotation is applied on the drill bit it crushes or cuts the formation. The crushed formation is called drill cuttings and needs to be transported to surface to enable further drilling progress. For this and other purposes as for example bit cleaning, bit cooling and cuttings suspension during pump stops, drilling mud is circulated down the drill stem. It enters the well through bit nozzles and transports the cuttings up the annulus, the space around the drill stem. At surface the drill cuttings are as far as possible separated from the drilling mud by means of shakers, hydrocyclones and/or centrifuges. Some mud will always adhere to the drill cuttings which are not used in the further drilling process and considered as drilling waste.

Until 1992, all cuttings were directly discharged to sea (Kaland, 2011). Cuttings contamination due to the use of oil based mud and the following discharge to sea resulted in environmental harm and large cutting piles around the platforms of the Norwegian Continental Shelf. Increasing environmental concerns led to the prohibition of this practice through implementation of new regulatory requirements for the discharge of cuttings. The regulation states that cuttings should not be discharged when the content of reservoir oil or base oil from the drilling fluid is higher than 10gr per kg of dry mass (Aktivitetsforskriften, 2013). Therefore the cuttings are either slurrified and re-injected into a suitable formation for storage or shipped to land for treatment and final disposal at approved sites (Kaland, 2011). Even though these cutting handling solutions are field proven, the oil and gas industry is meeting challenges.

During the last years, cuttings re-injection was decreased or has stopped completely at several fields due to slurry leakages to surface which lead to environmental harm (NPD, 2011). The cost and emissions due to the drilling of dedicated cuttings re-injection wells are high and the waste volume to be disposed is increased due to slurrification of cuttings. The alternative shipment of cuttings is logistical demanding and can stop the drilling operation when weather conditions prevent the cuttings to be loaded onto supply vessels (Svensen, 2011). Furthermore, several crane lifts are necessary to transport the cuttings. Each lift implies the risk of falling objects and should be avoided.

Thus, operators have been seeking for alternative cutting handling options for oil contaminated cuttings and identified the Thermomechanical Cuttings Cleaner (TCC) as the most promising one. The TCC is a thermal desorption unit which separates the incoming waste into water, oil and solids (Thermtech,2014). The solid part of the cuttings is transformed into a dry powder which fulfils the requirements for offshore cuttings discharge while the in the process recovered oil can be re-used as base oil for new drilling mud. The TCC technology was authorized and taken in use both on-, and off-shore by the United Kingdom where it is considered as field proven technology (OIC, 2007). To date the TCC is solely used for onshore treatment of oil contaminated cuttings in Norway, but Total E&P is willing to implement the TCC technology offshore at the Martin Linge field. Various papers have been written on this subject. Kleppe described the TCC's treatment principle, separation process, energy demand and recovered oil quality

(Kleppe, 2009), while Kirkness et al. presented the drivers for offshore cuttings treatment and revealed the development process of the TCC for offshore use (Kirkness, 2008). However, detailed information about the TCC's efficiency, real treatment capacity and environmental considerations is missing in these papers and requires further investigation. Therefore, this thesis addresses and answers following issues:

- Is the TCC cuttings treatment in compliance with the regulations at the NCS?
- Does the theoretical treatment capacity of TCC match the observed values?
- Is the environmental impact due to TCC cuttings treatment acceptable?

Issues to be answered with regards to Total E&P's Martin Linge field development:

- Is offshore TCC cuttings treatment the best option for the Martin Linge field?
- Can the TCC technology be implemented on the Mærsk Intrepid jack-up?

1.2 Objective of the Thesis

The aim of this thesis is to introduce and qualify the Thermomechanical Cuttings Cleaner technology for offshore treatment of oil contaminated cuttings on the Norwegian Continental Shelf with particular reference to the Martin Linge field development.

This will be achieved through:

(1) reviewing information about drilling waste,

(2) obtaining overview over regulations for offshore discharge of cuttings & mud,

(3) procuring an overview of the TCC technology,

(4) verifying the TCC technology through field data analysis,

(5) presenting environmental studies,

(6) screening field experience reports,

(7) evaluating the different cuttings treatment solutions for the Martin Linge field and planning the implementation of the TCC system on the Mærsk Intrepid rig.

Chapter 2: Drilling Waste

In this chapter the types of drilling waste and its quantity are presented to show the need for adequate waste handling solutions.

2.1 Types of Drilling Waste

"Drilling waste" is defined as the by-product of drilling activities which can be harmful for the environment (Svensen, 2011) and comprises Drilling Cuttings, Used Drilling Fluid, Slop and Oil Contaminated Mass (DNV, 2013).

Drilling Cuttings are drilled out formation material which is contaminated by adherent drilling fluid.

Drilling Fluid or drilling mud is defined as any fluid or mixture of fluids and solids that is used to drill wellbores into the earth (Schlumberger, 2014). Its composition may change during the drilling operation due to for example the accumulation of solids, salt contamination, and influx of acid gases (Baker Hughes, 2010). The adverse effects caused by fluid contamination might lead to the point where the drilling fluid cannot perform its task and will be characterized as drilling waste.

Slop denotes oil and water emulsions. Examples are drilling-, or displacement-fluids, water from the cleaning process of equipment/tanks and drilling fluid contaminated rain water entering the drain system on the rig floor or mud pit area. (Massam et.al, 2013).

Oil contaminated mass from drilling activities is mainly produced through slot recovery performed in platform drilling and plug and abandonment operations. These operations generate swarf, which describes milled steel chips. Other waste reported as oil contaminated mass comes mainly from production and maintenance activities and comprises oil filters, cleaning fabrics, used gloves, tank deposits and further stable material (DNV, 2013). This type of waste has to be sent to land where it is treated and disposed in accordance to the Pollution Law.

2.2 Quantity of Oily Drilling Waste on NCS

The quantity of oily drilling waste depends strongly on the used drilling mud which will be chosen taking technical, environmental and economical parameters into consideration (Svensen, 2011).

2.2.1 Historical Development of Oily Drilling Waste

Even though the operators made an effort to reduce the amount of oily drilling waste by for example pledging the mud suppliers to purchase the drilling fluids after use, (Svensen, 2011) the amount of generated oily drilling waste (cuttings and mud) has been relatively stable as presented in Table 1 and Figure 1 (DNV, 2013). In the time period from 2006 to 2009 it averaged out at 223.050 tons per year whereof around 46% was injected and 54% taken to shore for treatment.

The turning point came in the year 2010 which introduced a rapid growth resulting in 284.179 tons of cuttings and mud from which only 8.8% were injected in the year 2011. In consequence 91.2% have been treated onshore. The growth in onshore treatment can be traced to problems with injection wells and the extended use of oil based mud (OBM) for drilling. Technical problems forced several operators to decrease the waste injection rate. Instead of injecting the waste, it was slurrified and sent to shore for treatment. To counteract this development, a couple of new injection wells have been drilled and the slurryfication has been decreased through alternative cutting handling solutions during the years 2012 and 2013.

In Table 1 an overview of the reported waste volumes is given:

	2006	2007	2008	2009	2010	2011
Drilling waste Onshore	100920	119396	129984	131348	231741	259010
Drilling waste Injected	112638	103622	100927	93368	54376	25169
Slop treated Onshore	7875	6783	8642	12695	19451	34338
Oil contaminated mass	1436	2399	2526	2479	2260	3266
Totalt	222869	232200	242079	239890	307828	321783

Table 1: Development in amount of drilling waste, slop and oil contaminated mass given in tons (DNV, 2013)

The following figure illustrates the increasing trend of the drilling waste generation:

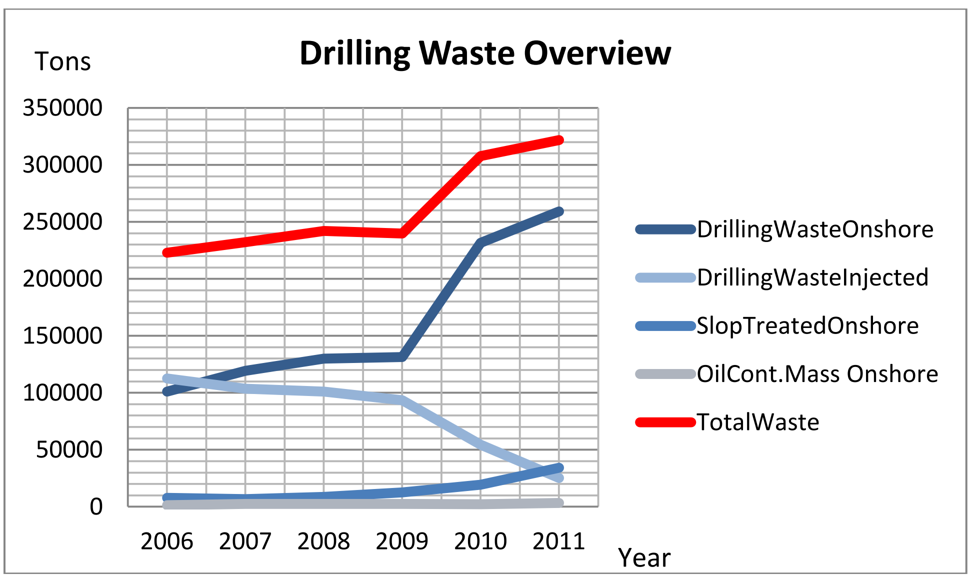

Figure 1: Amount of drilling waste, slop and oil contaminated mass (DNV, 2013)

Regarding slop that was treated onshore, the amount has increased by 436% in the years between 2006 and 2011. This increase needs to be interpreted with caution since slops often are mixed with and registered as drilling fluid waste due to tank capacity problems on the rig. The amount of oil contaminated mass is relative stable since it is mostly dependent on field production.

The increase of oil contaminated mass seen in 2011 is due to an increase of casing milling where the swarf, fine milled steel, is reported as oil contaminated mass.

2.2.2 Prognosis for Onshore Oily Waste Treatment and Disposal

The general trend is to drill longer and more demanding wells which necessitate a drilling fluid offering both optimum wellbore stability and drilling efficiency (Svensen, 2011). Since OBM delivers better results than water based mud (WBM) regarding technical parameters, the generation of oily drilling waste is likely to increase.

Det Norske Veritas (DNV) has performed a study in 2013 on behalf of the Norwegian Oil and Gas Association (NOROG) to predict the development of the generation of oily waste on the NCS in the coming years (DNV, 2013). Based on historical data and Norwegian Petroleum Directorate's (NPD) prognosis for future drilling activity, a prognosis regarding the oily waste generation has been elaborated which was focusing on the waste to be treated onshore to see if the treatment capacity was sufficient in the time period from 2012-2017.

Further, three cases were established:

- Maximum case with more waste than expected and little re-injection:
- Minimum case with less waste than expected, high re-injection and offshore treatment of cuttings from 2013 with TCC:

- Most reliable case based on average waste volume of the years 2009 and 2010, expected reinjection level and introduction of TCC offshore in 2013.

Note that the offshore cuttings treatment with the TCC has not started yet. Therefore the real amount of cuttings will most likely be between the most reliable case and the maximum case. To access if there is sufficient treatment capacity, it is advisable to assume a worst case scenario which is the maximum possible amount of oily waste to be treated in the time period considered. This would be ca. 145.000 ton drill cuttings and 260.000 ton mud/slop in the year 2017. These need to be treated and disposed according to the governing regulations presented in chapter 3.

Chapter 3: Regulations for Discharge of Mud & Cuttings and Chemical Use

The offshore environmental legislation in the western European states rest upon the Convention for the Protection of the Marine Environment of the North-East Atlantic (called OSPAR) (Wills, 2000). OSPAR is the platform where 15 European governments meet with the European Union to work for the protection of the marine environment of the North-East Atlantic (OSPAR1, 2014). OSPAR's Offshore Industry Committee (OIC) is responsible for the implementation of work with regards to the oil and gas industry (OSPAR2, 2014).

3.1 OSPAR

The most important principles of OSPAR are the precautionary-, and polluter pays-principle (OSPAR3, 2014). Moreover the best available techniques (BAT) and best environmental practices (BEP) need to be applied to eliminate or at least limit pollution

The precautionary principle implies that preventive measures need to be taken as soon as negative consequences for the environment are likely. Therefore a scientific proof is not necessary. The polluter pays principle states that the polluter needs to pay for pollution prevention, control and introduce reduction measures.

On this basis the OSPAR convention and commission have worked out the decisions and recommendations presented in Table 2 which Norway, the United Kingdom and the other contracting parties have to follow up (OSPAR, 2010).

Decision 2000/3 (OSPAR4, 2014) counteracts pollution through organic-phase drilling fluid (OPF). It requires the operator to obtain permission to use OPF while the use of diesel in drilling fluids in general and the discharge of OPF to sea are banned.

Discharges of chemicals and oil
Decision 2000/3: Restriction of use and discharges of organic-phase drilling fluids and contaminated cuttings Recommendation 2006/5: Management of offshore cuttings piles Recommendation 2001/1: Management of produced water and 15% reduction target for oil discharged with produced water
Use of chemicals offshore
Decision 2000/2: Harmonised Mandatory Control System to manage use and discharges of chemicals offshore Recommendation 2000/4: Harmonised chemical pre-screening scheme Recommendation 2000/5: Harmonised chemical notification Recommendation 2005/2: Phase out of OSPAR priority chemicals Recommendation 2006/3: Phase out of candidate substances for substitution
Decommissioning
Decision 98/3: Ban of disposal of disused offshore installations
Environmental management
Recommendation 2003/5: Promotion of use and implementation of environmental management systems

Table 2: OSPAR measures to manage pressures from offshore oil and gas industry (OSPAR, 2010)

Regarding offshore discharge of cuttings the maximum concentration of oil based fluid on dry cuttings is set to one percent by weight. The disposal of cuttings contaminated with synthetic fluids shall not be granted if it is not absolutely required with regards to BAT and BET.

Decision 2000/2 shall ensure that hazardous substances are substituted and reduce the impact of chemicals used offshore. This shall be achieved through the application of a designated management system which introduces permits for use and discharge of chemicals. The authorities shall encourage the operators to use non-hazardous substances, avoid discharges, develop better alternatives and reduce the use of chemicals in general.

Recommendation 2005/2 steers the phase out of chemicals which are standing on the OSPAR2004 list of chemicals for priority action. These are phased out due to their properties including toxicity, degradability and/or their potential for bio-accumulation. No permission for use of these chemicals should have been given since the 1. January 2010.

Recommendation 2006/3 sets the target for the phase-out of chemicals identified for substitution to 1. January 2017. Until then the industry shall have found substitutes.

The OIC has been discussing whereas the TCC technology presented in this thesis is to be considered as BAT for handling of oil contaminated cuttings offshore or not (OIC, 2007). While the UK wanted to characterize the TCC technology as BAT, Denmark required more information about the technology and to the author's knowledge no decision has been made yet.

3.2 Norwegian Continental Shelf

Norway's legislation is strongly influenced by OSPAR since Norway is a contracting party. The use and discharge of drilling fluids and cuttings is governed by the Norwegian Environment Agency through discharge permits, (Wills, 2000) which are given in accordance to the Pollution Law (Forurensingsloven, 2013).

The evaluation of discharge applications is based among others on the Activity Regulations which describe how activities in the Oil and Gas Industry shall be performed (Aktivitetsforskriften, 2013). Paragraphs concerned with discharges to the environment are found in chapter eleven and a short version of selected paragraphs is given below:

§60 – Discharge of oil containing water, states that the oil content in discharged water shall be as low as possible and not overcome 30mg oil per liter in monthly average. The treatment process shall give the best environmental effect regarding both cleanliness of water and chemical use in the process. A discharge Permit is necessary in compliance with the Pollution Law.

§62 - §65 deal with the testing, categorization, environmental considerations and final choice of chemicals. Chemicals which pose lowest possible environmental risk shall be chosen as long as it is possible with respect to safety and technical reasons.

§66 – Use and discharge of chemicals, require a permit in accordance to the Pollution law and shall be reduced as much as possible. The discharge of unused chemicals is prohibited. The chemicals used shall have least possible contaminants.

§68 – Discharge of cuttings, sand and solid particles, states that these should not be discharged when the content of reservoir oil, other oil or base oil of the drilling fluid is higher than 10gr per kg of dry mass.

Recommended guidelines for waste management in the offshore industry are provided by the Norwegian Oil and Gas Association (Norwegian Oil and Gas, 2013).

Since the TCC technology has not been used for treatment of oil contaminated cuttings on the NCS yet and experience with this offshore handling solution is missing, a dedicated paragraph for the offshore discharge of TCC treated cuttings is missing and §68 should apply.

3.3 United Kingdom Continental Shelf

The legislation of the United Kingdom is based on the decisions and regulations of the OSPAR commission since the UK is a contracting party (OSPAR1, 2014).

The UK key regulations that ensure compliance with OSPAR are the Offshore Chemical Regulations 2002 and the Offshore Petroleum Activities Regulations 2005 (Oil & Gas UK, 2013). The later regulations introduce a permit system for discharges, amongst others for drilling mud and cuttings which is called Oil Pollution, Prevention and Control (OPPC) (DECC, 2013). An overview of drilling discharges which require an OPPC Permit is given in Table 3. The application for Permits is to be send to the department of energy & climate change (DECC). It needs to contain a BAT/BEP assessment, information about expected environmental impact and quantities of oil, water and solids which are planned to be discharged.

Discharges	Comments
Hazardous drainage system	-
Non Hazardous drainage system	-
Drill cuttings and associated drilling fluids	Covers reservoir hydrocarbons. Drill mud regulated through Offshore Chemical Regulations only.
Drill cuttings and associated drilling fluids - injection	As above
Minor discharges	General permit is required

Table 3: Drilling discharges which require OPPC permit (Oil & Gas UK, 2010)

The Offshore Chemical Regulations 2002 deal with the use and discharge of chemicals including drilling fluids. To obtain a chemical discharge permit, a Petroleum Operation Notice 15 (PON15) which ensures that environmental considerations are taken and all other requirements are fulfilled, needs to be submitted to DECC (DECC, 2011).

The Environmental legislation shall involve the general public and representative organizations (Wills, 2000). Therefore a non-technical summary shall follow every technical report and a public notice needs to raise awareness of the planned activity. During a time period of four weeks, the public is invited to comment on the planned activities. All comments will be accounted for in the evaluation process.

It is important to note that cuttings contaminated with a low toxic oil and which have been treated so that the oil content is less than one percent per weight are falling under the Offshore Chemical Regulations 2002 and do not require an OPPC Permit. This is the case for TCC treated cuttings. The TCC technology is considered as BAT for oil contaminated cuttings treatment offshore (OIC, 2007) and is one of the waste management option which will be presented in chapter 4.

Chapter 4: Waste Management

Due to increasing focus of politics and society on the environmental impact of the oil and gas industry, Waste Management is necessary for gaining future access to markets where changes in the regulations described in chapter 3 are expected to sharpen the access requirements (Brantley, 2013). The best way to avoid waste is to reduce its production at source or reuse it (EPA, 2013). This approach both reduces pollution and saves money. If this is not a valid option it should be recycled, e.g. the waste should be decomposed into its primary components which can be remanufactured into new products. Non-recyclable waste can be converted into usable heat, fuel or electricity. First when these possibilities are exhausted a treatment and disposal of the waste shall take place.

Report 093 *Recommended guidelines for waste management in the offshore industry*, provided by the Norwegian Oil and Gas Association, is a general guide that interprets the Norwegian legislation and offers information about waste prevention and effective waste management as seen in Figure 2 (Norwegian Oil and Gas, 2013).

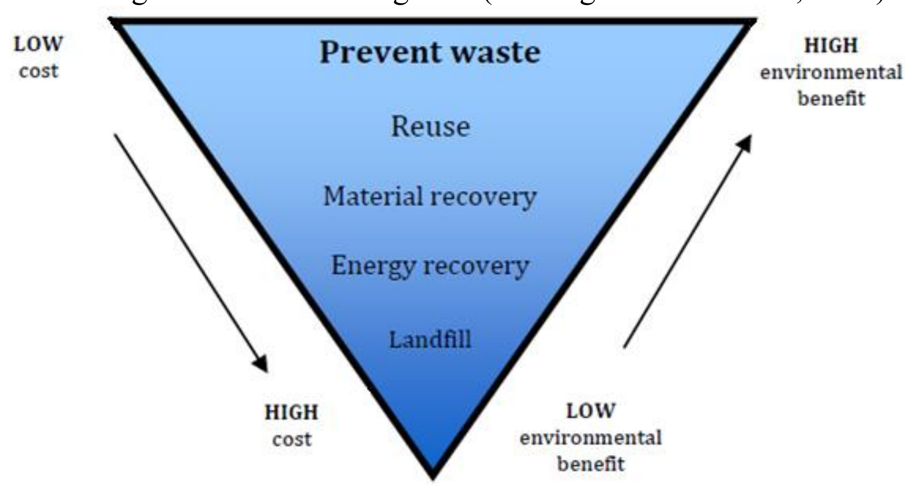

Figure 2: Waste Management Hierarchy (Norwegian Oil and Gas, 2013)

Waste Prevention should start in the design phase of operations. A general awareness for how waste is created, implementation of BAT/BEP and waste reducing processes are necessary to avoid waste generation. The two major options for waste management in the drilling process are (1) used Drilling Techniques and (2) treatment and disposal techniques for drill cuttings and drill mud.

4.1 Drilling Techniques to Prevent Waste

Regarding drilling waste, the biggest contributors are drilling cuttings and mud/slops. Reduction strategies include the use of chemicals with least possible environmental impact, application of “slimhole” design and avoidance of slurrification.

Since a part of Drilling mud will always adhere to drilling cuttings, the used chemicals have an impact on the handling and treatment of the drill cuttings (Speirs, 2009). In order to reduce the environmental impact of drilling waste it is therefore a good strategy to use chemicals with the lowest possible toxicity, high biodegradability and which do not tend to bioaccumulate. In general, WBM is less polluting and generates less drilling waste than OBM (Attia, 2010). Regarding the recent development of high performance water based mud (HPWBM) which approaches the expected drilling performance of OBM, the replacement should be considered for all sections OBM was the preferred solution in the past

Slim hole design describes the drilling of wells with smaller diameter in comparison to conventional wells (NPD, 2011). Downsizing of the well diameter has a high potential for reducing cuttings volume, chemical-, and cement- usage. Since the reduced diameter leads to a higher pressure drop in the well, this technique is rather used for exploration wells than production wells. The development and use of expandable casings might enable an increased use of slim hole drilling in the future.

Monobore well design is a slim hole design which keeps the well diameter constant during the whole drilling process. The casing used has a smaller diameter and is of a special steel quality that allows it to be expanded as soon as it is in place. This method reduces the drilling waste by up to 50% and is especially useful when there is a need for many casing strings to reach the reservoir.

Another strategy to reduce drilling waste lies in the reduction of the number of well sections. A Large well diameter section will be replaced with a longer small diameter well section, e.g. replacement of 26” section with a longer 17 ½” section. This might reduce the generated drilling waste by up to 50% in this section and will save steel used for the casing. The application of this waste reduction strategy is depending on formation properties and the mud-weight window.

Multilateral well design comprises several lateral wells which are starting from one main wellbore close above the reservoir instead of the surface. This results in less number of wells, cuttings, chemical-, and cement-usage but requires more complex completion solutions if the production of different zones shall be steered.

Slurrification of cuttings should be avoided since the volume of waste becomes five to six times as large due to the addition of water (Svensen, 2011).

Re-use of drilling mud can be encouraged by obligating the fluid supplier to take the drilling fluids back after the operation. Therefore the maximization of profit comes along with a drilling fluid that is designed for re-use and that implies waste reduction.
Another possibility to increase the re-use of drilling mud is the use of MudCubes instead of the conventional shale shakers (NPD, 2011). MudCubes recover the drilling mud with help of a vacuum that sucks the drilling fluid through a finely woven steel mesh while the cuttings and particles will stay on top of it and will be transported further. This technique

has operational benefits since it is vibration free resulting in less noise and the MudCubes are closed avoiding health damaging vapors in the working area.

Slops should be collected in dedicated storage tanks. The mixing of old drilling mud and slops should be avoided to enable the recovery of the most valuable content of the mixture, the base oil (DNV, 2013).

4.2 Treatment and Disposal Techniques for Drilling Waste

Primary solid control has the aim to maximize the recovery of Drilling Fluid while removing the drilled solids efficiently (MI Swaco, 2010). Thereby it reduces the overall cost of the well. In a first step, shale shakers are used to separate as much of the drill cuttings as possible from the drilling fluid. Fines that are not discarded by the shale shaker can be eliminated by hydro cyclones and centrifuges. There are several different techniques available to separate organic components from drill cuttings. These techniques need to be tailored and combined to achieve the best possible result. This is necessary in order to meet the tightening environmental rules which are the driving force behind the recent developments of treatment and disposal techniques (Pierce, 2006). Other factors that govern the choice of cuttings treatment are the operators' environmental standards, cost, safety and logistics (Kirkness, 2008). Oil companies became in recent years more concerned about the environmental impact of their activities and started to establish own environmental standards which regulate among others the disposal of OBM contaminated solids. The high cost of OBM makes it generally economical to take measures to recover the oil from the cuttings. If the drilling waste is treated with a thermal desorption unit the oil and water can be recovered and under circumstances be used in new drilling mud (Stephenson, 2004). Safety regarding the treatment and disposal technique is increased when the transfer of large quantities of drill cuttings can be avoided, especially when cranes are involved in the operation (Kirkness, 2008). The same transfer of cuttings to land processing facilities implies logistical problems when it comes to weather limitations. These can in turn stop the drilling operation. As stated in section 3.4, the recovery of drilling mud or at least its energy is to be preferred in comparison to disposal.

An overview of the available treatment and disposal techniques including possible offshore usage, cleaning/disposal mechanism and usable end product is given in Table 4.

Method	Offshore usage	Cleaning/Disposal Mechanism	Usable End Product
Incineration	No	Oxidation or combustion of organic components	-
Indirect Thermal Desorption	No	Evaporation and Condensation of oil and water	Oil as fuel
Thermomechanical Cuttings Cleaner	Yes	Evaporation and Condensation of oil and water	Oil as new base oil/ oil as fuel
Bioremediation/ Landfarming	No	Biodegradation	-
Dispersion by chemical reaction	No	Solidification, oil/metals stabilized in cuttings matrix	Construction material
Cuttings Dryer	Yes	Centrifuge forces mud/solids separation	-
Cutting Re-Injection	Yes	Injection of slurrified cuttings into formation	-
Microwave Treatment	Yes	Magnetic field transfers energy to water.	Oil as new base oil
Liquefied Gas Extraction	No	Liquefied HC gases solve and remove oil	Oil as new base oil

Table 4: Overview of Cuttings Treatment and Disposal Techniques

4.2.1 Land

Treatment at land might make use of high temperature, natural occurring bacteria & fungi or chemicals to recover, disintegrate or capture organic matter.

4.2.1.1 Incineration

Incineration describes the oxidation or combustion of organic components of waste. One example is the use of rotary kilns where the drilling waste is treated at temperatures between 1200 and 1500 degree Celsius resulting in a material which is less harmful (Ifeadi, 2004). On the contrary, incineration is not suitable for the treatment of inorganic components of waste like metals which will only oxidize and leave the process as ash or vapor. The ash needs to be disposed in a prudent manner while the metals can be removed from the vapors by air pollution control equipment prior to discharge.

It is considered to be a robust treatment for drilling cuttings (DNV, 2013). However, slurrified cuttings that shall be incinerated will require additional energy supply. On top of that it is a very energy intensive treatment option where only a part of the heat energy can be recovered for other purposes and a high amount of CO_2 and NO_x is generated (Thermtech, 2010).

4.2.1.2 Thermal Desorption

In thermal desorption a distillation process is used to achieve oil-free solids which can be disposed (Stephenson, 2004). In this process free oil & oil-water emulsions are evaporated before additional energy is applied to remove the interstitial oil which is bound in the interstices by molecular forces and surface tension. Water will evaporate first. The formed steam will lower the boiling point of oil. Therefore the process can be run at lower temperatures than the boiling point in question.

The evaporated fluids are condensed in a two-stage condenser to separate water and oil. There are different desorption units on the market:

- Drum type units use a rotating drum that is warmed up by burners
- Screw type units circulate hot fluid through the hollow screw and jacket
- Thermomechanical Cuttings Cleaner is using friction to heat the cuttings
- Chemical desorption units mix cuttings with acid to generate heat

The Drum-,and Screw-type units use indirect heat. This requires the temperature of the indirect heat source to be higher than the process temperature necessary for evaporation of the water and oil contained in the cuttings (Kleppe, 2009). Therefore these types require more energy to treat the cuttings than the Thermomechanical Cuttings Cleaner.

In order to guarantee a good treatment, the feeding of the thermal desorption unit needs to be consistent (Pierce, 2006). If the feeding rate is reduced, the temperature might increase leading to cracking of the oil. On the other hand, if the feed rate is increased, the temperature might drop too much so that the treatment is not able to remove the oil. In every thermal desorption unit the oxygen level needs to be kept below eight percent to avoid combustion because of the high temperature developed.

The advantage of these units is that the recovered oil might be reused as base fluid for drilling mud (Stephenson, 2004). If it is not suitable for re-use since high temperature and contamination changed its chemical composition or cracking occurred, the recovered oil will be used as fuel in the burners of the indirect desorption units.

4.2.1.3 Bioremediation and Land Farming

Since hydrocarbons are known to be biodegradable, several deposit methods are used to enhance the biodegradation of oily waste (Chaîneau, 2002).

When bioremediation is applied to oily waste, nutrients are added and an aerobic condition is maintained to establish a perfect environment for microbial degrading through natural occurring bacteria and fungi. The application of the micro-organisms is performed through tilling or spraying (Baker Hughes, 2006) while nutrients are added to make up for the insufficient nutrients in oil and enable proper growth of microorganisms (Chaîneau, 2002).

Landfarming describes the process of extensive spreading of drill cuttings on land close to the source of cuttings (Ladousse, 1996). The spreading is important to prevent negative consequences on the fertility of the soil. A part of the bacteria contained in the ground is able to process hydrocarbons and tests have shown that these bacteria populations increase in number when hydrocarbons are available. Therefore they are capable to clean the soil in a reasonable amount of time.

Both methods are sensitive to external factors as for example the temperature of the environment and are therefore less robust than the other methods (DNV, 2013). Furthermore, these methods require a huge land area and do not recover the energy contained in the drilling waste (Thermtech, 2010).

4.2.1.4 Dispersion by Chemical Reaction

Dispersion by Chemical Reaction (DCR) describes a solidification and stabilization method which treats the cuttings with dispersant, e.g. hydrophobized Calcium Oxide, resulting in a dry solid which can be used as construction material (Ifeadi, 2004). This method protects the environment through immobilization of organic content and heavy metals in the matrix of the cuttings. All interaction between living organisms and these components is therefore successfully suppressed.

The DCR treatment consists of two steps. First the cuttings need to get into a finely dispersed state to ensure that all contaminants will be treated in the second step where the dispersed form is transformed into a dry powder. This method works for oily-, -non-aqueous and aqueous solutions. The necessary items are relatively cheap comprising mixers, materials and chemicals. It is important to note that the end-product is non-polluting and can improve the economics of the treatment method.

The disadvantage implied in the demobilization of the organic content is the disuse of its energy.

4.2.2 Offshore

Cuttings treatment and disposal offshore is the most favorable option if economical and technical practicable with regards to governing environmental legislation (Pereira, 2013). The instant processing of cuttings will reduce the space necessary for storage offshore and make the drilling operation less weather depending (Stephenson, 2004). Separation of drilling fluids and cuttings takes place in centrifuges and Thermomechanical Cuttings Cleaners or the drilling waste is simply injected into a suitable formation for storage.

4.2.2.1 Cuttings Dryer

Cuttings Dryers are based on centrifuges which are spinning at high speed to remove drilling fluids from the cuttings (Seaton, 2005). Under the best circumstances, the dried cuttings contain between two and three percent of oil per weight. This oil level is too high regarding to direct discharge of the cuttings with respect to OSPAR Decision

2000/3 and further treatment is necessary. The recovered fluid is contaminated by fines. Therefore it is unsuitable for re-use as drilling fluid but is well suited to be used as fuel.

4.2.2.2 Cutting Re-Injection

Cutting Re-Injection (CRI) describes the process of collecting cuttings and waste fluids to prepare stable slurry which can be pumped into a formation for permanent storage (Alba, 2007). The formation needs to be able to receive large amounts of slurry and be isolated by a non-permeable rock to avoid leakage to surface. In general, the injection can take place in dedicated injection wells or into the annulus of a producing well. Before the cuttings can be injected they need to be transported to the Slurryfication System which consists of a coarse tank, classification shaker and fines tank and enables the production of slurry with acceptable properties regarding injection. In the coarse tank the cuttings are mixed with water by circulation with centrifugal degradation pumps. The solids are partly degraded due to impact forces prior to transferring the slurry to the classification shaker and grinder for further size reduction. When the particles reach the wished particle size, they will move through the screen of the classification shaker and enter the fines tank where the slurry is conditioned. After transferring the slurry into the holding tank it is ready to be injected using the injection pump. Monitoring of the process and injection parameters as injection rate, injection pressure, injection time and shut-inn time are required to minimize the operational risk.

The main advantage is that the waste is stored at the subsurface. Nevertheless, problems might occur due to plugging of casing or piping because of settling solids and erosion by reason of pumping of solids at high pressure (Ifeadi, 2004). Cuttings/slurry leakages to surface have stopped re-injection at several fields and show the need for good planning and risk evaluation before CRI is chosen as disposal technique (NPD, 2011). Moreover, the energy contained in the cuttings is not recovered but lost (Thermtech, 2010).

4.2.2.3 Thermomechanical Cuttings Cleaner

The Thermomechanical Cuttings Cleaner (TCC) is a thermal desorption technique which uses friction to heat cuttings. Experience has shown that this treatment can reduce the adhered oil on treated cuttings to less than one percent per weight (Amundsen, 2011). Therefore the recovered solids are suitable for offshore discharge regarding OSPAR decision 2000/3. The mode of operation will be explained in detail in chapter 5: Thermomechanical Cuttings Cleaner.

4.2.3 Other Experimental Techniques

In this Paragraph two experimental techniques will be presented which are still in the development phase and not ready for field use yet.

4.2.3.1 Microwave Treatment

Microwave treatment is a technology under development where a magnetic field is developed which interacts with the molecules of the material and transfers energy directly to substances with a high dielectric loss factor (Pereira, 2013). The interaction with the molecule's dipole results in a higher rotational momentum and increased temperature. The influence of the radiation on materials with low dielectric loss factor or conducting materials is limited since it respectively simply passes or gets reflected. This selective heating of material results in a lower energy consumption of the microwave treatment in comparison to thermal desorption treatments since not the whole matrix needs to be heated up. Applied on drill cuttings it is the water phase which is heated, vaporized and drags the hydrocarbons along as it escapes the matrix. A pilot scale continuous treatment system has been build using a variable power (5-30 kW) microwave generator which enabled the treatment of 400-450kg/h to one percent OBM by weight on dry cuttings (Robinson, 2009). When the throughput was reduced, an average of 0.1 percent OBM by weight on dry cuttings could be achieved. The pilot is scalable and therefore the development of a modular offshore treatment system with low space requirements and flexible processing rates seems possible.

4.2.3.2 Liquefied Gas Extraction

Liquefied hydrocarbon gases as propane and butane can be utilized to solve and remove oil from cuttings (Seaton, 2005). The first test was performed at ambient temperature with butane as solvent at 500psi pressure. An ester/olefin blend on cuttings was treated with butane and the oil on the cuttings decreased from 21 to 0.24 percent. Analysis of the recovered base fluid showed that its quality was unchanged and could be reused in drilling operations. In further testing, propane flowed through a bed of cuttings in order to solve the soluble parts. These tests resulted in 0.5 to 4 percent by weight oil on cuttings. One identified problem was possible channeling of propane through the cutting bed and the test set-up was modified to include mixing through a jar rolling mill. This new set-up resulted in less than 1 percent of residual oil on cuttings which qualifies the treated cuttings to be discharged to sea in most regions. These tests showed the feasibility of liquefied gas extraction, but a system capable of treating cuttings in the field is yet to be designed.

4.3 Transportation Systems for Drill Cuttings

A need for transportation of solids and fluids exists both rig internal and as a means for transfer to land. For the transportation of drilling cuttings to land, two main techniques are available (Svensen, 2011).

Skip and ship describes the technique where cuttings are moved by blowers or conveyors to skips which will be replaced when filled up. For the handling of skips a crane is necessary. This solution is easy to implement but has limitations because of the needed storage place for skips. The weather limits the loading and back loading of skips by use of cranes and boats and therefore can stop the drilling operation or reduce the rate of penetration (ROP). Another disadvantage is that several crane lifts per skip are necessary. Crane lifts should be avoided in order to decrease the likelihood of falling objects and injuries of involved personal (Kirkness, 2008).

Bulk transfer uses holding tanks for interim storage and pneumatic pumps for transfers between tanks or to boats which can be connected to the system by a hose (Svensen, 2011). The advantage lies in the avoidance of crane lifts during operation while the operation still is limited by bulk space of the tanks and weather conditions which do not allow for connection of the hose to the boat for cuttings transfer.

Other systems which are used mostly for internal transportation on the rig site are gravity collection systems, where the force of gravity alone enables the transfer of cuttings and fluids to a lower elevation, and vacuum transportation systems, where a vacuum blower unit establishes a vacuum to draw the cuttings and fluids through lines (Alba, 2007).

4.4 Treatment Capacity Onshore

The actual treatment capacity for cuttings and mud/slops onshore is estimated to be 387000 tons/year and 537000 tons/year respectively in 2014 (DNV, 2013). These values are of theoretical nature. In reality, the given treatment capacity might be less than stated since it is a function of the chemical composition of the waste, steady delivery to the treatment facilities, maintenance-, and operation stops. Especially the slurrification of cuttings could roughly reduce the treatment capacity by up to 30% according to the service companies. This would result in a new treatment capacity for cuttings of 270900 tons/year. Since the worst case prognosis for the year 2014 in section 2.2.2 estimated the need for onshore treatment to be ca. 130000ton for cuttings and 285000ton for mud/slops, it can be seen that there is adequate capacity to treat oily waste in the marked as illustrated in Figure 3. However, the offshore treatment and disposal is still desirable due to the reasons stated in 4.2. To the author's knowledge, the TCC treatment is currently the only offshore treatment & disposal option besides of CRI that fulfills the governing regulation on the NCS and will therefore be presented in chapter 5.

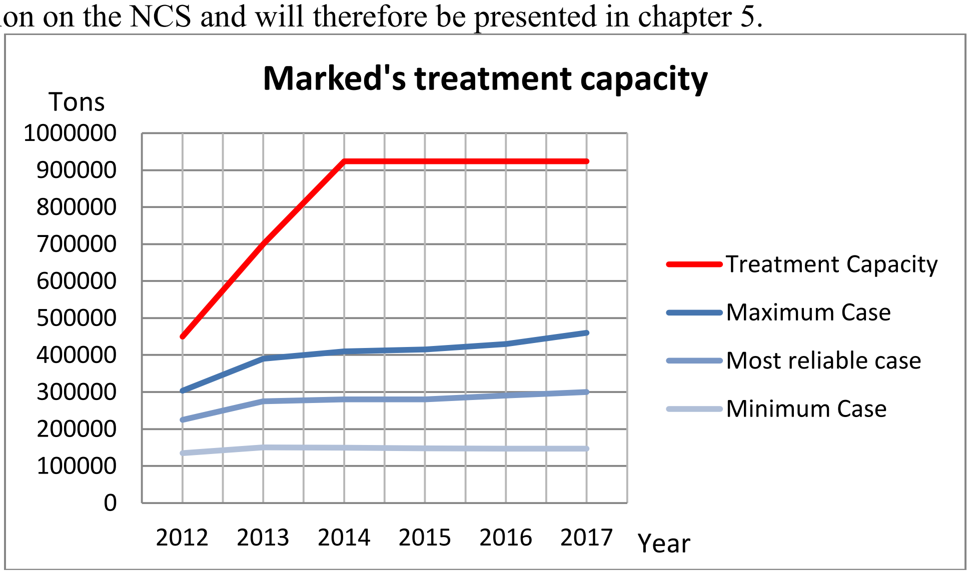

Figure 3: Prognosis for Market's treatment capacity and waste generation. (DNV, 2013)

Chapter 5: Thermomechanical Cuttings Cleaner

In this chapter the TCC, its control system and planned improvements are presented.

5.1 General Information

The TCC is a thermal desorption unit which separates the incoming waste into water, oil and solids (Thermtech, 2014). It has been developed by Thermtech AS who is giving out manufacturing licenses to several service companies as Baker Hughes, Halliburton, MI Swaco and TWMA. During the 1990's the qualification process of the TCC technology started on the United Kingdom Continental Shelf (UKCS) with the aim of offshore cuttings treatment (Kirkness, 2008). Emphasize was put to meet or exceed regulatory requirements regarding the treatment results, modularization of the unit, weight-, & footprint- reductions, and securing an adequate processing capacity. Each module's weight was not allowed to exceed the lift capacity of typical offshore cranes. For safety reasons the unit was computer steered and connected to the rigs emergency shutdown system. This development process led to the installation of the first 945kW process plant on the Ocean Guardian Rig in 2003. To date, TCC units are used both on-, and offshore to treat oil contaminated drill cuttings in several countries.

5.1.1 Working Principle

The TCC changes kinetic energy supplied by a drive unit into thermal energy through the development of friction in the mill (Thermtech, 2014). The drive unit is rotating the shaft on which hammer arms are mounted. The shaft is situated in a process chamber in which the waste is pumped. Through fast rotation of the hammer arms the waste fed into the mill will be pressed towards the inner wall and heat is generated due to the friction between the waste particles. The implied intense agitation in the process has two advantages (Murray, 2008). Firstly, the retention time is decreased since the solids are crushed and diffusion distances for oil reduced, helping it to vanquish the capillary forces which keep the oil bound to the solids. Secondly, the oil can be vaporized at lower temperatures compared to its atmospheric boiling point since the laminar oil vapor layer around the oily solids is reduced and the surrounding vapor is dominated by super-heated water vapor. Therefore the temperature in the process can be kept between 240 degree Celsius and 260 degree Celsius which is sufficient to evaporate both oil and water (Kirkness, 2008). The vapor will leave the mill and be freed from fines by a cyclone before the oil and water are condensed separately in connected condensers (Thermtech, 2014). Light oil fractions might be condensed together with the water and will be separated in an oil-water separator. The recovered oil and water can be recycled and be re-used in new drilling fluid. The fines from the cyclone are comingled with the dry solids which are leaving the process chamber through a rotary valve. This valve is controlled by a PLC controller which steers the process by keeping process variables in the programmed range. If the temperature is exceeding a certain level, the controller will automatically start the feed pump and the entering of colder waste will decrease the temperature of the process chamber. This feed implies an increasing load in the mill. The measured load is given as an input to the controller which in due time will steer the rotary valve to decrease the load. The treatment process requires that the drill cuttings are retorted prior to treatment in order to get an overview regarding the percentage of oil, water and solids content (Reid, 2013). After treatment the recovered solid powder and the process water have to be analyzed for determining their hydrocarbon (HC) content to document the effective waste treatment process.

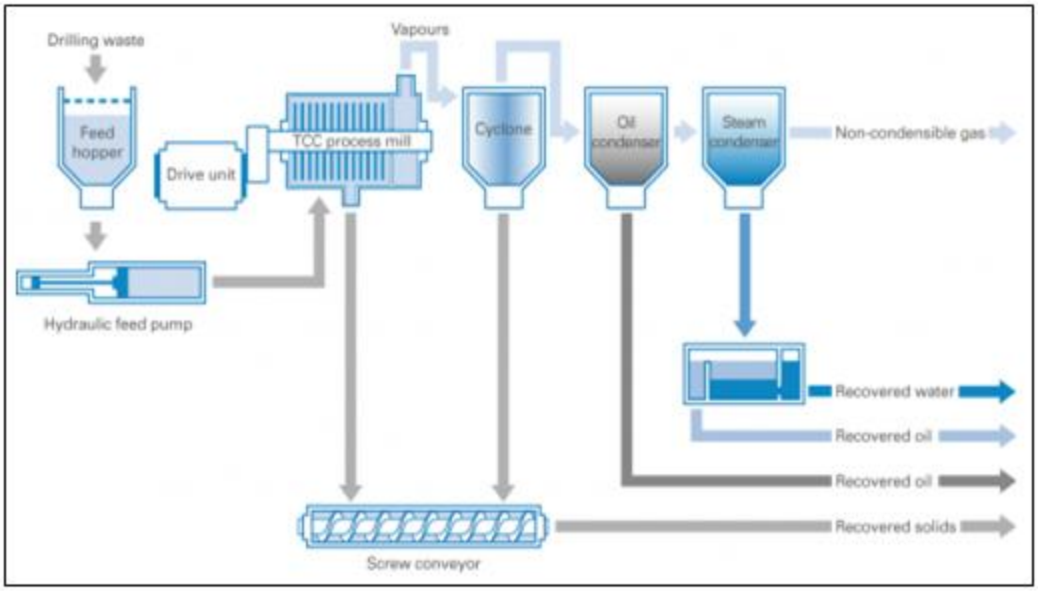

Figure 4: The principles of thermal treatment (Thermtech , 2014)

Experience showed that the content of HC in the solids is smaller than one weight percent while the HC content in the water phase is lower than 20ppm. The recovered oil needs to be tested for contaminations before it can be safely used as base oil for the production of a new drilling mud. In Figure 4 the working principle of the TCC is illustrated.

5.1.2 Footprint and Mobility

In comparison with other thermal desorption units the footprint of the TCC is smaller given that the process chamber does not need a large surface area to transfer the heat to the cuttings (Thermtech, 2014). Instead the heat is generated in the process chamber itself and transmitted to the fluids by the surface area of the small solid particles. The mill itself has an internal areal of around one square meter (Murray, 2008). One TCC variant is called TWMA Rotomill. The TWMA Rotomill is currently 12.8m long, 3.5m wide and 4.35m high. It is divided into three containerized modules (Reid, 2013):

- Mill module with 18 tons tare weight (19 tons operational weight)
- Process module with 16 tons tare weight (17 tons operational weight)
- Engine module with 25 tons tare weight (27.5 tons operational weight)

All modules are constructed to be easily transported and installed. Their weight can be handled by common offshore cranes. In consequence the TCC is to the knowledge of the author the only thermal desorption technology in use offshore (Murray, 2008).

5.1.3 Energy Consumption

The drive of the 1400kW TCC has a maximum diesel consumption of 450 liters per hour while the electrical driven unit needs at most 1400kW to treat 7-9 tons of cuttings per hour (Reid, 2013). Additional electrical power is needed for the control systems and process equipment as for example fans and pumps. This energy consumption is however negligible small in comparison to the energy needed by the drive system.

5.1.4 Recovered Oil Quality

The recovered oil quality is depending on temperatures developed in the mill and processing time before the oil is leaving the system (Thermtech, 2014). If one of them is too high, the oil can be degraded. In the TCC the oil is subjected to high temperatures only for a couple of seconds before it is evaporated and leaves the system. In comparison to other thermal desorption technologies the TCC process temperature is moderate and the evaporation more gentle resulting in a high quality of the recovered oil. This is shown in Figure 5 by a gas chromatography / mass spectrometry (GC/MS) profile of used base oil before and after treatment. This particular base oil's most abundant hydrocarbons are C11, C12, C13 and C14. These are as well present after TCC treatment.

Although the abundance of C11-C14 decreases slightly, the recovered oil can be instantly re-used as base oil for new muds (MI Swaco, 2013).

Another advantage of the TCC treatment is that contaminants as benzene, toluene, ethyl-benzene and xylenes (BTEX) (Eugris, 2013) and other light fractions will be found in the oil which is separated from the water stream after the water was condensed (Thermtech, 2014). This fraction is relatively small and can be discarded to get rid of BTEX which is highly volatile and can affect the workers' health (Eugris, 2013).

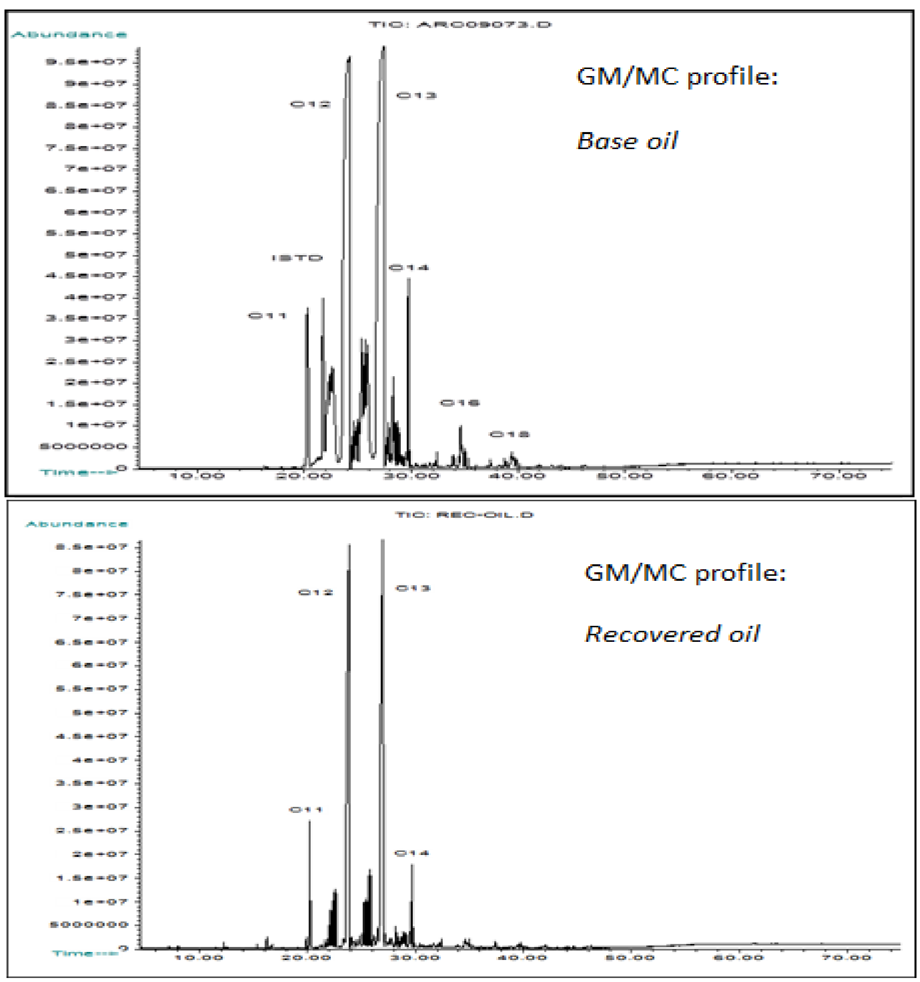

Figure 5: GM/MC profile of base oil and by TCC recovered oil (MI Swaco, 2013)

It is important to mention that the Flash Point of the oil is not altered by the treatment and will be the same in the recovered oil (Thermtech, 2014). This is important since oil with a lower flash point is more easily ignited. Operators as Total E&P have set a lower Flash Point limit for the use of oil due to security reasons. Therefore a decrease in the Flash point might have prevented the re-use of the recovered oil.

To sum up, the recovered oil is suitable for reuse as base oil in new drilling mud.

5.1.5 Theoretical Treatment Capacity of TCC

The theoretical treatment capacity can be derived by setting up the energy balance for the TCC (Kleppe, 2009). A natural control volume to be chosen is the process mill. Figure 6 shows the transfer of material across the border of the control volume. Cuttings enter the mill from the side and an electric-, or diesel-motor supplies energy to the system by rotating the shaft which is equipped with hammers. The resulting friction heats up the cuttings and the contained fluid is evaporated and will leave the system as oil and water damp while dry solids are ejected (Thermtech, 2014).

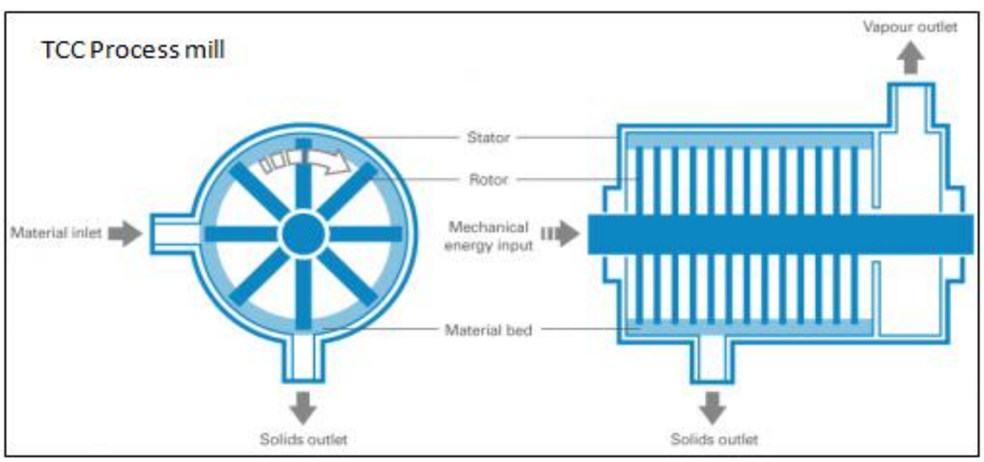

Figure 6: Process mill: Transfer of material. (Thermtech, 2014)

The required evaporation temperature is in general dictated by the heaviest oil fractions and varies with different base oils (Kleppe, 2009). Since the heat transfer is non-selective, oil, water and solids will be heated to operation temperature of the unit.

Therefore the energy supply to the process needs to be sufficient to:

1. Heat oil from feed temperature to process temperature (Q_{oil_1}), evaporate it (Q_{oil_evap}) and heat oil vapor to process temp. (Q_{oil_3})
2. Heat water (w) from feed temperature to its boiling point (Q_{w_1}), evaporate it ($Q_{w\_evap)}$
   and heat the water steam to process temperature (Q_{w_3})
3. Heat the solids (s) from feed temperature to process temperature (Q_s)
4. Overcome heat losses

It is known that the raise in temperature of a substance with a given mass is proportional to the heat energy Q supplied.

$$Q = \mathrm{C}\Delta\mathrm{T} \; = \; \mathrm{mc}\Delta\mathrm{T} \; (1)$$

where C is the heat capacity which describes the amount of energy that needs to be supplied to raise the temperature by one degree (Tipler, 2003). The heat capacity divided by the mass defines the specific heat c.

$$c = \frac{C}{m}$$

Formula (1) can be used to calculate the needed heat to raise the temperature of oil and solids to process temperature. It is as well useful to calculate the heat to raise the water temperature to its boiling point and the water vapor to process temperature, but it does not apply to phase changes where the energy supplied leads to fusion, melting, vaporization, condensation or sublimation. In the TCC process the phase change occurs from liquid oil and water to gas and the heat required can be calculated as:

$$Qv = m\,Lv\ (2)$$

Where Lv is defined as the latent heat of vaporization.

Using formula (1) and (2), the heat necessary to treat the cuttings can be calculated as the sum ΣQ of

1. $Q_{oil\_1} = m_{oil}\, c_{oil}\, (T_{boilingpoint\_oil} - T_{feed})$

   $Q_{oil\_evap} = m_{oil}\, L_{vapour\_oil}$

   $Q_{oil\_3} = m_{oil}\, c_{oil}\, (T_{process} - T_{boilingpoint\_oil})$
2. $Q_{w\_1} = m_{water}\, c_{water}\, (T_{boilingpoint\_water} - T_{feed})$

   $Q_{w\_evap} = m_{water}\, L_{vapour\_water}$

   $Q_{w\_3} = m_{water}\, c_{water}\, (T_{process} - T_{boilingpoint\_water})$
3. $Q_s = m_{solids}\, c_{solids}\, (T_{treatment} - T_{feed})$

In reality, a part of the heat generated in the process will leave the TCC as heat loss (Qhl). Assuming no other losses and that all the energy supplied by the engine will be converted to heat by friction (Qinput):

$$Qinput = \Sigma Q + Qhl\ (3)$$

To find the treatment capacity $\dot{m}$ of the system in kilogram per hour we need to subtract the heat loss per hour from the energy input per hour and divide the obtained value by the sum of the heat necessary to treat one kilogram of cuttings.

$$\dot{m}\left[\frac{kg}{h}\right] = \frac{Qinput - Qhl\left[\frac{kJ}{h}\right]}{\Sigma Q\left[\frac{kJ}{kg}\right]} \quad (4)$$

As seen above the treatment capacity $\dot{m}$ of the TCC depends on the energy supplied and the waste composition (Thermtech, 2014). Thermodynamics define the amount of energy necessary for heating and evaporation of the waste. Especially, the water content of the waste has a huge impact on the treatment capacity. As lower the water content as higher is the treatment capacity due to the higher energy demand to heat water in comparison to oil and solids. Figure 7 illustrates the treatment capacity using formula (4) and the parameters stated in Table 5 in chapter 6. The amount of solids present is assumed to be constant at 60 % while the water content is varying. 1400kW energy is supplied and heat loss is neglected.

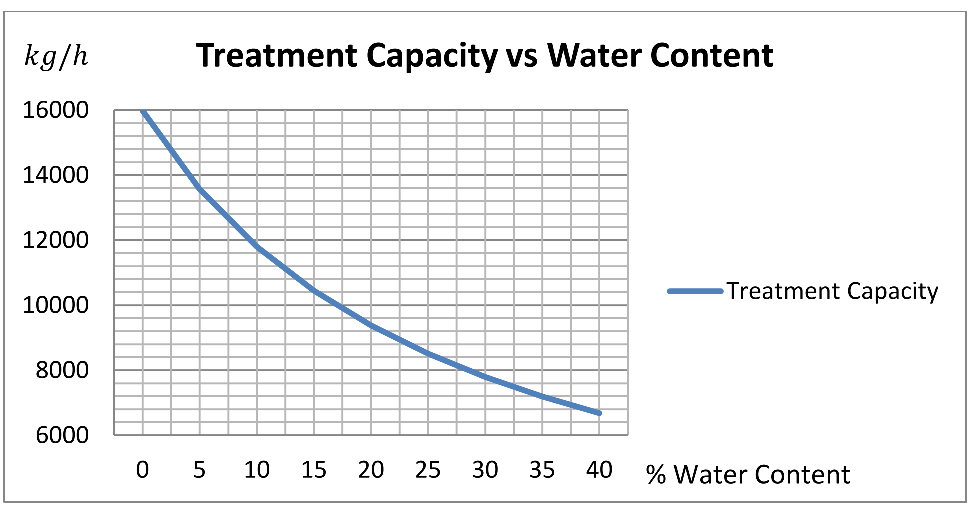

Figure 7: Treatment capacity of TCC vs. water content of cuttings.

Another important influence has the temperature of the feedstock. The treatment capacity increases in accordance with increasing feedstock temperature since less energy is required for the cuttings treatment. Figure 8 illustrates the influence of feed temperature on the capacity of the TCC using formula (4) and parameters from Table 5. The oil/water/solids ratio is assumed to be constant at 20/20/60, the heat loss is neglected and the energy supply is 1400kW. Experience shows that the 945kW unit and the 1400kW TCC can respectively process between 4-6 and 7-9 metric tons of oily drilling waste per hour (Reid, 2013). This processing capacity might not keep up with the generation of drill cuttings in the 17 ¾” well sections. Therefore additional storage should be installed to avoid restrictions of the ROP. One example of cutting storage is the cutting storage tank (CST) unit from TWMA. It comprises temporary storage and transfer capabilities. Each CST has its own recirculation line used to agitate the drilling waste and avoid settling, dewetting and compaction of the waste. As soon as less waste is generated than the TCC can process, additional drilling waste is fed from the CST’s so that the TCC can process at maximum rate and the excess waste is gradually decreased.

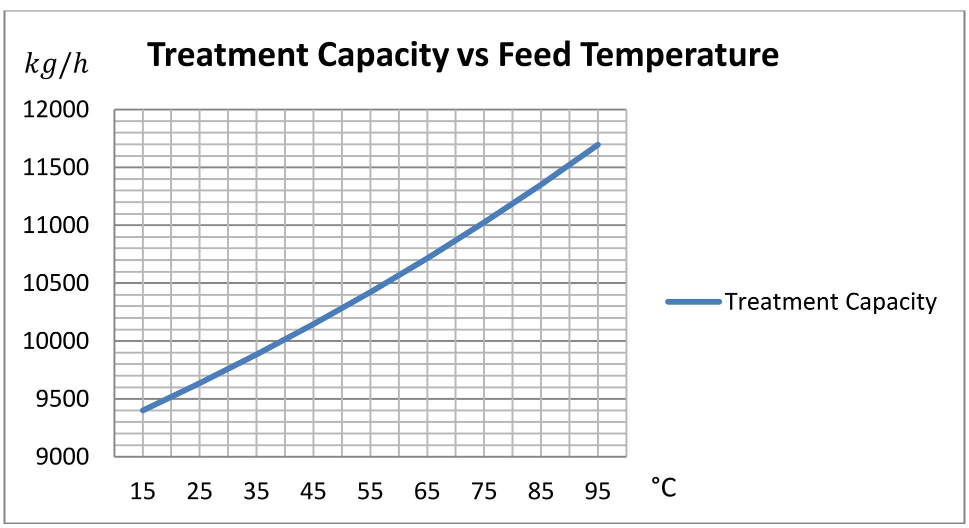

Figure 8: Treatment capacity of TCC vs. feed temperature of cuttings.

5.2 TCC Control System

The TCC cuttings treatment process presented in section 5.1 is steered by a Programmable Logic Controller (PLC) which ensures that the oil is successfully separated from the cuttings. The PLC monitors the inputs to the system, runs the user defined program logic and adjusts the outputs accordingly (AMCI, 2013). This automation of the process is preferred to manual process control since it increases efficiency, it is more consistent and it avoids human errors (Nygaard, 2013). Because of its importance to the TCC treatment, the PLC control system is an industrial secret.

Variance of the following properties affect the treatment capacity and need to be included in the TCC control system.

First, there is the mechanical energy supply. It supplies the energy which is converted to heat in order to vaporize the liquids contained in the cuttings. A higher mechanical energy input enables a higher treatment capacity.

Secondly, the properties of the cuttings fed into the mill are important. Changes in the oil, water and solids ratio lead to different energy demands due to the different specific heat capacities of oil, water and solids respectively. This is a function of the setup of solid control equipment, usage of drill mud and further variables.

Thirdly, temperature changes of the feed stock will as well lead to a different energy demand which is proportional to the difference in temperature.

A minor factor is the mineral's susceptibility to abrasion. The heat generated due to friction is depending on the solids composition of the cuttings since the mineral's susceptibility to abrasion varies.

More information on this subject is provided in Appendix A, where a simplified TCC control system is developed and presented.

5.3 Planned Improvements of TCC

The TCC system is under continuous development and both the license owner and the licensees are working to improve the system.

According to Thermtech's Marketing and Sales Director, Rocco V. Valentinetti, new PLC software shall improve the treatment process of the TCC. The aim of this and future design changes of the TCC unit itself is to provide a system which eliminates the small amount of oil which still adheres to the treated solids.

Another improvement lies in the customization of the TCC unit for different offshore vessels which have different cuttings treatment needs.

Footprint reduction of the TCC unit is desirable in order to enable offshore treatment on vessels with little deck space available.

Treatment capacity of the TCC shall be improved to reduce the needed storage for bigger well sections. The additional treatment capacity would as well allow for cuttings treatment at a central offshore facility which receives oil contaminated cuttings from several rigs (OIC, 2007). Sharing of a TCC unit would decrease the cost for cuttings treatment offshore and improve the overall economy of projects.

On top of that adjustments for different regions could be made and the design of the equipment could be improved in order to cope with extreme conditions which can be found behind the polar circle or in desserts.

Chapter 6: Qualification of TCC Technology for Use on NCS

Since the information presented in chapter 5 is missing details regarding the real treatment capacity, the TCC's efficiency and its environmental impact, these subjects require further investigation. Chapter 6 compares the theoretical treatment capacity of the TCC to observed treatment capacities, analyses the treatment efficiency, considers the environmental impact and presents available field experience in order to qualify the TCC for use on the NCS.

6.1 Verification of TCC Technology

6.1.1 Match between Theoretical Capacity and Observed Values

In order to verify formula (4) derived in chapter 5, real data from the TCC cuttings treatment on the Elgin field is entered and the result compared to the observed capacity. Several cuttings samples have been retorted to gain values for solid-, water and oil- average volume percent. The average volume percent is used to calculate the respective mass percent of the sample. For example the mass percent for solids is calculated in Table 6 according to:

$$\text{Mass percent solids} = \frac{\%solids * \rho\ solids}{\%Solids * \rho\ solids + \%water * \rho\ water + \%oil * \rho\ oil}$$

(%solids = volume percent solids, %water= volume percent water, %oil = volume percent oil, ρ solids = density of solids, ρ water = density of water, ρ oil = density of oil)

In the next step, the heat to treat 1kg of cuttings ∑Q (kJ/kg) is found as described in chapter 6.1. Finally the energy input by the drive system of the TCC Q_{input} (kJ/h) is divided by ∑Q to find the treatment capacity $\dot{m}$ (kg/h) in Table 6.

Parameter	Value	Unit
rho_s	2700	Kg/m^3
rho_w	1000	Kg/m^3
rho_o	870	Kg/m^3
c_s	0,88	kJ/kgK
c_oil	2,1	kJ/kgK
c_w	4,17	kJ/kgK
L_vapour_w	2260	kJ/kg

Parameter	Value	Unit
L_vapour_oil	275	kJ/kg
c_oil_v	1,9	kJ/kgK
c_w_v	1,95	kJ/kgK
T_feed	15	degree C
T_process	260	degree C
T_bp_oil	260	degree C
T_bp_water	100	degree C

Table 5: Parameters assumed in calculations (Kleppe, 2009)

The energy input by the drive system was assumed to be 945kW. Since 1W is defined as 1J/s, 945kW is equal to 3402000kJ/h. Other assumptions made can be found in Table 5. In Table 6 it can be seen that the theoretical and observed value do not match perfectly. It was expected that the observed treatment capacity would be less than the theoretical as seen in the 12 ¼" and 5 5/8" well sections. The arguments for this expectation were the neglected heat loss of the TCC system and eventual mud additions. Heat losses will in reality decrease the treatment capacity since less energy is available to vaporize the fluids. Mud additions possibly required to transport sticky cuttings to the TCC and enable a smooth feed of the mill will as well lower the capacity because of the higher energy which is required to heat oil and water in comparison to solids.

In the 17 ½" and 8 ½" sections however, a higher treatment capacity was observed than in theory possible. This fact suggests that there are favorable treatment conditions which were not considered in the calculation of the theoretical value.

For instance the feed temperature was set to 15 degree C. The data available did not include the actual feed temperature. However the EIB 22-30c-G12 well was a High Pressure High Temperature (HPHT) well and it is reasonable to assume that the cuttings have been treated with the TCC before they could cool down to the ambient 15 degree C. Therefore less energy would be required to vaporize the oil and water present.

Retort weight		**Section**	**solids** Vol.%	**water** Vol.%	**oil** Vol.%
Well	EIB 22-30c-G12	17 ½"	45,96	23,09	30,97
		12 ¼"	61,43	15,29	23
		8 ½"	54,00	14	32
		5 ⅝"	50,00	12	38
Mass percent		**Section**	**solids** mass %	**water** mass %	**oil** mass %
Well	EIB 22-30c-G12	17 ½"	0,712657	0,132605	0,154738
		12 ¼"	0,824519	0,076009	0,099473
		8 ½"	0,77702	0,074611	0,148369
		5 ⅝"	0,74975	0,066644	0,183605
∑Q (kJ/kg)		**Well EIB 22-30c-G12** 17 ½"	12 ¼"	8 ½"	5 ⅝"
$Q_{oil\_1} = m_{oil}\ c_{oil}\ (T_{bp\_oil} - T_{feed})$		79,61272	51,17863	76,33596	94,46501
$Q_{oil\_evap} = m_{oil}\ L_{vapour\_oil}$		42,55296	27,35495	40,80153	50,4915
$Q_{oil\_3} = m_{oil}\ c_{oil\_v}\ (T_{process}-T_{bp\_oil})$		0	0	0	0
$Q_{w\_1} = m_w\ c_w\ (T_{bp\_w} - T_{feed})$		47,00191	26,94131	26,44585	23,62213
$Q_{w\_evap} = m_{water}\ L_{vapour\_w}$		299,6878	171,7798	168,6208	150,6165
$Q_{w\_3} = m_w\ c_{w\_v}\ (T_{process}-T_{bp\_w})$		41,37282	23,71474	23,27862	20,79307
$Q_s = m_{solids}\ c_{solids}\ (T_{process}-T_{feed})$		153,6488	177,7662	167,5255	161,6461
Q in kj/kg		**663,877**	**478,7357**	**503,0082**	**501,6343**
Treatment capacity		**Section**	**Theory** kg/h	**Observed** kg/h	**variance** kg/h
Well	EIB 22-30c-G12	17 ½"	5124,443	5220	-95,5565
		12 ¼"	7106,218	6350	756,2179
		8 ½"	6763,309	7120	-356,691
		5 ⅝"	6781,833	5640	1141,833

Table 6: Theoretical treatment capacity of TCC vs. observed capacity

As it can be seen in Figure 9 the theoretical treatment capacity increases with increasing feed temperature. As a result the offshore cuttings treatment directly after drilling is to be recommended. The higher treatment capacity of the 8 ½”-, in comparison with the 17 ½”-well section can be explained with the lower water content of the cuttings. Positive effect on the treatment capacity emanates from the steam stripping effect (Kleppe, 2009). This effect implies that the removal of the oil can be performed at lower temperatures than the maximum evaporation temperature of the contained oil. The superheated water steam acts as the stripping medium (Eschenbach, 2001). Liquids in the mill spontaneously evaporate and thereby split up the solids which are dried in the process. The supplier stated that the 945kw TCC has a capacity of 4000 – 6000 kg/h while the observed values were in the range of 5220 – 7120 kg/h. It seems that the supplier is using a conservative approach of capacity estimation in order to ensure its contractual commitments. In reality higher treatment rates can be obtained which is favorable for the TCC treatment solution.

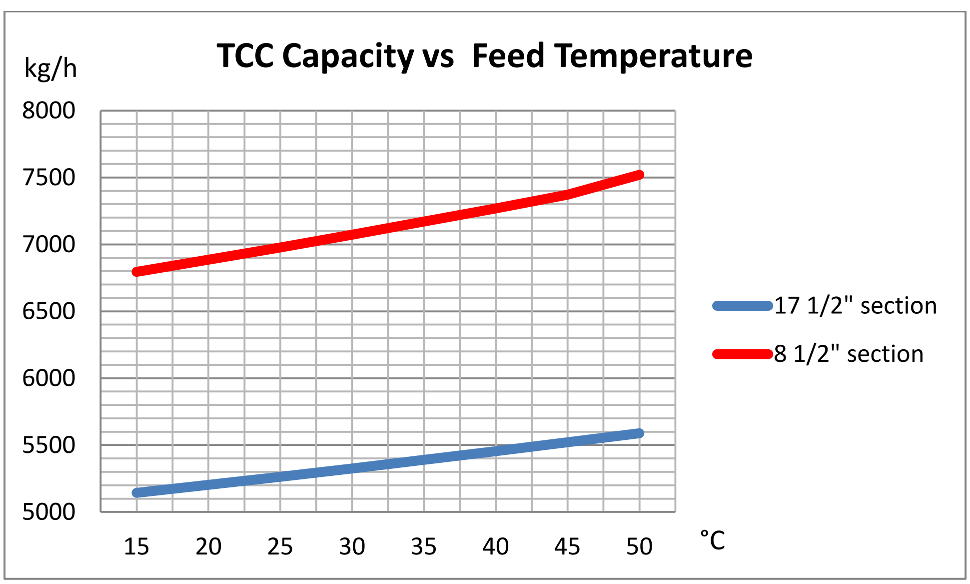

Figure 9: TCC’s treatment capacity as a function of temperature

6.1.2 Treatment Efficiency of TCC

Ideally, the TCC treatment would separate the cuttings into dry powder, oil and water. However the treatment is not perfect and some oil will be found both in the powder and water. In the following section the amount of oil which could not be recovered will be analyzed based on data provided by TWMA. In the time period of 2009-2013 they treated over 37.000 tons of oil contaminated cuttings with their TWMA Rotomill both off-, and onshore. Samples have been taken according to TWMA procedures every third hour of cuttings treatment. The samples were analyzed and the results were presented as an average over the drilled section. To analyze the efficiency of the TCC technology, the data for the well sections was combined in Table 7 using a weighted average. The Oil on powder showed a min/max value of 0.009/0.175% with a mean value of 0.033%. Since there is some variation in the data, the median gives a better description of the central tendency of oil on powder (Lund Research, 2013). The median was calculated to be 0,026%. It can be seen that the weighted average of oil on powder is well below the one percent by weight limit.

Regarding the oil in water, the min/max value is 5.5/21.4 ppm respectively with a mean value of 14.1 ppm. According to the Norwegian pollution law, the average of oil in water is not allowed to overcome 30mg per liter if it is going to be discharged (Forurensingsloven, 2013). The unit ppm is defined as mg/kg. To convert ppm to mg/l the density of the fluid needs to be known. Since the fluids are vaporized and condensed, it is reasonable to assume that the contained salts will follow the dry powder and that the condensed water has a density of around 1kg/l. It follows that 1ppm equals 1mg/l. The comparison between the allowed 30mg of oil per liter of water and the weighted averages for the TCC shows that the water is suitable for offshore discharge. In Figure 10 the data is plotted onto a stem weight to give a quick overview over Table 7.

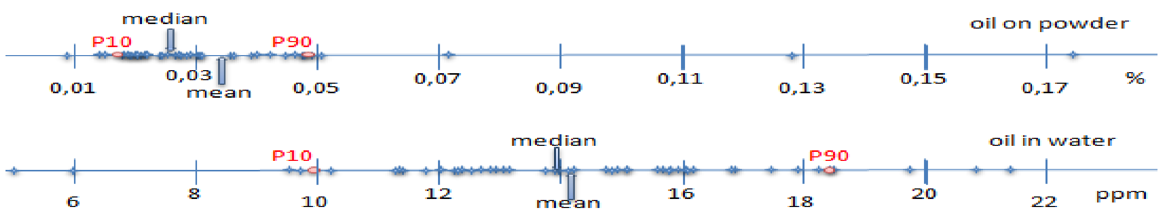

Figure 10: % oil on powder/ ppm oil in water after TCC treatment plotted on stem weight

Well	Cuttings processed (tons)	Oil in water (ppm)	Oil on powder %	Well	Cuttings processed (tons)	Oil in water (ppm)	Oil on powder %
#1	1058,41	20,953887	0,0480848	#26	1811,73	9,723765	0,1750829
#2	748,31	13,911898	0,027954	#27	625,63	14,24711	0,0170936
#3	982,16	13,96	0,04	#28	739,71	15,60387	0,0301826
#4	640,14	16,460413	0,0249323	#29	221,13	15,778	0,049
#5	536,04	11,815584	0,0188365	#30	739,71	15,60387	0,0301826
#6	516,15	12,02	0,017	#31	774,94	14,16957	0,0178556
#7	147,3	11,415	0,018	#32	527,41	18,51771	0,024412
#8	1503,26	16,16734	0,0507794	#33	428,15	15,91764	0,0188342
#9	315,91	12,039556	0,0268293	#34	559,36	14,82832	0,0412941
#10	416,41	18,302088	0,0205273	#35	455,99	21,35275	0,0379847
#11	511,07	17,933482	0,0472578	#36	475,48	16,07245	0,021
#12	1476,53	19,699905	0,0454694	#37	204,84	15,8	0,02
#13	982,05	16,479369	0,0432914	#38	283,21	17,36171	0,0266857
#14	532,17	12,434369	0,0230082	#39	1553,6	5,970116	0,0091667
#15	643,47	15,837845	0,0271062	#40	1323,05	12,36155	0,0483755
#16	539,54	14,718373	0,0223706	#41	631,2	9,403634	0,0258663
#17	362,3	11,52	0,02	#42	819,02	12,77	0,023
#18	305,08	12,58	0,029	#43	888	13,76	0,022
#19	566,49	11,282587	0,0258684	#44	354	14,9	0,0269
#20	367,26	13,14788	0,0234691	#45	446,63	5,5	0,018
#21	656,49	11,49107	0,0152689	#46	676,84	10,31	0,029
#22	832,01	13,043725	0,015	#47	1533,7	12,9769	0,0373725
#23	1921,36	12,790569	0,0737513	#48	1590,92	18,61334	0,1289405
#24	877,55	12,925939	0,0168812	#49	1244,92	16,05584	0,0297823
#25	1374,87	12,543185	0,0187724				

Table 7: Weighted average of Oil in Water (ppm) and Oil on powder (%)

6.2 Environmental Considerations regarding Use of TCC

Results of environmental studies regarding on- and off-shore deposition of TCC treated cuttings and treatment related emissions are presented in the next section.

6.2.1 Onshore Deposition of Processed Cuttings

Bioforsk analyzed the processed drill cuttings on behalf of TWMA to demonstrate that they meet the Norwegian legislation regarding the heavy metal content, organic components and other parameters (Amundsen, 2011). To reach this goal, the processed drill cuttings have been compared to and classified regarding Norwegian Soil Quality Classes which are concerned with Norwegian legislation and possible applications of the solids with regards to their composition. Soil quality 1 is defined as non-polluted while soil quality 2 describes weak polluted soils. Solids with both qualities can be deposited in private gardens/play grounds and pose little to no risk to the environment. This study was made with regards to the disposal of processed drill cuttings on land. Nevertheless, the results are important as well for the disposal at sea.

The particle size distribution of the solids evaluated was established. It showed that the relative amount of silt (particle size 2-63um), clay (particle size < 2um) and sand (particle size 63-2000um) was between 50-70%, 5-15% and 20-40% respectively.

The heavy metals content has been analyzed and for most metals it was within the mean concentration of natural soils and overbank sediments. This is shown in Table 8. The concentration of copper/barium was measured to be 2-3/20-25 times higher than the mean value of overbank sediments respectively. However, the copper content is still within the limits of natural soils and barium can be found as barium sulfate which is insoluble in water. The metal content of the cuttings is within Soil Quality Class 2.

Parameter	Unit	Overbank Sediments	Soil Quality Class 1	Soil Quality Class 2	Mean/Max TCC Monthly samples
Arsenic	mg/kg	4	8	8 - 20	8 / 12
Barium	mg/kg	-	-	-	5980 / 17000
Cadmium	mg/kg	-	1,5	1,5 - 10	1 / 3
Chromium	mg/kg	32	50	50 - 200	35 / 81
Copper	mg/kg	22	100	100 - 200	54 / 73
Mercury	mg/kg	-	1	0 - 1	0,1 / 0,21
Molybdenum	mg/kg	2,2	-	-	3 / 14
Nickel	mg/kg	22	60	60 - 135	33 / 48
Lead	mg/kg	22	60	60 - 100	29 / 89
Tin	mg/kg	-	-	-	0,5 / 1
Vanadium	mg/kg	41	-	-	35 / 52
Zinc	mg/kg	54	200	200 - 500	115 / 470

Table 8: Concentration of heavy metals in overbank sediments, soil quality classes and monthly samples of TCC process (Amundsen, 2011)

The organic component (C10- C40) concentration presented in Table 9 was higher than in soils found in Norway and can be described with Soil Quality Class 4. However, the majority of the remaining hydrocarbons (HC) were long chained (>C16) which are in general less solvable and assumed to be less toxic than short chained HC.

Parameter	Unit	Minimum	Mean	Median	Maximum
Oil in sand	% by weight	0.01	0.12	0.11	0.26

Table 9: Concentration of hydrocarbons in monthly random samples (Amundsen, 2011)

The mean value of Policyclic Aromatic Hydrocarbons (PAH) is low enough (1mg/kg) to be considered as Soil Quality Class 1.

Several leaching tests have been executed to determine the amount of water soluble compounds present and to show that the solids are suited for landfill disposal. The batch leaching test illustrated the disposal suitability of the processed solids for all other parameters than the dissolved organic carbon which transcends the set limit. The column leaching test resulted in acceptable leaching potential for all parameters besides of chloride and fluorine.

This means that negative effects on the environment are possible, though they are likely to be decreased by dilution of seepage from treated cuttings. The high concentrations of calcium & dissolved organic carbon might as well reduce the toxicity of the solids.

The solids analyzed showed high silt content. As a consequence, the solids have a high water holding capability. To determine the liming and nutrient potential of the solids, more experiments should be performed. However the information available does not indicate great potential. Therefore the prior use of solids will be as filler material or as add on to soil mixtures or growth media to increase the water holding capacity.

To sum up, the treated solids may be disposed onshore, but since some eluate concentrations are higher than the given limits for land disposal, a risk analysis for the disposal environment should be performed in advance.

6.2.2 Offshore Discharge of Processed Cuttings

The TCC technology is field proven, but not qualified for use on the NCS yet. Since the use of this technology for cuttings cleaning is desirable, a working group was established by the Norwegian Oil and Gas Association. The working group consisted of Total Norge, Conoco Phillips, Det Norske, Eni, Lundin, and Statoil. The objective was to finance a project with the objective of qualification of the TCC technology (Blytt et al., 2013). The project was carried out by Aquateam COWI, who was 1) organizing the sampling and analysis of untreated and treated cuttings, 2) reviewing available information regarding the TCC technology and environmental data, and 3) performing an evaluation of both the TCC technology and the environmental risks associated with discharge of treated oil based cuttings offshore.

Environmental harm caused by discharge of treated oil based drill cuttings, can be caused by increased particle content in the water column, sedimentation on the seafloor or by leaching oil, PAH and heavy metals to the water (column or sediment pore water) and exposing organisms living in the water column or in the sediment. To determine the environmental risk, the spreading of cuttings has been modeled for an exploration well by Ditlevsen and Daae with the DREAM model (Ditlevsen, 2012). The model assumed discharge of 1118 tons of processed cuttings 1m below the sea level. The result of the modeling showed that the maximum expected concentration of treated cuttings in the water column was 1-5mg/l while the maximum thickness of the cuttings on the sea floor was estimated to be 1.8mm in a distance of 250-300m from the rig.

Studies have been performed to determine the effects of particles arising from water based drill cuttings.

The studies illustrated that a continuous particle concentration of over 0,5mg/l in the water column is expected to harm organisms as mussels and codfish since they can take up the particles (Bechmann, 2007). The harm will increase with increasing particle concentration, but according to the PROOFNY project the harmful concentration will be limited to 1-2 km distance from the discharge point (Brooks, 2011).

Regarding the sedimentation on the seafloor, the negative effects are expected up to a distance of 250m. Organisms as corals will get silted up, though the effect on corals will be limited as long as the silt layer isn't thicker than 6mm according to the results of Bakke et al. (Bakke, 2012).

In the evaluation of the influence of oil, PAH and heavy metals on organisms, leaching tests have been performed and PEC and PNEC values have been calculated (Blytt et al., 2013). Because of the dilution of oil, PAH and heavy metals which are discharged to the sea water, there are no harmful environmental effects expected. This is valid both for the water column and the sediments.

Based on these results and more detailed information presented in the Aquateam COWI report, Blytt et al., (2013) concluded that the environmental risk of the discharge of TCC treated oily cuttings is comparable to the risk implied in the discharge of water based cuttings. Due to dilution no accumulating effect on the water column is expected and the effects of siltation will be limited to the area with highest sedimentation of processed cuttings. Since the particles of the processed cuttings are smaller than the water based cuttings, the resulting siltation might be less due to wider spreading

6.2.3 CO_2 and NO_x Emissions

The environmental impact of cuttings handling is not only a consequence of the deposition or discharge of treated cuttings, but also CO_2 and NO_x emissions during handling (Saasen, 2014). Emissions resulting from TCC cuttings treatment are estimated to be lower than the emissions arising from CRI into a dedicated injection well.

The majority of emissions are created during the drilling, completion and later plug & abandonment of the dedicated CRI well because of the drilling's rig fuel use, needed supply boats and helicopter traffic. Furthermore, the cuttings are preferred to be injected in batches since several smaller fractures are developed and interference with other wells and leakage risk is minimized (Turner, 2009). This method requires injection breaks where the cuttings need to be stored on the rig (Saasen, 2014). When the cutting storage is exhausted, a part of the cuttings needs to be transferred to land for treatment. This implies additional emissions for fuel of the supply boat and later cuttings handling onshore. Therefore the TCC cuttings handling is to be preferred, both on-, and offshore.

There is no obvious answer whether the TCC treatment on-, or offshore should be chosen when aiming for the minimization of CO_2 and NO_x emissions. This needs to be analyzed for each drilling project and depends among others on the distance to shore, the energy supply of the TCC unit, the amount of cuttings and weather conditions. Regarding the distance to shore, an increase in distance implies an increase in fuel needed to transport the cuttings and therefore a large distance favors offshore treatment. The TCC unit can be either driven by an electrical-, or diesel-engine. Electrical energy is available onshore and connected emissions are smaller than those from rig power or diesel which drive the offshore TCC. The use of electrical power for treatment favors onshore TCC treatment. If the amount of generated cuttings is large as in the case of the 17 ½" and 12¼" sections, a dedicated vessel is needed for the transportation and storage of cuttings. This implies higher emissions in comparison to the case where the usual supply boats could be used for this purpose and is in aid of the offshore TCC treatment where these emissions are avoided. On top of that, the offshore TCC might save rig emissions by avoiding waiting time when the weather conditions prevent the cuttings transfer to the storage and transportation vessel.

6.3 TCC Field Experience

To the author's knowledge, 55 TCC units are running scattered over the following countries: Algeria, Angola, Azerbaijan, Cameroon, Canada, Colombia, Congo, Jordan, Kazakhstan, Netherlands, Nigeria, Norway, Russia, Turkmenistan, United Arab Emirates, United Kingdom.

These units are run by several competing service companies and as a result, there is no central database with field experience established. In the following section, the field experience collected during the TCC cuttings treatment of selected wells which were drilled by Total E&P is summarized.

6.3.1 Land

In Bolivia, Total E&P is in charge of fields located at depth in the Andean foothills. Several wells have been drilled in a challenging environment where the cuttings had to be transported by trucks to central treatment facilities (MI Swaco, 2012).

A cost comparison was performed for the treatment of 1389 tons oil contaminated cuttings with a TCC-, and an indirect Thermal Desorption Unit (TDU) which has been used before. While the processing charges were the same, the TCC unit used 66 days less to treat the same amount of cuttings. This implied lower cost with regards to the rent of an excavator to fill the unit, accommodation and food for the workers which added up to 55941 US $. Due to the remote location, base oil was very costly and the recovery of as much base oil as possible desirable. The TCC unit managed to recover two times more oil from the cuttings than the TDU. This reduced the cost for new base oil by 205281 US $.

As a result of the higher oil recovery and less time use with the TCC unit, the savings were higher than the actual cuttings treatment cost.

6.3.2 Offshore

On the UKCS, Total E&P has been using a 945kW TCC unit for the cuttings treatment onboard of the Rowan Gorilla 5 rig (Gregoire, 2013). OBM was used from the start of the 17 ½" well sections. Since the expected cuttings generation in the fast drilled 17 ½" well sections was higher than the treatment capacity of the TCC, a buffer storage system was installed which consisted of up to three 70MT tanks and a skip station. The storage tanks were installed in a flexible manner so that they could be demobilized when not required. Cuttings were transferred by augers. As a contingency, cuttings transfer pumps or vacuum equipment could be used to transfer cuttings and a skip and ship station was installed. In Figure 11, the buffer storage system is shown on the left while the installed TCC unit is on the right picture.

The TCC has been operated permanently during the drilling process. Excess cuttings have been stored in the tanks for later TCC treatment or placed in skips for transportation to land. At no point of the operation the drilling had to be stopped because of the cuttings handling, though the ROP had to be adjusted during the fast drilled 17 ½" well sections. Cuttings from the other sections have been treated in batches of 50MT. The TCC proved to be reliable, but since it is a mechanical unit the risk of a breakdown is present. This risk needs to be met by a backup solution as temporary cutting storage or skip and ship. To decrease the probability of TCC downtime, focus was directed at preventive maintenance.

The recovered base oil was stored in one of the rigs pits. It contained between 1 to 2% fine solid particles which settled out in the pit and did not have a negative impact on the produced mud. The Flash point observed a small decrease from 103.5 degree C to 101.5 degree C. There was as well a slight increase in aromatics, PAH and BTEX observed.

Figure 11: Rowan Gorilla 5: Skip station, buffer tanks and TCC unit installed (Gregoire, 2013)

It was analyzed and concluded that it did not come from the TCC treatment process. The recovered oil has been continuously used for the mixing of new mud and negative effects regarding the mud quality have not been observed.

The oil on powder was measured to be between 0.04 and 0.10 % by weight of dry cuttings and the discharged water's oil content was between 7 and 23 mg per liter. These values were well within the permitted limits.

For the initial installation of the TCC unit offshore, 7-10 days were calculated. In order to avoid hot work, the equipment was designed to be bolted in place. Several service connections as water, diesel etc. had to be made. Therefore the installation should be for long term usage and the process should be preferably performed in a dry dock.

Due to the good results, the TCC unit has become a part of standard cuttings treatment equipment on the UKCS and is planned to be used at the Martin Linge field on the NCS. The reasons for the TCC implementation and the implementation process are presented in chapter 7.

Chapter 7: Martin Linge Case Study

In this case study, the question of the ideal cuttings handling solution for the Martin Linge field shall be answered. It will be shown that offshore TCC treatment is the best option with regards to Health, Safety & Environment (HSE)-, cost-, and operation reliability-considerations. Recommendations for the data and sampling program during operation will be given. The establishment of an environmental monitoring program and risk evaluation will be outlined and the currently ongoing implementation process of the TCC will be described in detail.

7.1 Field Information

Martin Linge field, former known as Hild, is situated around 180km west of Bergen. It comprises a high permeable oil reservoir and several high pressure gas condensate reservoirs at 1750 and 3500-4000m depth respectively with estimated reserves of 190 million barrels of oil equivalents (Total, 2013).

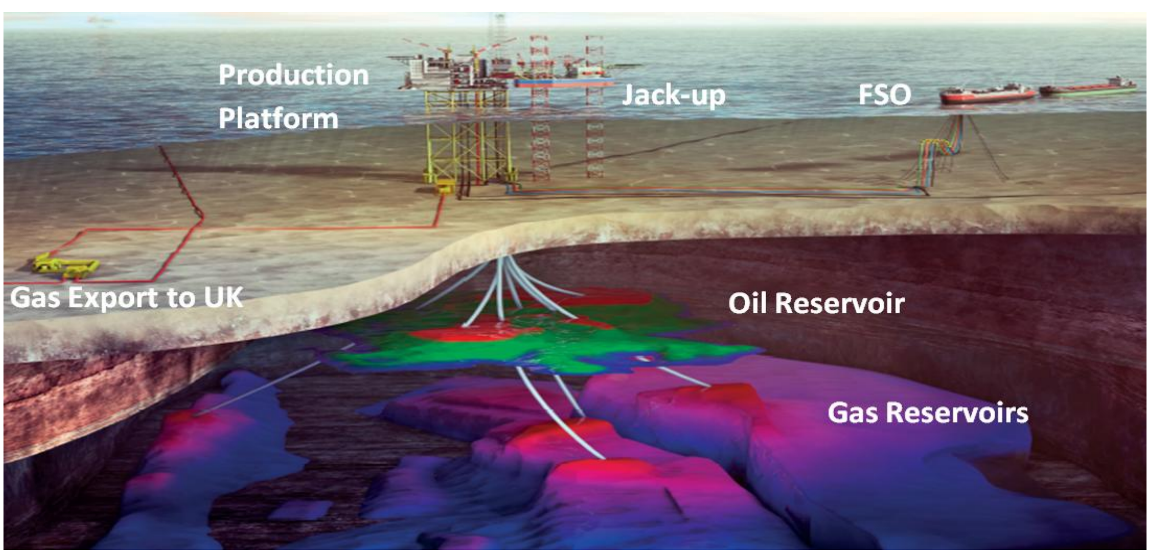

Figure 12: Updated Martin Linge Poster (Total, 2013)

The field development is based on an integrated wellhead, production and living quarters platform and a connected floating storage and offloading unit (FSO) which is able to separate oil and water. The oil will be offloaded to tankers and the water re-injected into the reservoir via a dedicated well. The gas from the field will be transported to the St Fergus Gas Terminal via a tie in to the existing 32” FUKA pipeline (Total_1, 2014). This can be seen in Figure 12.

In total, eleven wells are planned to be drilled by the Mærsk Intrepid jack-up rig: four oil producers, six gas producers and one water injection well. For eventual future development, ten additional wellhead slots are available on the platform. The field will be connected to the Norwegian electrical grid.

7.2 Amount of Drilling Waste Expected

Eleven wells are planned to be drilled to develop the Martin Linge field. The 36” sections will be drilled with seawater and bentonite pills with no return to the rig. The 26”-sections will have return to the rig. WBM will be used and the cuttings will be discharged to sea. In the 17 ½”-, 12 ¼” and 8 ½” sections OBM will be used. The estimation of generated oil contaminated drill cuttings is performed in Table 10.
Length values for drilled well sections are taken from the well path reports for the eleven wells. The composition of the formations present at the Martin Ling field lead to an assumed value of 1.8 s.g. for cuttings density. The washout is estimated to be maximum 10 percent in the 17 ½” section and 5 percent in the 12 ¼”-, and 8 ½”-section. This estimate is rather conservative since the formation is expected to be well compacted and stable. The amount of generated drilling waste is higher than the estimated 7339tons of cuttings since OBM and water will adhere to the cuttings and require adequate treatment or disposal.

Drilled open hole section with OBM (meter)												
	Oil				Water	Gas						Total
Sectio	O-A	O-B	O-C	O-D	PWRI	C-A	E-A	E-B	E-C	E-D	W-A	
17 ½	959	996	1030	1137	986	1497	1640	1713	1735	1871	1948	15512
12 ¼	933	1095	1002	1170	1052	1208	1351	1408	1433	1527	1508	13687
8 ½	1496	1488	1494	1139	1439	416	162	165	169	159	623	8750

Oil based cuttings estimation					
	Cuttings generated	Drilled meter	Volume cuttings	Washout	Cuttings
	(m^3/m)	(m)	(m^3)	(%)	(MT)
17 ½	0.1552	15512	2407.46	10	4766.77
12 ¼	0.07604	13687	1040.76	5	1967.04
8 ½	0.03661	8750	320.34	5	605.44
Total generated Cuttings contaminated with OBM:					**7339.25MT**

Table 10: Expected amount of oil contaminated cuttings at Martin Linge

7.3 Presentation of Cuttings Handling Solutions

For the handling of cuttings at the Martin Linge field four methods have been considered. They had to cope with the expected cuttings generation assuming an average rate of penetration (ROP) of minimum 20 meters per hour.

7.3.1 Skip & Ship and Bulk Transfer

"Skip & Ship" and "Bulk Transfer" are well known methods were the cuttings are transported for treatment and deposition to shore (Turner, 2009). These approaches are logistical demanding because of the large amount of cuttings generated during the drill process of the eleven wells, but feasible. A skip's capacity is 3.6-, or 4m^3 while a bulk tank's capacity is around 15 m^3 (Svensen, 2011). Using this numbers as basis for the transport of the expected 7339 tons of cuttings (ca. 4077 m^3), a minimum of 1020 skips or 272 bulk tank loads would need to be shipped to shore. Experience has shown that the number of skips/tanks calculated to hold the drilled out formation has to be roughly multiplied by 1.7 due to mud and water which follow the cuttings and the tendency of cuttings to pack unevenly. In offshore operations, the available deck space limits the number of skips/tanks stored on board. Relating to the Martin Linge development the cuttings generation of the 17 ½" gas well sections are most critical. Storage place for at least 270m^3 cuttings are needed which stands for 68 skips or 18 tanks. Knowing that not more than 25 skips are stored on the rig at a time, the operational risk regarding harsh weather becomes obvious. Harsh weather can prevent crane lifts necessary to transport skips and it can preclude the crew from transferring cuttings from bulk tanks to the supply vessels due to the need of hose connection. Therefore the ROP might need to be decreased or in worst case the drilling operation would need to be stopped because of exhausted storage capacity (Svensen, 2011). Drilling stops are costly due to deferred production and running costs. Other risks which go along with “skip and ship” are connected to the crane lifts necessary for transportation:

1. Lift on supply vessel
2. Hoist on rig
3. Transport to skip station for filling
4. Transport to temporary storage
5. Backload on supply vessel
6. Lift from supply vessel to shore

Further lifts might be performed due to operational needs offshore or for treatment/disposal needs onshore. In each of the lifts there is a risk for falling objects and injured workers.

7.3.2 CRI

Cuttings Re-Injection is a feasible option at the Martin Linge field (Turner, 2009). In general, injection of cuttings using the annulus of production wells is cheaper than drilling and completing a designated CRI well. Regarding the Martin Linge field however, annular injection is not recommendable since there is the risk of surface breakouts in shallow injection zones. Therefore the cuttings re-injection must take place into a dedicated CRI well which is designed to dispose the cuttings in an area that minimizes risk for other wells.

Geological analysis showed that suitable zones are available for CRI. To reduce the cost it would have been favorable if the CRI well could have been combined with the Produced Water Re-Injection (PWRI) well. In this case the injection slurry and produced water could have been injected into the same zone. However, this option had to be discarded due to the unconsolidated Frigg formation which requires screens to be run for the PWRI completion. If cuttings would be injected, these screens would get plugged and prevent further injection of both water and cuttings.

There are two common injection procedures for CRI:

Continuous-Injection describes an operation where a large fracture is continuously propagating and is kept open between injections. This operation is simpler and has a higher waste disposal capacity than Batch-Injection.

Batch injection describes an operation where the injection is temporary stopped to enable the fluid to leak off. The fluid leak-off traps the waste in the formation when the fractures close. The advantage of batch injection is that several smaller fractures are developed which are less likely to interfere with other wells, reservoirs, faults and reduce the risk of leakages. Hence, the Batch injection is the preferred injection procedure.

The advantage of CRI is that it is not weather depending and can continue even when skip and ship or bulk transfer is prevented due to crane limitations.

The challenge to the application of CRI is the high amount of cuttings which needs disposal during the drilling the 17 ½" well sections with OBM. Before injecting the cuttings, they need to be treated and converted into injection slurry. Thereby the volume of waste is more than doubled. The required buffer storage for both unprocessed cuttings and injection slurry would take a lot of deck space. High injection rates would be necessary to cope with the planned ROP of minimum 20 meters per hour. Batch injection is the preferred option since it disposes the cuttings closer to the injection well. However, the rate of cuttings generation and limited buffer storage would not allow for the required injection stops which are necessary for the fractures to close. Therefore part of the cuttings would need to be shipped to shore for treatment and final deposition.

7.3.3 TCC

The offshore use of TCC was field proven on the UKCS, but it has not been used on the NCS yet. Encouraged by the Norwegian authorities, operators have been searching for alternative treatment methods for oil contaminated cuttings and the TCC has proven to meet the requirements for offshore disposal of the treated cuttings as stated by the OSPAR convention (Blytt, 2013). The TCC system comprises three containerized modules constructed to be easily transported and installed on 48m^2 of deck space (Reid, 2013). Additional deck space will be necessary for buffer storage: The 1400 kW TCC has an approximate treatment capacity of 7-9 tons per hour (TWMA, 2013). Assuming an average ROP of 20 meters per hour in the 17 ½" section and that 0.307 tons of cuttings are produced per meter drilled (derived from Table 10), 6.14 tons of cuttings are generated which can be multiplied by 1.7 to take account for the adhered mud. The resulting 10.44 tons of cuttings to be treated per hour exceed the treatment capacity of the TCC. According to Table 10 the highest amount of cuttings will be developed in the gas well W-A. This is the design base for the required buffer storage calculated in Table 11.

Cuttings to be treated				
Meter drilled	ROP	Time to drill 17 ½ section	Cuttings/hour	Cuttings to be treated
(m)	(m/h)	(h)	(tons/h)	(MT)
1948	20	97.4	10.44	1016.86

Required Buffer Storage						
TCC capacity		Tank footprint	Tank Volume	Storage required		Deck space
(tons/h)	(MT)	(m^2)	(MT)	(MT)	Tanks	(m^2)
8	779.2	17	65	237.66	4	68

Table 11: Required Buffer Storage regarding use of TCC at Martin Linge

The required buffer storage for the 17 ½” section is 237.66 tons and takes up 68 m^2 of deck space. The total space requirement of the TCC handling system is therefore 116m^2 which is reasonable regarding deck limitations. As a contingency, Bulk transfer of cuttings to supply vessels is chosen. The advantages of this solution are the elimination of lifts to transport cuttings and a planned re-use of the recovered oil in the process (Kirkness, 2008). Another benefit is that the dried cuttings can be deposited at sea. Therefore the environmental impact due to the transportation of cuttings to shore is avoided. On the other hand there are possible risks related to the offshore discharge of dried cuttings.

7.4 Cost Comparison of Available Solutions

For the cost comparison of available solutions, several assumptions were taken:

- Drilling of the 11 wells is scheduled to take 1460 days
- Handling solution shall cope with cutting generation in 17 ½” section
- Total cuttings volume to be treated was assumed to be 9083 tons
- Slops generated are set to 15 tons per day

Different service companies have been contacted regarding the delivery and cost of cutting handling and treatment. The submitted offers have been screened and sorted into required handling packages so that an average cost could be presented for the different posts in Table 12. Posts that are common for all are mobilization fees, personnel costs and eventual needed engineering work. These have not been considered in this analysis. Mobilization fees which will be incurred for the different packages are in general small in comparison to the overall handling cost and are not included in the total cost. The cost for personnel involved in the handling of cuttings is comparable for the different solutions and does not influence the outcome. Note that the need for engineering work can first be determined after having performed a site survey of the rig to be used.

Skip and ship		quantity	days	Average unit cost (NOK)	Average total cost (NOK)
Cutting handling equipment	Daily Rental operation	1	500	5678,75	2839375
	Daily Rental stand - by	1	960	3480,25	3341040
Buffer storage	Daily Rental operation	2	100	2687,5	537500
	Daily Rental stand - by	2	1360	1794,25	4880360
Cutting blower	Daily Rental operation	1	500	2372,5	1186250
	Daily Rental stand - by	1	960	1667,25	1600560
Cutting skips rental		120	500	121,75	7305000
Supply boat cost		1	50	221000	11050000
Onshore drill cutting treatment		9083		1884	17112372
Onshore slops treatment		21900		1868,75	40925625
Total Skip & Ship cost :					**90778082**
Cuttings Re-injection		**quantity**	**days**	Average unit cost (NOK)	Average total cost (NOK)
Slurrification skid	Daily Rental operation	1	500	8904,75	4452375
	Daily Rental stand - by	1	200	6128,695	1225739
Holding tank	Daily Rental operation	1	500	3540	1770000
	Daily Rental stand - by	1	200	2592	518400
Data monitoring package	Daily Rental operation	1	500	5649,5	2824750
	Daily Rental stand - by	1	200	4700	940000
High pressure pump skid	Daily Rental operation	1	500	14364	7182000
	Daily Rental stand - by	1	200	11345	2269000
Injection well		1			41250000
Total Cuttings Re-injection cost :					**433682264**
TCC		**quantity**	**days**	Average unit cost (NOK)	Average total cost (NOK)
Rental TCC	Daily Rental operation	1	200	41375	8275000
	Daily Rental stand - by	1	1260	33475	42178500
Buffer storage	Daily Rental operation	4	200	2687,5	2150000
	Daily Rental stand - by	4	1260	1919,25	9673020
Cutting blower	Daily Rental operation	1	200	2372,5	474500
	Daily Rental stand - by	1	1260	1667,25	2100735
Offshore drill cutting treatment		9083		0	0
Onshore slops treatment		21900		1868,75	40925625
Total TCC offshore treatment cost:					**105777123**

Table 12: Cost comparison of different waste handling solutions for Martin Linge

Table 12 shows that CRI is by far the most expensive option for cuttings treatment of the 11 planned wells. This is due to the high initial cost implied with the drilling of the injection well. The renting of the injection equipment itself is less costly than the renting cost of the respective TCC-equipment and skip and ship solution. Therefore CRI is only cost effective when many more wells were to be drilled. The Martin Linge platform has 10 slots available for future needs (Total, 2013). Figure 13 illustrates the cost development including the optional 10 wells. The cost for Skip and Ship regarding required equipment, transport and renting of skips is lower than the other two solutions and would be the preferred option if there weren't hidden costs involved as fuel for the offshore crane during handling, offloading at the base, temporary storage cost at the harbor and land transportation of the skips to treatment facility/ultimate disposal place. These are difficult to estimate and are not included in Figure 13.

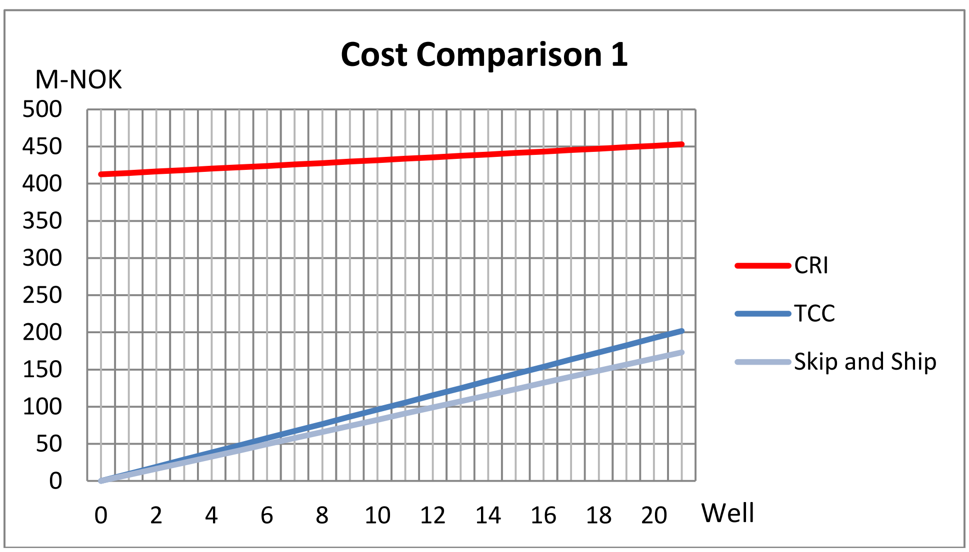

Figure 13: Cost in million NOK vs. number of wells for different solutions

If the cuttings were to be treated with the TCC, the base oil which follows the cuttings could be recovered for direct re-use. The resulting savings in the purchase of base oil should be included in the cost comparison. Assuming that twenty percent recoverable oil follows the 9083 tons of cuttings, 1816.6 tons of oil could be recovered. The used base oil has a density of 0.81 s.g. so that 2242.7 m^3 of base oil could be gained in the treatment of cuttings from the planned Martin Linge wells. Each m^3 of the used EDC 99 DW base oil costs approximately 6500kr. Therefore there is a realistic saving of 14577550kr during the drilling campaign of the first 11 wells or 1325232kr per well.

Correcting Figure 13 for these numbers it can be seen in Figure 14 that the treatment cost using the TCC unit are comparable to the cost of the Skip and Ship solution. The difference in estimated cost for the treatment of 11 wells is less than 0.5%. In fact, if an operational stop due to weather can be avoided due to the TCC offshore treatment, the TCC is the cheapest option. Both TCC and Skip & Ship solutions are cheaper than CRI even if all 20 available slots of the Martin Linge Platform were used.

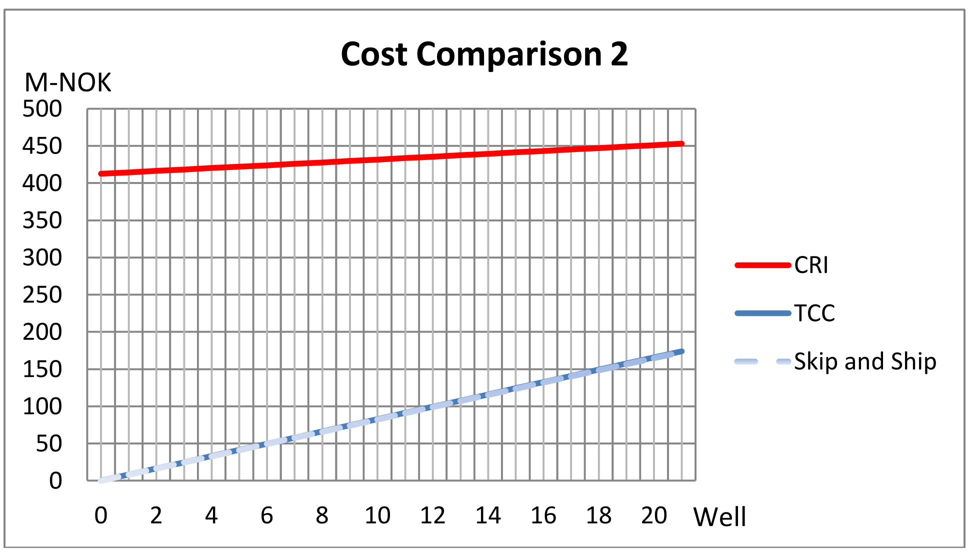

Figure 14: Cost corrected for oil savings vs. number of wells for different solutions

7.5 Assessment of Environmental Impact of Cuttings Treatment

The general assessment of the TCC's environmental impact is performed in section 6.2. In section 7.5 the focus will be on expected CO_2 emissions and oil discharge to sea due to the TCC cuttings treatment at the Martin Linge field.

7.5.1 Carbon Footprint of Cuttings Handling Solutions

As stated earlier it needs to be analyzed for each drilling project whether the TCC treatment on-, or offshore should be chosen when aiming for the minimization of CO_2 emissions. The emissions of a dedicated CRI well are estimated to be of greater magnitude (Saasen, 2014). A rough calculation is performed on the drilling campaign of the Martin Linge field. For this purpose, diverse contractors have been contacted to get estimates about the energy consumption of various operations.

The following assumptions are used as the basis of the calculation in Table 13:

- TCC treatment capacity: 2MT/h onshore at Mongstad ; 8MT/h offshore
- Energy consumption TCC onshore: 450KW/h
- Energy consumption TCC offshore: 450l diesel/h or 1400kw/h for 7MT
- Crane lifts performed: minimum 6 crane lifts per skip
- Energy consumption crane: 0,05 m^3 diesel/h
- Crane: 5min handling time per skip ; 12 skips per hour
- Deck space Supply boat: 400m^2 or 100 skips
- Supply boat: 20km/h transit speed , LNG use transit 10,9MT/24h
- Distance to base in Dusavik: ca. 250km
- Transportation to Mongstad: 5 skips/truck ; 330l diesel for way and return
- Electricity Emissions: 0,42kg CO_2/KWh;
- Fuel Emissions: 2,68kg CO_2/l diesel; 2,56kg CO_2/kg LNG

CO2 Emissions	Treatment method			
	offshore TCC		onshore TCC	
	Well 1-7	Well 8-11	Well 1-7	Well 8-11
Amount of cuttings to treat (MT)	5080,31	2258,94	5080,31	2258,94
Skip to land (MT)	0	0	5080,31	2258,94
Diesel use TCC (m3)	285,77	0	0	0
Electricity use TCC (kWh)	0	395314,5	1143070	508261,5
Skips required assuming 5MT/skip	0	0	1016	452
Crane lifts required	0	0	6096	2712
Diesel use crane (m3)	0	0	25,4	11,3
Supply boat trips for skip transport only	0	0	3	2
LNG use Supply Boat (MT)	0	0	817,5	545
Truck trips to Mongstad required	0	0	204	91
Diesel use trucs (m3)	0	0	67,32	30,03
CO2 emissions in kg due to electricity use	0	166033	480090	213470
CO2 emissions in kg due to diesel use	765863,6	0	248489,6	110764,4
CO2 emissions in kg due to LNG use	0	0	2092800	1395200
Total emissions in ton CO2 per group	765863,6	166033	2821380	1719434
Total emissions in ton CO2	**offshore TCC**		**onshore TCC**	
	931,9		4540,8	

Table 13: CO_2 footprint of TCC onshore and offshore treatment

After the first 7 wells are drilled, the drilling rig is planned to be connected to the onshore electricity grid. The offshore TCC will have an electrical drive which will be able to run both on energy provided from shore or an offshore diesel generator. Note that emissions due to the production and shipping of diesel and LNG are not considered. The emissions because of forklift handling of skips at the base are neglected in the calculations as well. It can be seen that the offshore / onshore treatment generates ca. 932 / 4541 ton of $C0_2$ respectively. The onshore treatment generates over 4 times as much $C0_2$ due to a less effective TCC unit and the transportation of the cuttings. The major contributor is the LNG use of the supply vessel.

Even though the estimation is rough, it illustrates that the total $C0_2$ emissions will be lower if the treatment is carried out offshore.

7.5.2 Oil Discharge to Sea

Both the CRI and "Skip & Ship" solution avoid the discharge of oil to sea. On the contrary, offshore cuttings discharge after TCC treatment will include oil due to the oil which adheres to the solids after treatment. Assuming that the median value for oil on powder (0.026%) calculated in section 6.1.2 is valid; 1.9 tons of oil will be discharged as a part of the 7339 tons of cuttings.

The base oil used on the Martin Linge field is Total's EDC 99 DW oil. Its environmental soundness can be summarized as non toxic for aquatic organisms, highly biodegradable and it does not contain benzene or PAH (Total_2, 2014). In fact, it is completely degradable during 28 days after discharge. Therefore no effects of oil discharge are expected.

7.6 Evaluation of Cuttings Handling Solutions

The best cuttings handling solution needs to be chosen based on Health, Safety & Environment- (HSE), cost-, and operation reliability-considerations.

CRI has the advantage that it can be carried out regardless of the weather condition and does not require crane lifts. Thus, it is a safe cuttings handling option. The cost difference between CRI and the other solutions shrinks with increasing well numbers. Nevertheless, the cost is expected to be unreasonable high in comparison with the TCC-, and Skip and Ship- solution. Problems with leakages and plugging of the injection well might require remedial work and result in increased cost of CRI. In case of the Martin Linge field, the expected amount of cuttings is larger than the injection capability and part of the cuttings would need to be shipped to shore for treatment and final deposition. The environmental impact comes mainly from the waste generation and emissions during the drilling/plug & abandonment of the dedicated CRI well. The emissions due to this process alone are expected to be of greater magnitude than the Skip and Ship or TCC solution which are to be preferred.

Skip and Ship solution is logistical demanding and weather depending. This might lead to operation stops when all skips on board are filled and can't be replaced due to a) poor logistical planning , b) offshore crane limitations as a result of wind or c) the supply boat's heave. Delays of each kind are undesirable since the daily costs continue to run while incomes from the field are postponed due to later production start. Therefore this solution might turn out more costly than the offshore treatment of cuttings with the TCC. Another disadvantage is the high number of crane lifts which imply an HSE risk regarding falling objects and workers getting caught between skips. In the case of the Martin Linge field, the emissions of the skip and ship solution are higher than those implied in the TCC offshore treatment due to a less effective onshore TCC unit and the transportation of the cuttings.

The TCC offshore treatment avoids the problems faced in the Skip and Ship solution since the cuttings are transported by blowers and the treatment capability is unaffected by harsh weather conditions. Taking the value of recovered oil into account, the treatment cost is nearly the same for the TCC and Skip and Ship solution. If the TCC offshore cuttings treatment prevents weather related drilling stops during the drilling campaign, it might turn out as the cheapest cuttings treatment option. No negative environmental impact is expected due to the discharge of oil adhered to cuttings since the base oil is non toxic for aquatic organisms, highly biodegradable and does not contain benzene or PAH. The discharge of the cuttings particles itself is not expected to have an accumulating effect on the water column due to dilution and the effects of siltation will be limited to the area with highest sedimentation of processed cuttings. The environmental risk of the discharge of TCC treated oily cuttings is comparable to the risk implied in the discharge of water based cuttings and is thus acceptable.

7.7 Best Cuttings Handling Solution for Martin Linge

The TCC is the best cuttings handling solution for the Martin Linge field development regarding HSE-, cost and operation reliability considerations. Hence, Total E&P is willing to implement the TCC technology and taking the necessary steps.

7.8 Recommendations regarding Implementation of TCC

It is recommended to gather data from the TCC treatment and samples of both treated cuttings and recovered water should be taken. This information is to be used together with the data from a dedicated monitoring program to verify that the environmental risk of oil contaminated cuttings treated with the TCC is comparable to the environmental risk of cuttings that are contaminated with WBM. On top of that, the data is to be used to improve the treatment process.

7.8.1 Data and Sampling Requirements during Operation on NCS

The TCC technology is field proven and the analysis of the presented data in section 6.1.2 showed that both average values for oil in water and oil on powder are well below the limit set for direct discharge to sea.

The oil in water level after treatment is closer to the allowed maximum than the level of oil on dry powder and requires special attention. For guaranteeing that no water containing more than 30mg of oil per liter is discharged, a continuous measuring system could be implemented. In case a higher value of oil in water would be measured against all expectations, the discharge could be prevented and further cleaning measures taken.

For the oil on powder sampling, two samples taken per every third hour of treatment are deemed to be sufficient. One sample will be directly analyzed offshore with help of a transportable InfraCal TOG/TPH analyzer which is using an infrared analysis method to determine the amount of oil on powder (Wilks Enterprise, 2009). The detection limit is 2ppm and the measured value has an uncertainty of +/- 1ppm. The second sample will be stored for eventual third party analysis at a later stage. It is important to document the results of each single analyzed sample to enable proper data analysis. These measurements are to be monitored and the results analyzed to verify the TCC's treatment efficiency. Other data related to the cuttings to be processed is to be collected to allow better understanding of the treatment process. The solid/water/oil ratio and feed temperature are of interest for later analysis. During the treatment process, data as the treatment rate and average energy input is to be logged. The data of the cuttings to be processed, treatment process and data from the analysis of the processed material can be used to optimize the treatment efficiency and update the PLC controller.

7.8.2 Monitoring Program and Environmental Risk Evaluation

To verify that the environmental risk of oil contaminated cuttings which have been treated with the TCC is comparable to cuttings that are contaminated with WBM, it is desirable to establish a monitoring program at the Martin Linge field.

Since the production drilling permit including offshore discharge of TCC treated cuttings has not been granted yet, Total E&P has not started with the development of a tailored monitoring program that shall gain information about the environmental effects of TCC treated cuttings discharge to sea. Given that this operation will be performed for the first time in Norway, it is recommendable to establish the monitoring program in cooperation with NOROG and other interested operators so that quality assured information about the TCC offshore treatment is available for future use on the NCS.

During operation, the particle size, volume of oil and amount of cuttings discharged should be recorded for later evaluation.

After obtaining treated cuttings from the first well, ecotoxicological tests are considered to be performed on Corophium, Skeletonema and Acartia and the results could be compared to the findings of Aquateam COWI's report: Karakterisering av varmebehandlet oljebasert borekaks.

Taking the result of the ecotoxicological tests into account, a new environmental risk evaluation should be made. Further mesocosm studies are advisable to be performed during the drilling campaign.

Samples taken of the sediments and fauna should be compared to those taken during the law imposed environmental background analysis performed by Unifob in 2008. In this study, the sediments and fauna of the Martin Linge field, former Hild, have been analyzed among others (Unifob, 2008).

7.9 Implementation of TCC

The feasibility of the TCC's implementation at the Martin Linge field is investigated. Before the TCC can be installed, the production drilling permit for the Martin Linge field needs to be acquired. The performed site survey at the rig illustrated that the TCC can be installed and necessary preparations were identified.

7.9.1 Application for Production Drilling Permit

Total E&P is intending to clean oil contaminated drill cuttings with the TCC. The planned offshore discharge of treated cuttings was included in the application for a production drilling permit and is currently evaluated by the Norwegian Environment Agency (Miljødirektoratet, 2013). A production drilling permit might be issued with reference to the Pollution Act and environmental evaluations. This permit is necessary before any drilling operation can be started at the Martin Linge field.

After the application was handed inn, a public notice raised awareness of the planned activity. The public was invited to comment on the planned activities and the received responses are considered in the evaluation of the production drilling permit. Summarized responses from e.g. the Institute of Marine Research, Norwegian Fishing Vessel Owners Association and WWF are presented below:

- Claimed lack of knowledge about impact on environment
- Concerns about influence of discharged material on marine organisms
- Desire to ban any discharge of treated oil contaminated cuttings to sea
- Skepticism regarding TCC as best treatment option

To date (27.05.14) the application's approval is still pending.

However, preparations for both approval and denial have to be made due to long lead items, necessary customization and certification of equipment.

7.9.2 Installation of TCC on Mærsk XLE Jack-Up

After a call for tender, Total E&P awarded the waste management and associated services contract to TWMA Norge.

7.9.2.1 Site Survey

To clarify if the TCC system and related equipment could be installed on the Mærsk Intrepid rig which is under contract to drill the wells on the Martin Linge field, Total requested TWMA to perform a site survey in September 2013 (Reid, 2013). This was necessary since the exact position of this cuttings treatment equipment was not considered in the original plans for the rig build.

The Mærsk Intrepid is a jack-up rig developed for ultra-harsh environment which is being built at the Keppel Fels Shipyard in Singapore. The planned delivery is in June 2014 and according to plan, the installation of the TCC system shall take place at the Westcon Ølensvåg yard.

During the survey TWMA focused on the location and type of existing drill cuttings equipment, contingency equipment and utilities to determine the ideal location of the TCC-, and CST-unit keeping the limited space, structural loading limits and generated engine fumes in mind.

The existing drill cuttings equipment is located inside of the cantilever. Currently, there are six shale shakers installed which move the cuttings to two screw conveyors. These go along three shale shakers each and transport the cuttings to a third screw conveyor which dumps the cuttings in two transition chutes leading to two air conveyors. Those have their distinct five inch line connected running along the low side of the cantilever for further transportation.

The needed utilities for the operation of the TCC can be found on port aft deck:

- Fresh Water supply for initial fill/periodic top ups of the cooling system
- Sea Water supply for cooling of process equipment and engine during operation
- Rig Air supply for pneumatically controlled valves, fire dampers, engine starters and air diaphragm pumps
- Diesel supply to engine (in case diesel driven TCC is used)

Furthermore, two five inch lines exist, mud return-, and slurry return-line, which can be connected to the TCC system to transport the recovered oil to a designated pit. The recovered powder and water can be mixed together with the sea water used for cooling the TCC system and be dispersed into the sea using an existing five inch line that ends close to the bottom of one of the jack-ups legs or the rigs main dump line which discharges 20-24 m below sea level and can be extended to a greater depth if needed.

On completion of the rig, there will be connections to the emergency shut-down system available which enables the direct shut-down of the TCC and its engine. Internet-, telecom-, and public address lines necessary for transfer of data, communication under operation and important announcements will be in place as well.

The structural loading on the main deck is limited to 4 tons/m^2 on plating and local stiffening and 2 tons/m^2 on girders.

The height of the equipment on deck is partly limited by the height of the cantilever since it cannot be restricted in its mobility.

In 2016 the field might be fully electrified and an electrically driven TCC is to be used. At the start of the drilling campaign rig power or an interim power generator has to be used for TCC power supply. An alternative is the diesel driven TCC.

Two options have been developed by TWMA which include the TCC, four CST's, a vacuum hopper, a vacuum unit and a generator. The difference is in the drive mechanism of the TCC which can be driven by electrical power or diesel. Although the electrical unit needs rig power or an interim diesel power generator, the conversation to shore power would be easier. Engineering work to exchange the drive system of the TCC could be avoided and an electric driven TCC is therefore the preferred option. The vacuum unit offers an alternative method of waste transfer in case when the primary rig equipment fails. The vacuum hopper will be installed on one of the CST's and allows collecting and dropping vacuumed material to the CST.

So that the TCC can process all the generated drilling waste implying drill cuttings and vacuum rig clean up, Mærsk is checking the feasibility to connect the existing rig vacuum system with TWMA lines.

Based on this information, TWMA proposed to transfer oil contaminated cuttings from the existing five inch lines under the cantilever via flexible hoses to a primary cutting storage and transport tank (CST) with help of a diffuser box. The flexible hoses will be tailored for different positions of the cantilever with regards to the fixed primary CST. In total, there will be four CST's installed to avoid limitations of the ROP during drilling of 17 ¾" well sections. Two of them will be placed permanently under the cantilever together with the TCC. The deck space under the cantilever has limited crane access and is therefore well suited for the installation of long term equipment. The other two CST's will be situated on the starboard area when needed and can be dismounted to free additional deck space. In the case of insufficient storage capacity, a flexible hose can be connected to one of the CST's and transfer waste via the Bulk transfer station to supply vessels. If the treatment lacks mud additions, the simultaneous position of the TCC and flow line under the cantilever enables the input of mud into the process.

To conclude, the installation and use of the TCC on the Mærsk Intrepid rig is possible. The final proposed drill cuttings handling is visualized in Figure 15:

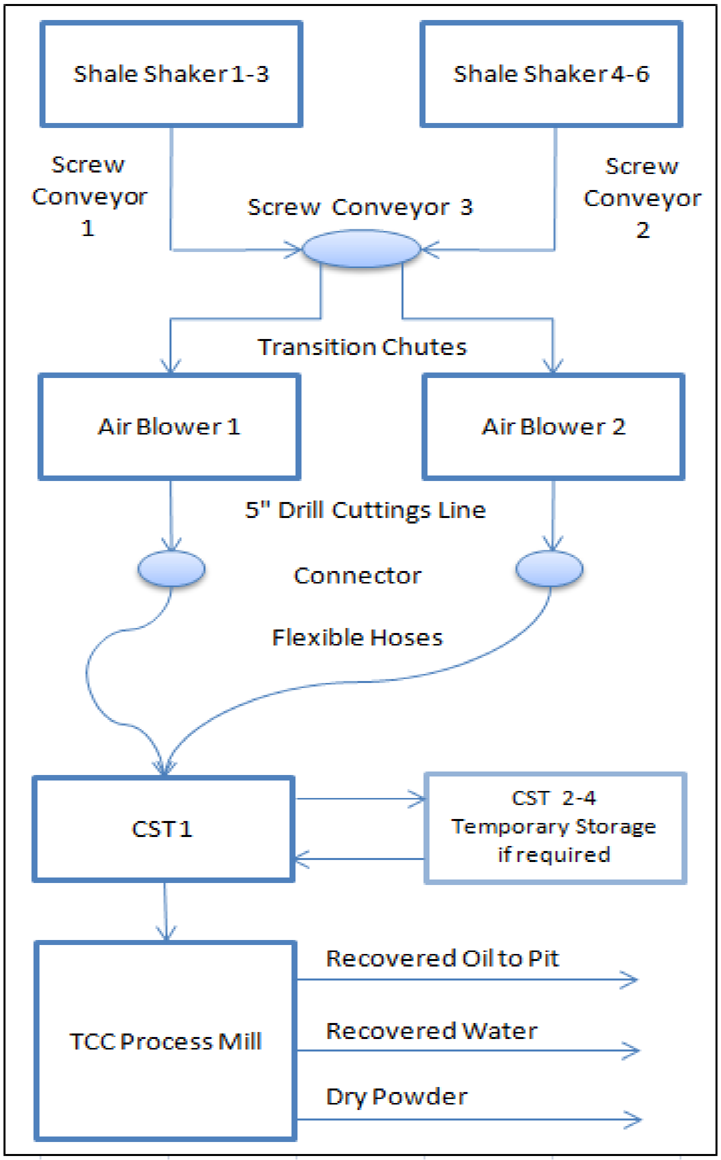

Figure 15: Block diagram of Cuttings Handling at Martin Linge

7.9.2.2 Preparations

Before the TCC unit can be installed on the Mærsk Intrepid rig in accordance to the plan proposed in the site survey, several preparations have to be made. These comprise the customization of the TCC unit, its electrical drive, CST's and their compliance with governing law.

The power supply of the TCC during the start of the drilling operation could be covered by rig power or a designated power generator. The possibility of rig power supply was investigated and it was concluded that only minor modifications on the existing rig electrical system would be required. Therefore the rig power was chosen for the initial power supply. At a later stage of the drilling campaign, shore power might be available. Therefore the design of the electrical drive system needs to be compatible with both the rig-. and onshore- power supply. Thereby modifications for switching between the different power supplies are avoided.

The maximization of deck space utilization required the TCC and two CSTs to be placed under the cantilever. The standard TCC unit with its height of 4.35m and CST are too tall for being placed as planned. The maximum allowable height which avoids restrictions of cantilever movement is 3.8 m. Engineering work needs to be performed to reduce the height of CSTs and to place the mill and related equipment in modules which fit in place. These adjustments are not allowed to complicate the maintenance and operation of the equipment.

All offshore service modules need to satisfy the governing law. DNV has been engaged to guarantee the compliance of the planned TCC unit and CSTs with valid standards and to certify them for use on the NCS. To enable the certification, both the TCC and CSTs need to be designed following the requirements stated in DNV's standard for certification No. 2-7.2. (DNV1, 2013).

These include:

- Structural technical requirements
- Safety related technical requirements
- Ignition prevention
- Fire and Gas detection, Passive fire protection and Fire Fighting
- Communications
- Escape routes
- Heating, ventilation and air conditioning

DNV will perform design assessment, production inspection, testing, plating and marking of the units. At the end of the certification process DNV will issue an “Offshore service module certificate” which documents that the units are certified for offshore use.

7.9.2.3 Installation and Testing

As soon as the discharge permit is granted, the TCC system shall ideally be installed at the Westcon Ølensvåg yard. Experience has shown that the rig up of the TCC system is easier performed in a dock than offshore. In case of later installation the system is designed to be bolted in place in order to avoid hot work on installations which are in operation. The testing and commissioning of the TCC unit will be prior performed at TWMA’s base in Peterhead, UK.

Chapter 8: Discussion

In this chapter the issues addressed in the introduction are discussed in view of the information presented in chapter 6 and 7.

Regarding the qualification of the TCC there were 3 issues addressed. The first issue is the question whether or not the TCC treatment is in compliance with regulations on the NCS. The Activity Regulations for the oil and gas industry states that (1) cuttings, sand and solid particles should not be discharged when the content of reservoir oil, other oil or base oil of the drilling fluid is higher than 10gr per kg of dry mass and (2) the oil content in discharged water shall be as low as possible and not overcome 30mg oil per liter in average during a month. The analysis of samples taken after the TCC treatment of 37000tons of cuttings showed that the maximum value of oil on solids was 1.75g per kg and the mean value was 0.33g per kg. This result is consistent with the result presented by Kirkness et al. who specified the typical value of oil on solids to be less than 1g per kg. Regarding the oil in water the measured maximum value was 21.4mg oil per liter and the mean value was 14.1g. Thus, the TCC treated cuttings and in the process separated water are in compliance with the governing regulation.

The second issue covers the real treatment capacity of the TCC. The supplier states that the 945kw TCC has a capacity of 4000 – 6000 kg/h while the observed values in a field case were in the range of 5220 – 7120 kg/h. This indicates that the TCC might have a higher treatment capacity than expected. The detailed discussion of this case is performed in section 6.1.1. One explanation for the deviation is that the cuttings have been treated with the TCC directly after generation and did not cool to ambient temperature before. Thus, less heat was required to evaporate the contained oil and water. Furthermore, the steam stripping effect contributes to the high treatment capacity.

It implies that the removal of the oil can be performed at lower temperatures than the maximum evaporation temperature of the contained oil. As stated earlier the supplier might be using a conservative approach of capacity estimation in order to ensure its contractual commitments. In reality higher treatment rates could be obtained, especially when the cuttings were treated offshore. This is favorable for the TCC offshore treatment solution. However, this conclusion should be quality checked when more operational data is available since the analysis of one field case has limited explanatory power.

The third issue deals with the environmental impact of the TCC treatment. The treated solids can contain oil, PAH and heavy metals which might have a negative impact on the environment. To evaluate the impact of onshore disposal of TCC treated cuttings, several leaching tests have been performed. Measured values of chloride, fluorine and dissolved organic carbon exceeded set values for land deposition. Therefore a risk evaluation regarding the disposal environment should be performed when choosing a suitable disposal place. Offshore the environmental harm might arise from increased particle content in the water column, sedimentation on the seafloor or by leaching oil, PAH and heavy metals to the water column or sediment pore water. Due to dilution the environmental harm resulting from the offshore discharge of treated cuttings is expected to be limited. The environmental risk is comparable to the risk implied in the discharge of cuttings contaminated with water based mud. If the used base oil is non toxic for aquatic organisms, highly biodegradable and does not contain benzene or PAH, no effects due to oil discharge are expected. Regarding CO_2 and NO_x emissions, the TCC treatment generates fewer emissions than CRI due to emissions connected to the drilling process of a dedicated well. Whether the TCC treatment on-, or offshore should be chosen to minimize CO_2 and NO_x emissions depends among others on the distance to shore, the energy supply of the TCC unit, the amount of cuttings and weather conditions. In the case of the planned cuttings handling at the Martin Linge field, a rough calculation of the CO_2 emissions showed that the offshore TCC treatment is to be preferred compared to onshore TCC treatment. To sum up, the environmental impact of the disposal of TCC treated cuttings is acceptable and might be less significant than the impact of particle discharges from other industries. To set the planned discharge of 7339 tons treated cuttings at the Martin Linge field into perspective, it might be appropriate to mention the planned yearly discharge of up to 2 million tons of crushed rock into the Repparfjord by the Nussir mining company (Rushfeldt, 2013).

There were two central issues with regards to the Martin Linge field development. The first issue to be examined is the cuttings treatment at the Martin Linge field. In the discussion performed in section 7.6 it was shown that the TCC is the best treatment option due to following reasons:

- Avoids crane lifts during cuttings movement, thus no risk of falling objects
- Cost similar to skip and ship or cheaper
- Environmental harm is expected to be limited due to dilution of discharges
- High operation reliability
- Recovered oil can be re-used as base oil
- Unaffected by harsh weather conditions

Even though experience gathered with the TCC system justifies the expectation of high TCC operation reliability, a preventive maintenance program has to be implemented. Furthermore, a contingency plan has to be in place since the cuttings treatment is critical for the drilling process and the TCC needs to be operative especially during the fast drilled 17 ½” sections. Bulk Transfer, interim storage of cuttings in the CST’s and transfers to supply vessels via hose for shipment to land, is the preferred contingency option.

The second issue is concerned with the implementation of the TCC technology on the Mærsk Intrepid rig which is in charge of drilling the wells at the Martin Linge field. The performed site survey confirmed that the implementation is possible. The installation is planned under the cantilever of the jack-up in order to optimize space utilization. This requires customization of the system due to height limitations. Both utility supplies and connecting points for cuttings/mud transfer are available. The TCC engine will be designed to run both on generator and shore power. The change to shore power will make the TCC treatment more environmental friendly since it implies a cut in emissions from the treatment. Further the unit will need to be certified before it can be installed. Since it is custom build and the requirements for certification are known, this process does not prevent the TCC implementation.

The only remaining obstacle for the implementation is the pending approval of the production drilling application by the Norwegian Environment Agency.

Chapter 9: Conclusion and Recommendations

The aim of this thesis was to introduce and qualify the Thermomechanical Cuttings Cleaner technology for offshore treatment of oil contaminated cuttings on the Norwegian Continental Shelf with particular reference to the Martin Linge field development. Even though several papers described the TCC technology and its development for offshore use, detailed information about the TCC's efficiency, real treatment capacity and environmental considerations was missing and required further investigation because of the planned implementation of the TCC cuttings treatment at the Martin Linge field. The addressed issues and answers are presented below:

1. Is the TCC cuttings treatment in compliance with the regulations at the NCS?
   The field data analysis in section 6.1.2 showed that the TCC treatment meets the requirements set in the regulations. The maximum values for oil on solids and oil in water after treatment were measured to be 1.75g per kg or 21.4mg per liter respectively while the regulation sets a max value of 10g per kg or 30mg per liter.
2. Does the theoretical treatment capacity of TCC match the observed values?
   The observed treatment capacity surpasses the supplier stated treatment capacity. While the supplier states that the 945kW TCC can treat 4 – 6 tons/hour the observed treatment capacity was between 5.2 and 7.1 tons/hour. This result is in favor of the TCC technology and is sufficient for offshore cuttings handling.
3. Is the environmental impact due to TCC cuttings treatment acceptable?
   Studies performed on the environmental impact with focus on (a) onshore deposition of treated cuttings, (b) offshore discharge to sea of TCC treated cuttings and (c) treatment related emissions concluded that the environmental impact of the TCC treatment is acceptable.

Issues addressed with particular reference to the Martin Linge field development:

4. Is offshore TCC cuttings treatment the best option for the Martin Linge field?

   The comparison between TCC, CRI and Skip & Ship cuttings handling solutions performed in section 7.6 illustrated that offshore TCC treatment is the best option for the Martin Linge field development with regards to HSE-, cost and operation reliability considerations.

5. Can the TCC technology be implemented on the Mærsk Intrepid jack-up?

   The performed site survey at the Mærsk Intrepid jack-up and ongoing preparations presented in section 7.9 showed that the implementation of the TCC technology is feasible.

In view of the information presented in this thesis, the author advises to grant the production drilling permit for the Martin Linge field. It has been shown that the TCC qualifies for offshore cuttings treatment on the NCS and the feasibility of TCC implementation was illustrated. A pilot TCC treatment could prove that the TCC is to be considered as best available technology for offshore oil contaminated cuttings treatment and enable the implementation of this cuttings treatment technology for further projects in the future.

The author recommends (1) the establishment of a suitable monitoring program in cooperation with NOROG and other operators to guarantee quality assured information about the TCC offshore treatment and (2) to continue research about alternative use of TCC treated solids to improve the waste management. One potential use for the solids is as substitution for bentonite in spud mud. This option is currently (spring 2014) being researched by Farid Taghiyev in his Master thesis: *Application of Thermo-Mechanically Treated Drill Cuttings as an Alternative to Bentonite in Spud Muds*.

Appendix A

Simplified TCC Control system

In this Appendix a linear control system as illustrated in Figure 16 will be used as basis for the development of a possible TCC control system. This is done for comprehension purpose only. Control engineering deals with establishing a reference value for a system and keeping a process value as close as possible to it (Nygaard, 2013). For this purpose a programmable logic controller PLC is used which is an industrial computer system.

In the illustrated control system, both feedback-, and feed forward-control is applied. The feedback consists of the measured value y which is reported to the error detector. It calculates the error e through subtracting the measured value y from the reference value r and sends an actuating signal to the feedback control element (Sivanagaraju, 2012). This signal is then manipulated to generate a control signal which will steer the control value u. Feed forward control is improving the control of the system through compensating the actuator u for known disturbances d, and changes in reference level r (Nygaard, 2013).

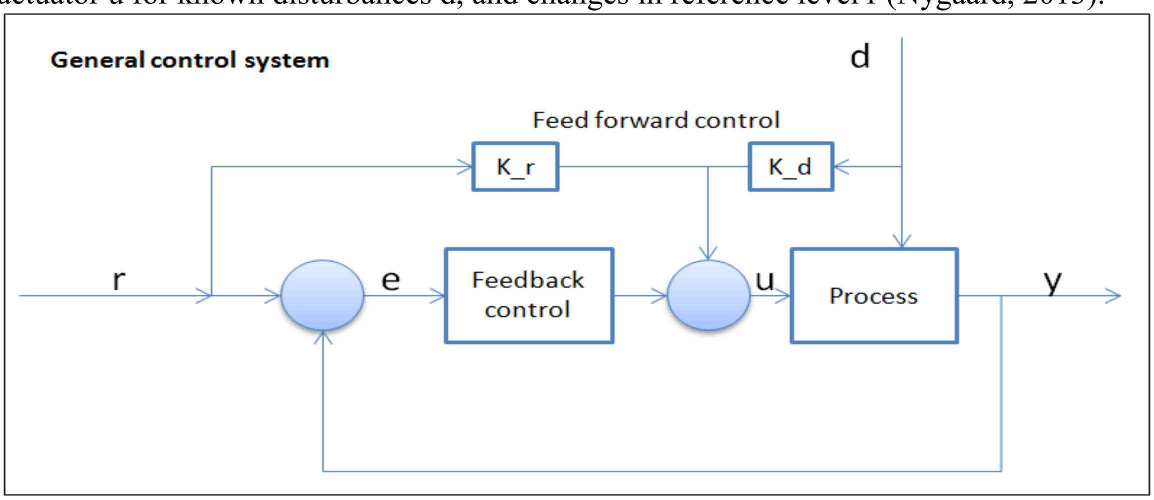

Figure 16: The control system terminology (Nygaard, 2013)

The development of the simplified TCC control system is based on personal communication and information gathered during a field trip. The TCC control system has several inputs which vary and affect the treatment capacity.

- Mechanical energy supply. The energy is converted to heat in order to vaporize the liquids contained in the cuttings.
- Oil, Water and Solids Ratio of Cuttings. Changes in the cuttings composition lead to different energy demands due to the different specific heat capacities of oil, water and solids respectively. This is a function of the setup of solid control equipment, origin of the cuttings, usage of drill mud and further variables.
- Temperature of cuttings feedstock. Temperature changes will lead to a different energy demand.

All these factors can disturb the process and will be displayed in Figure 17 as disturbances d. Information gathered is fed into the TCC control system for process optimization purposes with regards to a given reference level r of process temperature and load on the drive system which steer the cutting cleaning process.

If the temperature in the mill is increasing and will soon reach the reference level, the PLC will activate the feed pump so that the injected cuttings decelerate the rise in temperature. Too high temperatures can degenerate the oil and must be avoided. When the temperature rises to a level higher than the set point, the feed progressively increases in order to achieve a drop in temperature. While the temperature is decreasing and approaches the set point, the pump reduces the supply of cuttings in a progressive manner.

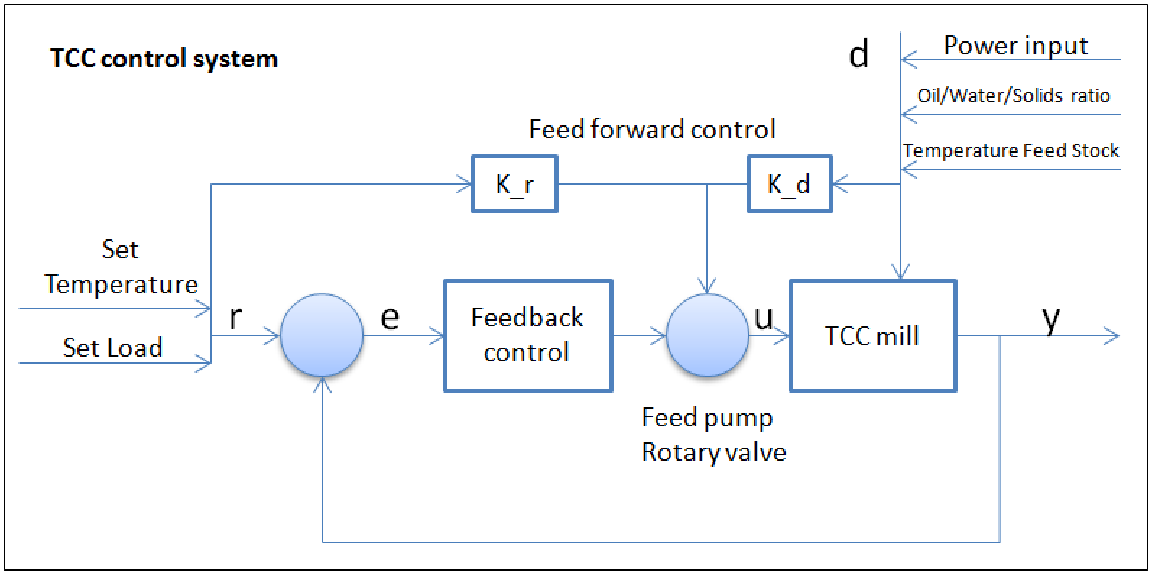

Figure 17: Block diagram of simplified TCC control system

Where the control value u comprises the feed pump and rotary valve, the disturbance d comprises the power input,oil/water/solids ratio, temp feed stock and power input, and the reference value r comprises the set temperature and set load.

The load on the drive system automatically increases when material is supplied to the mill. When the load approaches a certain level r, a rotary valve installed on the mill is activated by the PLC to eject a part of the material and decrease the load. A rotary valve is a device which can discharge bulk powders through rotation of a multi-vane rotor (Blackmore, 2014). It maintains an airlock and thereby acts as a barrier against explosions.

As the load increases towards the reference level, the PLC activates the rotary valve which will progressively eject more material through an increase of rotation velocity. When the load has passed the reference level and starts dropping, the rotation speed of the valve will decrease in a progressive manner. If no disturbances are present, the PLC will enable a stable temperature through a stable feed rate. The rotary valve will as well settle at a stable rotation speed and maintain a stable load.

The PLC system ensures proper treatment through taking the mass balance approach into account. Both the feed into the mill and the mass contained should be monitored at each time of the process. Together with information about the water/oil/solids ratio this information could be used to prevent oil containing solids to be ejected.

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