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The Fate of Waste Drilling Fluids from Oil & Gas Industry Activities in the Exploration and Production Operations

James Njuguna[a,b*], Shohel Siddique[a], Lorraine Bakah Kwroffie[a], Siwat Piromrat[a], Kofi Addae-Afoakwa[a], Urenna Ekeh-Adegbotolu[a], Gbenga Oluyemi[a], Kyari Yates[c], Ajay Kumar Mishra[d,e], and Leon Moller[f]

[a]Advanced Materials Research Group, School of Engineering, Robert Gordon University, Garthdee Road, Aberdeen AB10 7GJ, UK
[b]National Subsea Centre, 3 International Avenue, Dyce, Aberdeen, AB21 0BH, UK
[c]School of Pharmacy and Life Sciences, Robert Gordon University, Aberdeen AB10 7GJ, UK
[d]Academy of Nanotechnology and Waste Water Innovation, Johannesburg, South Africa
[e]Department of Chemistry, School of Applied Sciences, KIIT Deemed University, Bhubaneswar, India
[f]Law School, Robert Gordon University, Aberdeen AB10 7QE, UK

[1]Centre for Advanced Engineering Materials, School of Engineering, Robert Gordon University, Garthdee Road, Aberdeen, AB10 7GJ, UK
[2]School of Pharmacy and Life Sciences, Robert Gordon University, Aberdeen, AB10 7GJ, UK
[3]Nanotechnology and Water Sustainability Research Unit, College of Science, Engineering and Technology, University of South Africa, Florida Campus, Johannesburg, South Africa
[4]Law School, Robert Gordon University, Aberdeen, AB10 7GJ, UK

[*]*Corresponding Author Email : j.njuguna@rgu.ac.uk; Tel. +44 (0) 1224262304*

Abstract

The operational discharge from oil and gas exploration industry, accidental spillage, or improperly disposed drilling wastes has serious detrimental effects on human and environment.

The oil-based fluids wastes generated every year all over the world and remain a serious challenge in compliance with the requirements of zero discharge for the oil and gas industry. To meet the sustainable environmental regulations, a sustainable and effective waste management is critical and missing in the oil and gas industry. This work aims to provide the current state of art in drilling waste drill cuttings and drilling fluids. The overview of the drilling fluid waste is first provided followed by its characteristics, environmental concerned constituents in this waste stream are then explored while considering the current waste management efforts. Environmental and regulatory issues regarding drilling waste and the shortcomings of regulations are also discussed. The work sums up with a foresight on to the future trends on drilling waste management, opportunities and challenges ahead including the potential for recycling and re-use of drill cuttings for commercial products development. There opportunities for waste valorisation especially in raw materials recovery for valuable products utilisation rather than incurring burden to the environment.

Keywords: Drilling fluid waste, oil and gas, waste management, environmental persistent waste; waste regulations, enhanced oil recovery

1. Introduction

A drilling fluid is an essential part of drilling operation in oil and gas exploration operation to perform several functions such as removing and cleaning drill cuttings from the downhole, cooling and lubricating the drill bit, controlling the hydraulic pressure to protect well blowouts (Caenn et al., 2011; Fink 2015; Khodja et al., 2010). Although Oil Based Fluids (OBM) is environmentally hazardous, but due to its special features such as reliable shale inhibition, excellent lubricity, OBM is still an essential part of deep drilling in oil and gas exploration industries (Zhong et al., 2011; Liu et al., 2004; Gholami et al., 2018; Guancheng et al., 2016).

This deep drilling operation intensifies the pollutants addition in OBM which is considered a big concern for different stakeholders including spent OBM waste treatment services, local authorities, environmental activists and regulators involved in running waste framework directives (Veil, 2002; Force, 2009; Addy et al., 1984; Cranford and Gordon, 1991).

Drilling fluids can generally be divided into two types based on the continuous phase present that carries fluids constituents: Water-based fluidss (WBM) or Non-aqueous drilling fluidss (NADM)/ The choice of drilling fluid is dependent on the requirements of the well or area being drilled. Usually both WBMs and NADMs are used in drilling a well. WBMs are used to drill top sections of the well where pore pressure is low and NADM used for deeper sections where there are higher pressures or water-sensitive formations like shale (Tullow Oil, 2012). Water based fluids is composed of water mixed with bentonite clay and barite (to control fluids weight) and other additives. The composition of a typical water-based fluids is shown in Figure 3

Figure 3

On the other hand, the NADM is comprised of *a non-aqueous base fluid* such as diesel or mineral oil, water and other additives to obtain desired fluids properties. The relative percentage of the various constituents of NADM is shown in Figure 3. They can also be subdivided into OBMs, Enhanced Mineral Oil-Based Fluidss (EMOBMs) and synthetic-based fluids (SBMs). SBMs are often used during drilling of deep water and directional wells and are also known as low toxicity oil-based mud – they are an invert emulsion mud with synthetic oil as the external phase instead of oil. This has made SBM's more environmentally acceptable than oil-based muds for use in offshore drilling despite the high initial cost. NADMs can be sub-divide into group I, II and III NADMs based on aromatic hydrocarbon concentrations as shown in Table 1.

Table 1

The World Oil categorised drilling fluids into nine distinct types including dispersed freshwater, non-dispersed fresh water, saltwater, oil-based, synthetic-based, air, mist, foam, and gasified drilling fluid systems (SPE International; Drilling fluid types, 2015, Fink, 2015). These drilling fluids can be broadly classified as either liquid or pneumatic (Azar and Samuel, 2007). Drilling fluid selection in a drilling operation depends mainly on the geological formation information of the wellbore area. However, drilling fluids should possess various physical properties, such as thixotropy and rheology to make the drilling operation economical and sustainable (Besq et al., 2003). After the drilling operation, accumulated drill cuttings are suspended, assimilated, or dissolved in the drilling fluids without affecting its physical properties (Zhou et al., 2016). These fluids may contain a wide variety of dissolved minerals, dissolved and dispersed oil compounds, salts, metal ions, naturally occurring radioactive materials (NORM) and dissolved gases. To meet the environmental regulations, these fluids may need to be treated to a satisfactory level before disposing them in landfill. To identify the concerning constituents, present in waste stream and to design the effective treatment process, the accurate and detailed physical and chemical characterisations of wastes are necessary (Piszcz et al., 2014).

The pressure applied to penetrate Oil & Gas reservoirs during drilling causes pieces of the rock being drilled to fall to the bottom of the well bore. These pieces, referred to as drill cuttings, clog the well if not carried out. Drilling fluid, also known as fluids due to its consistency and appearance (Oil & Gas UK, 2015), is circulated in the well to transport the drill cuttings to surface. The composition of the drilling fluid enables it to perform this and other functional characteristics including cooling and lubricating the drill bit to reduce friction between the drill pipe and the well bore as well as controlling the formation pressures (Neff et al. 2000).

During the drilling process, fluids suspend drill cuttings during the drilling operations. Oil present in fluids contaminates cuttings; these cuttings must be cleaned or treated to meet regulations set for disposal and reuse of drilling fluids and cuttings. Drill cuttings, as shown in Figure 4 are fragments of rock removed from the wellbore by the drill bit. During drilling, fluids is circulated downhole through drill pipe and up through the annulus of the wellbore to maintain hydrostatic pressure and clean the hole, as shown in Figure 4.

Figure 4

They have variable physical and chemical characteristics depending on the rock formation that is drilled. The cuttings size ranges from clay to gravel (Reddoch, 2001) and can be categorised based on the drilling fluid they are dispersed in. They are oil-based, water-based and pseudo-oil-based drill cuttings. During exploratory drilling, analysis of drill cuttings gives an indicator of the depth of the reservoir, oil and water saturations, porosity and permeability, morphology of cuttings and mineralogy of the rock being drilled. They provide essential petrophysical information in the absence of cores, that helps characterise reservoirs. These include porosity, nuclear magnetic resonance, permeability, and transverse relaxation time (Denney, 2008).

Page et al. (2003) studied data from core samples, reporting that the cuttings particle size from the North Sea ranged from 10 µm to 2000 µm whilst cuttings from North West Hutton, United Kingdom ranged between 13 µm to 500 µm. Their study also showed that cuttings analysed were composed of claystone, sandstone, siltstone, limestone, fluidsstone and shale. They also contained high concentrations of quartz and barite. The presence of inorganic salts and halides, from drilling fluids, were detected from the study. Saasen et al. (2008) also carried out research on the characterisation of simulated drill cuttings that showed particles ranging from 1 µm to 15 µm composed of mainly dolomite that was determined with the use of Raman spectroscopy.

Oil and Gas Operators must strike a balance between reducing the environmental impact, maintaining borehole stability, and increasing the drilling efficiency. The drilling fluid in use can often be the most harmful for the environment though advantageous for drilling, preventing cracking and for a stable well that is safe to drill clean bore. However, these operational discharge from the oil and gas (exploration and production) industry, accidental spillage, or improperly disposed drilling wastes has serious detrimental effects on human and environment health.

When drilling fluids and cuttings during and after oil & gas exploration process are disposed on the ground surface, the liquid fraction of chemicals starts seeping through the ground and eventually these chemicals destroy the living organisms in the ground and pollute the groundwater (Caenn et al., 2011). Thus, waste drilling fluids and associated drill cuttings have become a major challenge in the industry for compliance with the requirements of zero discharge. Spent drilling fluids, drill cuttings and adhered oils are the key target ingredients to deal with drilling waste treatment operations in oil and gas exploration industry (Tuncan et al., 2000, Arce-Ortega et al., 2004) and forms the ‘waste drilling fluid in the context of this study. It should be noted that drilling fluid waste can also be characterised based on on the type of key components in the drilling fluid i.e., either water or oil. Following the processing at the waste treatment plant the products are liquid (water and oil), gases, and solid waste.

In early oil and gas operation industry, wastes drilling fluid were discharged after the drilling operation directly to the landfill site or ocean which caused serious environmental pollution to the dumping site and its surrounding zones (Muschenheim and Milligan, 1996, Sadiq and

Hussain, 2005, Sadiq et al., 2003). In 2008, the Waste Framework Directive 2008/98/EC, identified and declared certain specific ingredients in drilling fluids waste as hazardous chemicals for the sake of environmental pollution control measures (Siddique et al., 2017, Chen et al., 2007). However, since the EU Waste Framework Directive (WFD) came into operation, waste drilling fluids must be treated before disposal to landfill. This includes various levels of treatment to meet the threshold limit of different chemicals including oil content and salinity (Robinson et al., 2009, Kogbara et al., 2016, Mokhalalati et al., 2000, Fijał et al., 2015).

However, since the first well was drilled in 1964 in the North Sea, the 'cuttings' of drilled rock were removed from the well bore and deposited into the sea. As the number of drilling rigs increased and major findings of oil, such as the AMOCO's Montrose field in 1969, to Shells Brent field off Shetland in 1971, the volume of cuttings and harmful contaminants deposited into the sea significantly increased. Over the course of several years, more and more environmental concerns have emerged, and this waste stream remains a global problem. In the North Sea, the drill cuttings have been found in piles of 100-150ft high and 200ft across the floor bed and In some cases, mineral oil has been found 2.5 miles away from one offshore platform (Burke, 2017). More environmental impacts can be caused by the improper treatment of the fluids which include air pollution due to moving the fluids to dispose of properly. The energy required to move the multi-million tonnage fluids and the effects on the site for waste disposal has high carbon emissions. In addition, the oil-based fluids disposed of in landfill sites can cause problems of leakage into groundwater which means the water supplies can be contaminated with hydrocarbons. Unfortunately, the environmental impact of waste drilling fluids and their waste is poorly communicated to communities globally due to the presumed public resistance to oil field development and exploration activities and negative effect on oil and gas profits. Equally the current treatment processes are energy- and chemical-intensive leaving regulators with no practical solutions.

A wide range of treatment and disposal options are currently in practice (Ball et al., 2012). However, a technical advancement of process optimisation to intensify the recycling and recovery of resources is necessary. Although the separated liquids (water and oil condensates) are currently reused in drilling fluids preparation and in some cases, the oil is utilised to provide power for the other equipment on the platform, it is important to note that, well conditions may vary and thus further analysis may be required to determine safest recycle or disposal options (Ormeloh, 2014, Thermtech, 2012). In addition, there may be the need for supplementary treatment due to the heavy metal and large amount of salts present in the original drilling waste in certain cases (Holdway, 2002, Xu et al., 2018). This is imperative especially concerning the produced solids, which are currently being disposed of at landfill sites or recycled in the construction industry which may cause a serious threat to human life (El-Mahllawy and Osman, 2010, Pamukcu et al., 1990). Thermomechanical Cuttings Cleaner (TCC) technology process the waste drilling fluid to dispose solid residue in landfill sites after treating the drilling waste to legal requirements (THERMTECH, 2012).

Ormeloh (2014) observed that between 2006 to 2009 approximately 220 tons per of year of waste drilling fluids were produced. Over 50% of this amount was treated onshore (Figure 1).

Figure 1

In 2010, there was a 26% increase in the cuttings and fluids volume produced. This was attributed to injection well problems and the use of oil-based fluids (OBM) for drilling. Increasingly, more OBM is used for wells due to the need to drill longer and deeper resulting in oilier waste production. The American Petroleum Institute (API, 1995) reports that about 150 million barrels of drilling waste was generated from exploration and production operations in 1995. API further reported that 1.21 barrels of waste was generated for every foot drilled (API, 2000).

Further, Fractracker Alliance indicates within 6 months at 264 sites, the Cabot Oil Company of Houston, Texas produced over 30,000,000 gallons of liquid waste (i.e., produced fluid, servicing fluid, hydraulic fracturing fluid waste, and drilling fluid waste) and solid waste drill cuttings that totalled 47,156 metric tonnes (Mattern, 2014). If each site produced approximately the same amount of waste it can be assumed that a single site produces 178.6 tonnes of drill cuttings every 6 months. As can be seen on the Figure 2 diagram there are a number of possibilities for what can be done with these drill cuttings that range from using it as a fuel source to saving it and using it to tap the well once it is no longer being used.

Figure 2 provides the snapshot of typical destinations of the drilling fluid wastes. It illustrates current practices of the waste drilling fluids disposal routes and identified consequences of its improper disposal. Environmental impact related with discharge of waste drilling fluids to the seas and oceans are also identified. As shown of Figure 2, there are also current efforts to treat and use of the waste in the construction industry.

Figure 2

An improvement in the monitoring mechanisms of oil and gas waste could be attributed to the increase in oil contaminated cuttings in the UK in 2014. New players in the oil and gas industry such as currently do not actively monitor, and measure levels of waste produced.

There is currently a significant increase in the oil and gas production and exploration, especially for the in fracking activities. While the typical yearly production of drilling fluid waste from an oil rig is typically over 1600 tons of drilling fluid waste, and tens of thousands of wells drilled or planned annually globally, there is a need to improve the understanding on environmental implications. Various issues from disposing of drilling wastes such as contaminant discharge to the seabed (Figure 2) which have the hazardous substance and provide the potential environmental impact to the biological community exist (National Petroleum Council, 2011). This study therefore is focused on providing the current state of the art in drilling waste fluids along with associated challenges and technological developments. For the readers benefit, a brief overview of the drilling fluid wastes is firstly provided and followed on with detailed characteristics, environmental concerned constituents in this waste stream are then explored. A special attention is taken on the current waste management efforts while weighing in on the environmental and regulatory issues. The perspective is then provided, and conclusions drawn. For detailed mathematical descriptions and analytical modelling is mainly limited to standard process in the regulation or procedures, we refer the interesed readers to the excellent works of (Perry and Griffin, 2001); (Onwukwe and Nwakaudu, 2012; Charles et al., 2010); (Aquateam et al., 2014) among others for detailed modelling works.

2. Characteristics of drilling wastes

In the oil and gas industry, the well drilling process produces two main types of waste i.e. drill cuttings and used drilling fluid (spent fluids). The drilling waste can be classified as shown in Table 2.

Table 2

The physical composition of drilling wastes is mainly based on the type of drill cuttings produced. These cuttings are generally a reflection of the geological constituents of the sub-surface being drilled as well as the individual solid or chemical components originally contained in the drilling fluid (Melton et al., 2000, Siddique et al., 2018b, Siddique et al., 2020). In 1996, drilling operation was estimated to accumulate 7 million m^3 drill cuttings in North Sea between the years 1964 and 1993 and was projected to 12 million m^3 by 2000. Although the sources and compositions of wastes vary from site to site, their behaviour towards biological activities, cohesion with oil rich silts remain the same in nature. In a typical drill cutting pile, the pile is assumed to compose of 20-60% water, a bulk density of 1.6-2.3 g/cm^3, and a particle size ranging from 10μm to 2 cm (Breuer et al., 2004), (Breuer et al., 2008). Hudgins (Hudgins and Charles, 1994) reported the most comprehensive study to date available in open literature covering ten operating companies and six chemical suppliers in North Sea that obtained data (see Figure 5) on the specific types and quantities of chemicals used in their operation and identified the properties of these chemicals.

Figure 5

The survey also presented the discharge quantities and concentrations of chemicals during exploration and production activities performed by these companies in the North Sea. However, based on the Hudgins (Hudgins and Charles, 1994) survey results it can be summarised that the WBM accumulated more than three times the volume of discharge compared to OBM. It also noticed that the weighting agents, salinity, and bentonitic chemicals accumulated about 90% of the total WBM discharge. It should be highlighted that about 53% of chemicals that are used in drilling operation are discharged as wastes and thus cause the pollutants burden in the environment (Hudgins and Charles, 1994) (Marsh, 2003).

The chemical composition of drill cuttings at the time of disposal is an indication of the drilled sub-surface strata and concentration of the chemical components of the drilling fluid that remain attached to the cuttings. The temporal trends towards drilling activities provide important information on the long-term effects of drill cutting discharges on geochemical and hydrogeological conditions (Phillips et al., 1998). Findings from different groups confirm the presence of certain metals in drill cuttings and their potential effect on the environment. Among these metals Cd, Cr, Ni, As, Co, Cu, Pb, V, Zn, Al, Ba, Fe, Mn are predominant in drill cuttings (Grant and Briggs, 2002) (Pozebon et al., 2005).

During the period of 1981-1986, the average annual discharge of oil on cuttings to the Norwegian Continental Shelf (NCS) was 1940 tons and that was eliminated gradually by implementing different directives such as OSPAR Commission in OSPAR regions. In addition to oil on cuttings discharge, the amount of produced water (PW) discharge has increased significantly due to the well ageing and the rising number of oil and gas exploration and production fields. Large volume of OBM cuttings and SBM cuttings piled up in the seafloor before the regulations implemented in 1993/1996. It was estimated that about 45,000 m^3, a height of around 25m, and a footprint of more than 20,000 m^2 cutting piles are still present in the northern and central part of the North Sea. About 79 large (>5000 m^3) and 66 small (<5000 m^3) cutting piles have been identified in United Kingdom Continental Shelf (UKCS) and NCS. Further, a significant concentration of total hydrocarbons (10,000 to 600,000 mg/kg) exists in the North Sea piles today [Bakke et al., 2013].

The variation in the amount of drilling fluid that remains adhered to the drill cuttings at the time of disposal is influenced by the size of the cuttings. The smaller the size of cuttings, the harder it is to separate it from the drilling fluid. In addition to these metals derived from the drilling fluid and geologic formation being drilled, cuttings may also contain some petroleum hydrocarbons closely linked to that of the reservoir rock as shown on Table 3 (Phillips et al., 1998).

Table 3

Water based fluidss (WBM), with typical composition shown in Figure 5, which were the earliest drilling fluids had fresh water or sea water as the continuous phase with clay and a weighting agent being the main constituents (Neff, 2005). They are relatively less expensive and about 80% of all wells are drilled using WBM (SPE International. Drilling fluid types, 2015). Barite or alternative weighting material, viscosifier, typically bentonite and different salts are generally more abundant than the other additives. Other additives may be included to improve or alter the properties of the WBM depending on the well type and technical performance desired due to anticipated well conditions. Nonetheless, these additives are not in concentrated elevations and are generally considered less toxic.

In the 1960s, oil based fluidss (OBM) with typical composition, as shown in Figure 5 were introduced particularly to address drilling problems encountered with using WBMs (SPE International. Drilling fluid types. 2015). However, they are very similar to WBMs in terms of the main constituents with the only exception being the formulation of the continuous phase with refined petroleum products such as diesel. One of the major advantages of using OBMs over WBMs is its ability to inhibit most shales and this is due to the formulation of OBMs with calcium chloride brine (SPE International. Drilling fluid types. 2015). Similarly, barite and bentonite are also major constituents of OBMs and provide the functional properties as with WBMs. Again, other additives are included in OBMs based on the desired performance of the fluids and anticipated well conditions.

Though highly effective, the use of diesel given its high aromatic compound content gradually phased out as its disposal offshore was banned in most countries. This however led into the development of Low Toxicity Mineral Oils (LTMOs) with significantly reduced aromatic compound content, strict regulations regarding discharge of cuttings coated with LTMOs led to the development of synthetic based fluidss (SBMs) (HSE, 2000). SBMs only differ from OBMs due to the use of oils not directly derived from crude as the base fluid. They are synthesised chemical compounds and may be in the form of organic esters, ether, acetyl, olefins or a mixture of any two (Neff, 2005).

Like OBMs, SBMs contain barite, clay, water and other additives and are rather simple in composition. Even though SBMs are more biodegradable and considered less toxic as compared to the OBMs, they are usually recycled and not disposed off into the environment due to their high cost. At their end of life however, they are usually re-injected and where this option may not be technically feasible, they are transported to an onshore site for further treatment before disposal; depending on specific country regulations permit (Jacques Whitford Stantec Limited, 2009). Cuttings may also have a similar chemical composition to the type of pneumatic drilling fluid used. Table 4 presents typical compositions of the elemental composition of typical water-based drilling fluid.

Table 4

3. Environmentally concerned constituents in drilling waste

Discharge of oil-based fluids causes the largest risk of environmental effect on the sea floor than the discharge of water or synthetic based fluidss. This fluids increases the oil quantity at the sea floor and will decrease biological organisms in the close environment. Further, the increase in toxicity up the food chain is of critical concern as it poses serious threats especially to humans. Even at very low levels, ingestion of a COCs such as lead can have dire consequences. Even where the concentration of the chemicals of concern (COCs) are low, and toxicity considered negligible, accumulation and further increase in concentration may occur gradually up the food chain (Rana, 2008). This eventually leads to an increase in toxicity. A pinnacle case study on Lake Erie by Clark (2002) reported the accumulation of toxic COCs and increase in toxicity up the food chain as part of the environmental impacts of drilling fluids and cuttings disposal. Research by the U.S. EPA suggests that characteristic neurobehavioral development of children and variation in the levels of particular blood enzymes in humans may be as a result of the presence of lead in very miniscule concentrations in the blood (Rana, 2008). Again, the presence of certain polycyclic aromatic hydrocarbons (PAHs) and COCs including but not limited to barium, chromium and mercury, have carcinogenic effects on humans and other negative impacts such as irritation to skin and eyes as well as damage to brain and nervous system (Rana, 2008).

SBMs usually contain less than 0.001% of PAHs and OBMs containing diesel or mineral oil as a base fluid contain about 5% to 10% PAH diesel oil and 0.35% in mineral oil (BERNIER et al., 2003). The PAH present in OBMS with diesel and mineral oil as base fluids have the following toxic pollutants-fluorine, naphthalene, and phenanthrene, and non-conventional pollutants such as alkylated benzene and biphenyls (USEPA 2000). Lichtenberg et al. (1988) mentioned that hydrocarbons increase the toxicity of both synthetic and oil-based fluidss. He refers to work carried out by Kelly et al. (1987) on the increase in toxicity of drilling fluid by the addition of mineral oil. Meanwhile, Gaetz et al. (1986) reported on the correlation between increase in petroleum hydrocarbons and toxicity to mysids, a type of crustacean resembling shrimp which is sensitive to drilling fluidss. Given these observations, Lichtenberg et al. (1988) concluded that the factors such as source, constituents and age of the drilling fluid tested contribute to the toxicity of drilling fluids.

Further investigations into the toxicity of OBM on Mara and Microtox (bacteria), *Skeletonema costatum* (algae) and *Acarti tonsa* (crustaceans) was carried out by Aquateam et al. (2014). The study revealed that leachate (water that drains through soil or landfill and leaches out some of its composition) stifled growth of algae. The toxic effect of the leachate on algae was attributed to the presence of copper. However, it was noted to be less toxic to bacteria and lower for crustaceans. It was concluded that a discharge of OBM drill cuttings is moderately toxic to algae and less toxic to bacteria and crustaceans. However, even WBM cuttings with less hydrocarbon content may seriously affect benthic fauna by elevating oxygen consumption in sediments. The risk of drilling waste associated with WBM cuttings discharge to the ecosystem is presently considered low, but this statement cannot be verified from the published literature.

Soil contamination is hazardous to health and environment through its action on surface waters, ground waters and vegetation (phytotoxicity, bioaccumulation). Oil and gas industries, like other process industries, have a detrimental effect on environment (Khodja, 2010). The hazardous effect of the environmentally significant constituents in the produced drilling wastes is predominantly dependent on each constituent, its concentration at exposure, biotic environment at point of discharge and the duration of exposure. The typical type of drilling wastes and their potential constituents are (Onwukwe and Nwakaudu, 2012) For the WBM cuttings specific constituents include heavy metals, inorganic salts, biocides, hydrocarbons while spent WBM: Metals including heavy metals, inorganic salts, hydrocarbons, biocides, hydrocarbons and solid/cutting. On the other hand, OBM cuttings typical composition includes heavy metals, inorganic salts, hydrocarbons, solid/cuttings and their spend spent OBM constitutes of heavy metals, inorganic salts, hydrocarbons, solid/cuttings, BOD, surfactants. The waste lubricants is mainly composed of heavy metals and organic compounds.

Some of the metals' concentration are present in significantly higher than the naturally occurring concentrations of the sediments, which makes the disposal of these wastes a critical environmental concern (Onwukwe and Nwakaudu, 2012) (Grant and Briggs, 2002). Arsenic, nickel, copper, chromium, zinc, anthracene, diuron, fluoranthene, naphthalene, phenanthrene, and pyrene are considered as environmentally significant chemicals according to the literature (Pozebon et al., 2005; Bakke et al., 2013; Khodja et al., 2010 and Bignert et al., 2004).

Although the amount of drilling fluid constituents is very low, most of them especially heavy metals have a chronic effect on environment. The pollutants are nowadays categorised in two different groups of pollutants: List I and List II as shown on Table 5 according to European Council Directive 76/464/EEC (DIRECTIVE HAT, 1976).

Table 5

List I group are substances, which are toxic, persistent, and possess the bioaccumulation properties while List II is a group of chemicals, which have deleterious effect on the aquatic environment. However, list II pollutants can be confined to a given area and the pollutants concentration varies based on the characteristics and location of the water into which the pollutants are discharged.

4. Developments in Waste Management

To protect the environment and to recycle or to recover the useful compounds associated with this waste stream, different techniques have been applied in drilling fluid waste treatment operation including, solidification technology (Tuncan et al., 2000), the solid-liquid separation technology (Zhou et al., 2011), MTC (fluids transform to cement) technology (Nahm et al. 1993), incineration technology (Onwukwe and Nwakaudu, 2012) and some other thermo-mechanical treatments (Mokhalalati et al., 2000). These processes have certain advantages and disadvantages in respect to operational or treatment time, cost, space requirement and treatment efficiency. However, these processes are successful in protecting environment in some extent, but the detrimental effects of this waste on the environment are common and raising in concerning level (Ball et al., 2012). The management of OBM waste is an important issue since most of the hazardous chemicals associated with OBM waste exist, even in solid form which are disposed of in landfill sites (Welch et al., 2012; Hainey et al., 1999). Interestingly, this

OBM waste contains significant amounts of clay minerals and metals which attract the use of this waste in engineering polymeric nanocomposites applications (Siddique et al., 2019a Siddique et al., 2018a; Siddique et al., 2019b).

The amount of total petroleum hydrocarbon (TPH) associated with OBM waste is the key factor in handling OBM waste in oil and gas industry due to the restriction of disposing OBM waste containing more than 1% oil on residue (Perry and Griffin, 2001). Perry and Griffin (2001) identified the TPH content in OBM and associated drill cuttings by using gas chromatography which was 65,000 ppm. Furthermore, particle size analysis results were also presented in that study and the average particle size was 210 µm by using sieve method reported in that study. Although the study by Perry and Griffin (2001) presented the insight of characterising the OBM waste it was limited to identifying the nanoparticles content of the OBM waste. However, Gbadebo et al. (2010) investigated the elements presents in both oil based and water based fluids using atomic absorption spectrophotometry and the content of Fe, Ca, Mg, Cr, Pb, Mn and Ni were reported. Another study performed by Adegbotolu et al. (2014) also highlighted the presence of heavy and trace metals using ICPOES analysis of oil-based drilling fluid and cuttings.

Waste management has always been an intrinsic constituent in the exploration and production of oil and gas. In fact, Rana (2008) estimates that about 1000m^3-5000m^3 of drilling waste is produced per well. The waste management system implemented by operators significantly impacts environmental performance, capital and operational costs and corporate reputation of the organisation (Garland et al., 2008). However, it is important to note that an effective waste management system is a continuing process that involves revision of the existing system and implementation of new approaches to best manage produced wastes. Innovations in waste management practices have significantly reduced environmental impacts over the years.

Nonetheless, the preferred hierarchy remains first and foremost ‘Waste Minimisation’, followed by ‘Waste Reuse’ or ‘Recycle’ and lastly ‘Waste Treatment and Disposal’.

4.1. Waste Minimisation

The first approach to achieving waste minimisation is by source reduction to eliminate or reduce the amount of drilling waste generated to as minimal as possible. Drilling of wells was mainly vertical at the onset of the oil industry. This was due to the perception that oil or water wells were generally vertical. It wasn’t until the 1950s that horizontal drilling was introduced into the industry (Rabia, 2002). The main applications for horizontal drilling were mostly for low permeability reservoirs and reservoirs with gas or water conning problems. However, it became apparent that it was more beneficial to drill one horizontal well as opposed to several vertical wells for the same level of productivity. This in effect significantly reduced the volume of drilling waste that was initially being generated as operators started realising the benefits of horizontal well drilling. Limitations in the application of drilling horizontal wells led to the development of multilateral wells and subsequently directional drilling. The application of directional drilling has significantly improved environmental impact with regards to the number of central drilling facilities needed offshore. Moreover, the added advantage of drilling multilateral wells from the same starting wellhead certainly reduces the volume of drilling waste significantly (Veil, 2002).

The next approach in minimising drilling waste generated is by eliminating or reducing to as minimal as possible, the level of toxic substances produced during the drilling process. In principle, input to any chemical process has a significant bearing on the output of the process. Advancements in drilling fluids used as mentioned earlier on have contributed immensely to efforts in reducing negative impacts to the environment. Although SBMs are relatively more desirable, the chemical constituents of the additives used should have a balance between technical performance and environmental safety. Table 6 suggest some substitute materials that could be used as additives. To minimise waste, practices such as directional drilling, smaller hole diameter drilling and drilling techniques that use minimal drill fluid are adopted.

Table 6

The use of drilling fluids and additives that have lower environmental impacts on the environment are also essential to prevent the creation of further wastes.

Reusing or recycling drilling waste substantially reduces the volume of wastes that would have otherwise been in the "disposal stream". This has been achieved in several ways, including but not limited to reusing reconditioned fluids for other wells, using waste fluids produced from one well to plug or spud other wells, reusing the drilling fluids to make cement and use of produced cuttings as concrete aggregate or construction fill after filtering to remove the liquid fraction (Onwukwe and Nwakaudu, 2012; Veil, 2002). However, it is important to note that to reuse or recycle drilling wastes, careful consideration must be given to the chemical constituents to control the occurrence of further environmental safety issues.

4.2. Development in Treatment Process

In the early years of the industry, waste management practices were mostly in this tier. Onshore drilling wastes were predominantly disposed off on lease sites or on nearby roads. Apparently, not much thought was given to the impact of this on runoff or groundwater contamination (Veil, 2002). In times that are more recent however, regulatory bodies have placed formal guidelines and restrictions on onshore disposal options especially concerning the chemical constituents of the wastes and level of toxicity. Offshore drilling wastes on the other hand were generally discharged into the ocean. It wasn’t until the 1970s and 1980s that awareness of the negative impact this had on the local ecology became prevalent (Veil, 2002).

Presently, several treatment options are being used to not only reduce the volume of drilling wastes, but also the toxicity of the wastes to make them better suited for disposal. One of such treatment methods as shown in Figure 6 is the thermal desorption method.

Figure 6

As the industry progresses, there has been substantial improvements in the process used to effectively remove solids from spent fluids. These can be grouped into primary and secondary waste treatment systems.

The primary waste treatment system involves the use of solids-control equipment including shale shakers, hydrocyclones (such as desanders and desilters) and centrifuges (Jacques Whitford Stantec Limited, 2009) (Azar and Samuel 2007, Gatlin 1960). Spent fluids containing the drill cuttings is first passed through the vibrating shale shakers and as this happens, the drill cuttings are left behind on the screens of the shale shakers. In the early 1980s, most of the screens had a mesh size ranging from 60 to 80. Nonetheless, presently, some offshore rigs use screens with mesh sizes of about 150 thus significantly increasing the efficiency of the system (Clark, 1994). The spent fluids collected from this process is then reused for drilling operations. To increase efficiency, most operators use at least two shakers in addition to the hydrocyclones and centrifuges, both of which achieve the same goal of effectively removing the solids and recovering as much spent fluids as possible. Figure 6 provides the optimum cut off points with regards to the efficiency of this equipment and justifies their need in the waste treatment process.

The secondary treatment of the drilling wastes is aimed at removing the drilling fluid retained on cuttings before final disposal. Several secondary waste treatment methods have been used in the past with the most common methods are the cuttings dryers method and the thermal desorption method. However, the inability of the cuttings dryer method to achieve the OSPAR ROC limit of 1% puts the thermal desorption method at an advantage (Jacques Whitford Stantec Limited, 2009). Nonetheless, the significant energy requirements coupled with the vast floor space required and huge costs involved for successful use of this method limited its use to onshore only when it was first developed (Stephenson et al., 2004). This eventually led to the development of a thermo-mechanical cuttings cleaner system (TCC). Thermtech AS in Norway (Thermtech, 2012) first developed the TCC, which has been used both offshore and onshore. In recent times however, other companies such as TWMA (TWMA, 2020), MI-SWACO (Murray et al., 2008) and Halliburton (Ayapbergenov et al., 2017) have developed and improved on the mechanism involved in the TCC process.

4.3. Thermal desorption process using the thermomechanical cuttings cleaner (TCC)

Thermal desorption involves heating above the boiling point of volatile substances present in a material to separate them. This heating may be done indirectly with the use of external burners directly with internal burners (Charles et al., 2010). The volatiles (which are base oil and water for waste containing OBM) are reclaimed through fractional distillation. Base oils are recovered between 200 °C to 350 °C. Thermal desorption carried out between 90 °C and 320 °C is generally classed as Low temperature thermal desorption (LTTD) and is used for removal of volatiles and lower chain hydrocarbons. It is referred to as high temperature thermal desorption when carried out between 320°C to 960°C to remove higher chain hydrocarbons (Vertase FLI ltd, 2020).

According to (McGowan et al., 1991 and Troxler et al., 1993) thermal desorption was initially used for treating environmental waste in 1985. Murray et al. (2008) notes that, in 1990 thermal desorption was adopted for onshore treatment of drill cuttings due to its effectiveness in treating soils contaminated through industrial activity. The technology has evolved for use onshore and offshore. The thermal desorption process of the TCC is a non-oxidising friction-based technique that vaporises the volatiles and semi-volatiles in the waste stream by applying heat to the system. The high speed applied to the chamber containing the drilling wastes causes friction, which in turn generates the heat, needed to vaporise the hydrocarbons and other volatile organics. Generally, the light hydrocarbons and other volatile organics are extracted at low temperatures, usually between 250°C and 350°C, whereas the heavier compounds including the PAHs require temperatures as high as 520°C. The secondary waste streams resulting from this process include produced solids, water and oil condensates and particles size cut points for solids-control equipment are shown on Figure 7 (Jacques Whitford Stantec Limited, 2009).

Figure 7

The technology has been licensed to companies such as TWMA, Halliburton and Schlumberger. Halliburton named the equipment it developed with this technology as the Halliburton Baroid Thermomechanical Cuttings Cleaner, whilst TWMA named its equipment the TCC Rotomill. In a typical process, drill cuttings treated by thermal desorption are crushed and heated to vaporise liquids (oil and water) present. The vaporised liquids are essentially distilled and recovered. The recovered material from the TCC is water, crushed rock and base oil. The highest temperature generated in the mill is through frictional heat generated by particles (Aquateam et al., 2014). The TCC uses heat generated through friction by milling drill cuttings as the primary or only source of energy. The operating temperature for the TCC is between 250- 300 degrees Celsius. Keeping the temperature in this range avoids reduction in quality of the recovered base oil (Kleppe et al., 2009). The TCC process is shown in Figure 8. Larger particles are removed through filtering by a vibrating screen covering the hopper before entering moving to the hydraulic pump.

Figure 8

Waste is fed under pressure, usually from double piston pumps. Fine solid particles escaping as vapours are removed by the cyclone separator before entering the oil condenser. Recovered fine solids are added to the stream of recovered solids via a screw conveyor. The central unit of the TCC is the process mill. It is a cylindrical chamber (shown in Figure 8) with interior dimensions measuring 1 m long and 1 m in diameter. It houses a shaft with a series of hammers (shown in Figure 9 connected to an electric motor or a diesel motor and a series of hammers.

Figure 9

The TCC operates by the principle of conversion of kinetic energy from a motor to thermal energy through thermal desorption. Thereby separating the waste streams (water, fluids and cuttings) without destroying components of the waste (Thermtech, 2012). As shown in Figure 9 drill cuttings waste enters the TCC and the rotor (hammer arms) and stator with the aid of a pump move the waste through the system.

The rotor moves generating mechanical energy which is transferred to the materials in the TCC chamber. The rotor's agitated hammering on waste material fed into the system generates friction, causing heat that flash separates oil and water. Flash separated oil and gas escape through the vapour outlet and solids leave the mill unit through the solid's outlet. Dimensions of the TCC vary for both onshore and offshore use. TCC units are designed to suit the volume of waste to be processed. The TCC mill unit however normally measures 1m in length and 1 m in diameter. The average retention time for is between 6 – 12 minutes for solids and 15 – 30 seconds for oils. Expected quality levels for treated material from the thermomechanical cuttings' cleaner are shown Table 7.

Table 7

The residual oil, particles in recovered base oil, water content in recovered oil and oil content in water phase are all dependent on equipment maintenance and the quality of base oil used.

A flaw in the thermal desorption process is the resistance of movement of oil to surface caused by capillary forces. To counteract this effect, heating above the boiling point of oil is necessary to attain the required vapour pressure to extract oil from solids. Hydrocarbon extraction from cuttings is accelerated by increased contact area or increasing the retention time. However, longer retention times and elevated temperatures thermally degrade base oil. This led to the development of the TCC, which used less surface area and had a lower temperature requirement (Murray et al., 2008).

5. Environmental Regulations on Disposal

In the early years of the industry, the accepted practice was disposal of drilling wastes into the ocean, regardless of the type of drilling fluid used. However, as the industry evolved, research has increased awareness of the negative impacts of this practice on the environment. This buttressed the need for stringent environmental regulations with regards to disposal of drilling wastes. The prevailing environmental regulations in the industry were established over a period of years but has dragged its feet compared to waste management in other sectors. In brief, several international conferences have been held in general on environmental protection from the oil and gas industry. Some of these conferences were organised between the period of 1975 and 1990 and specifically deliberated on wastes associated with drilling operations, particularly drilling fluids (Clark, 1994). During this period, and subsequent interaction, the industry became familiarised with the capacity and competence of regulatory agencies, which further gave insight into the use and impacts of drilling fluids for both parties. Regulations pertaining to the management of drilling wastes differ from country to country and occasionally, regionally within a country. These regulations are also influenced by economic, social and political factors peculiar to the country (Garland et al., 2008).

Internationally, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal 1992 provides for the control and strict regulation of transboundary shipment of hazardous wastes in order to protect human health and the environment. In relation to the oil industry, Annex I of the Convention (which lists wastes to be controlled) includes waste oils, water/hydrocarbon mixes as well as several heavy metals, organic compounds, organohalogens and asbestos.

The main objectives of the Convention are to a) reduce transboundary movements of hazardous waste; b) to treat and dispose hazardous wastes and other wastes as close as possible to their source of generation; and c) to minimise the generation of hazardous wastes and other waste. The 1992 OSPAR Convention (which entered into force on 25 March 1998) is a regional instrument covering the North-East Atlantic, aims to prevent and eliminate pollution, and to protect the maritime areas against adverse effects of human activities including offshore oil and gas activities. OSPAR provides for detailed guidance on offshore installations, carbon capture and storage, offshore chemicals, and discharges. It prohibits the dumping of wastes from offshore installations. OSPAR Commission adopted several measures to reduce discharges from the oil and gas industry. For example, the OSPAR Recommendation 2006/5 on a Management Regime for Offshore Cuttings Piles aims to reduce the impacts of pollution by oil and /or other substances from drill cuttings piles, to a level that is not significant, on the basis of two thresholds: persistence over the area of seabed contaminated of in excess of 500km^2/year; and rate of loss of oil to the water column of greater than 10 te/year (OSPAR Commission, 2015).

On a regional level, the EU has been taking the lead in developing clear guidance to Member States on the protection of the environment from the oil and gas industry operations. Various EU Directives have been adopted on the protection of the environment and the management of waste. The 2006 Mining Waste Directive (MWD) 2006/21/EC was adopted on a European level to regulate the extractive waste (including drilling fluidss, drill cuttings, and well completion fluids) from drilling activities in Member States, including the UK. The MWD requires a Waste Management Plan for the management of extractive waste, not involving a waste facility, generated from onshore oil and gas prospecting activities of drill, core and decommissioning without well simulation for water-based drilling fluids (Environment Agency).

The Waste Framework Directive 2008/98/EC, which revised the Directive 2006/12/EC, brought legal changes to the list of waste and hazardous waste criteria based on the source and composition of wastes (Parliament E. Directive, 2008). In this amendment the source of waste is identified into 20 chapters (from 01 to 20) and the different types of waste in the list are fully defined by the six-digit code (first two digits is chapter heading and the rest four digits for identifying sub-groups). Based on this Commission Decision, environmentally significant and hazardous elements or compounds which are present in drilling fluid wastes are denoted by * mark in Table 7 (European Commission, 2014).

In terms of the Waste Framework Directive, waste is regarded as a valuable resource which can provide raw materials for sustainable growth in a low carbon economy. In terms of the WFD, waste means “any substance or object that the holder discards or intends or is required to discard”. The oil and gas exploration and production operations generate a significant amount of waste that must be disposed of safely. As was explained earlier, the wastes are generated at various stages of the industry and usually come in different states, i.e. solid and liquid, hazardous and non-hazardous materials. Over the years, the industry developed modern disposal and recycling techniques, including engineered landfill, incineration and recovery of waste oils, which resulted in better environmental performance.

The WFD therefore aims to optimise material productivity and to reduce reliance on consumption and disposal. The WFD adopted a waste hierarchy which prioritise how waste should be managed, i.e. prevention of waste and its potential harmful effects, the reuse of materials and the recovery and recycling of waste, with disposal as the least desirable option. Following the WFD, in Scotland, SEPA adopted key principles for the management and reporting of waste, which are: early engagement, WFD alignment, duty of care, improve waste inventory reporting, and active waste management planning.

In addition, country specific requirements for discharge of drilling fluids and cuttings also do play a role in environmental protection. For instance, in the United Kingdom the OSPAR2000/3 discharge regulation comes into play and compliance requires limit of less than 1% oil on cuttings and do advice on when to inject cuttings or return to shore and oil recovery. The OSPAR2000/3 regulation does not permit discharge of synthetic based fluids (SBM) cuttings offshore (DIRECTIVE HAT, 1976 and OSPAR Commission, 2015). However, Neff et al. (2000) argues that some of these metals (barium, chromium, lead and zinc) are highly likely to be present in concentrations significantly higher than the naturally occurring concentrations of the sediments thus disposal of wastes containing these is of critical environmental concern.

Some countries, including the UK, have well-established regulatory regimes, which include comprehensive environmental regulations, and competent regulators with clear guidance on the effective management of industry waste. Offshore emissions and discharges in the UK are regulated by the Offshore Petroleum Regulator for Environment and Decommissioning (OPRED), part of the Department for Business, Energy & Industrial Strategy (BEIS). All operators on the UKCS must apply for a permit for emissions to air or discharges to sea, and these must be reported to OPRED through the Environmental Emissions Monitoring System (EEMS). Companies are obliged to assess the potential environmental effects of their operations and put in place mitigation measures. These industry emissions and discharges monitored include produced water, chemicals, drill cuttings, greenhouse gas emissions, gas flared and vented, and the amount of waste generated by upstream oil and gas operations.

Most of the UK's oil and gas operations are taking place on the UKCS. Companies are permitted to discharge water-based fluid drill cuttings to sea because it poses a lower environmental hazard. Companies cannot simply discharge oil-based fluid cuttings to sea before treatment to reduce the oil-on-cuttings content to below 1 per cent of the total mass. As part of the overall permitting process for both oil and water-based drill cuttings, all operators are obliged to conduct stringent environmental assessments to determine the risks posed by cuttings discharged.

As established earlier, the mass of drill cuttings discharged to sea by the offshore industry is closely related to drilling activity. According to the OGUK, in 2017 there was an increase in drill cuttings discharged at 47,200 tonnes in comparison with the previous two years. In 2017, an overall 320 kilometres drilled on the UKCS represents 147 tonnes of cuttings discharged per kilometre drilled (OGUK, 2018). The OGUK established that of the 32,400 tonnes of cuttings coated with water-based fluids, less than 1 per cent were returned to shore for treatment and disposal, with the rest discharged to sea as permitted. Of the 39,100 tonnes of oil-based fluid cuttings, 54 per cent (21,000 tonnes) were returned to shore for treatment, down from 66 per cent in 2016. Around 15,000 tonnes were thermally treated offshore to reduce their oil content to below 1 per cent and discharged to sea; the remainder were injected into the reservoirs (OGUK, 2018).

In Scotland, the Scottish Environment Protection Agency (SEPA) regulates waste management activities in accordance with the Environmental Protection Act 1990. The Waste Management Licensing (Scotland) Regulations 2011 (WMLR) requires that waste management facilities are licensed by way of a Waste Management Licence. The Special Waste Regulations 1996 cover special waste (i.e. waste with hazardous properties which may render it harmful to human health or the environment). In general, the regulations imposed on drilling operations and disposal of wastes in any country generally follow results from analytical tests conducted on various samples and therefore depend on scientific works. Regulatory bodies with the sole mandate to carry out the analysis and present the findings and recommendations to the government usually conduct these tests. Government then approves the recommendations and pass them as legal regulations and guidelines within the industry. Contrastingly however, there are many instances where results from analytical tests conducted by independent research bodies do not correlate with that of the regulatory bodies. One of such instances is the independent study performed by EPA and API in 1986, on heavy metals, inorganics and organics present in drilling fluids, produced water and associated wastes. Both organisations performed laboratory tests on samples from the same field and even used considerably identical methods to analyse the results (Holliday and Deuel 1990). Holliday and Deuel (1990) carried out a statistical review of the sampling methods, analysis and results from both parties and presented their findings at a Society of Petroleum Engineers (SPE) conference in 1990. They concluded that in most cases, there was no correlation between the analytical results of both EPA and API with regards to the drilling waste samples; correlation between samples with regards to key elements such as barium, lead, chromium, pH etc. was not consistent; there was uncertainty as to whether results from a third laboratory will offer some form of correlation; and that the procedures used to analyse water samples could not be used to analyse samples that were either pit solid or pit liquid.

Also, another instance as elaborated on by Clark (1994), is the Mysid Bioassay Test, which was conducted on eight generic fluidss in the United States of America (USA) in 1986. The results of the 96-hour LC_{50} Mysid Bioassay Test led to a corresponding 30,000 ppm toxicity limit, which is still effective in the USA. However, the test results are highly inconsistent since results were based on 96 hours only and do not consider effects following a fluids discharge after days or weeks. These leaves room for an error margin to account for unforeseen events. Operators are thus able to comply with the regulation at a level that suits them with reference to previous LC_{50} tests conducted on the same fluids type they use. Unfortunately, this comfort level gives operators the advantage of operating with toxicity limits as high as 100,000ppm (Clark, 1994).

To curb adverse effects of oil and gas waste in the North Sea regulations have been tightened. The UK and Norway signed the OSPAR; Decisions 92/2 and 2000/3 of OSPAR restrict the release of OBM) cuttings with more than 1% oil to cutting ratio by weight into the sea. Complying with this rule, the UK curtailed the discharge of cuttings contaminated with mineral oil in 1997 (Al-Ansary & Al-Tabbaa 2007). Ormeloh (2014) noted that OSPAR's precautionary principle and principle of taxing polluters are key in effective waste monitoring. Ormeloh (2014) also reflected on that the most noteworthy principles of the OSPAR is the *polluter pays-principle*, the best available techniques (BAT) and the best environmental practices (BEP) applied to reduce pollution. The study also indicated that the Decision 2000/2 must aim to reduce hazardous substances, substituting them thereby reducing the environmental impact. This is achieved through regulations requiring obtaining permission before using the NADM for instance.

In recent years, African oil producing countries are adopting more stringent regulations to govern the discharge of drill cuttings waste by following examples in Europe. In Angola revised its regulation that allowed the discharge of WBM, OBM and SBM cuttings to adopting a zero discharge policy (TWMA 2020). Meanwhile, Ghana signed the Marine Pollution (MARPOL) Convention and is expected to have facilities for full reception of ‘MARPOL’ classified wastes such as oil waste and refuse. It also signed on to The Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention) which caters for instances where hazardous waste cannot be handled or treated locally (Tullow Oil 2009). Ghana’s Environmental Protection Agency (EPA) also permits the discharge of SBM with 3% oil on cuttings by weight in water depths greater than 500m (World Bank 2015). Most countries such as Ghana have regulations to manage drill cuttings waste but create loopholes which promote development of fields whist undermining efforts to properly manage waste. The Basel Convention stipulates that countries can transport waste across borders to countries with the capacity. The optimum decision would be to make operators pay to treat waste before disposal outside borders of Ghana but stipulations like the allowable limit for cuttings allow operators to discharge waste into oceans at a cheaper cost.

In addition, Nigeria requires oil companies to adopt good oil-field disposal practices in accordance with the guidelines and standards from the industry regulator Directorate of Petroleum Resources (DPR) in dealing with WBM, OBM and SBM. Companies are also expected to comply with environmental monitoring requirements (including post-drilling seabed surveys) (Onwukwe and Nwakaudu 2012). Many more African countries have adopted basic frameworks for the exploitation of oil and gas resources and have been successful in attracting petroleum investment and international oil companies to the country. Most countries do not have detailed provisions on the protection of the environment nor specific guidance on regulating and dealing with drilling waste from oil and gas operations.

6. Future trends on drilling waste, opportunity, and challenges

Existing drilling waste management techniques in oil and gas industry are facing a big challenge as these techniques hinder the economic robustness and very limited to protect the environmental pollution too. To meet the strict environmental regulations, a sustainable and effective waste management is a big demand now in oil and gas industry. Fortunately, advancement of waste treatment operations demonstrates improved clean-up operations in oil and gas industry. Although these processes are successful in some extent to meet the discharge/disposal regulations, but in the long run these techniques may pass this pollution from one stage to another stage or secondary level of environmental pollution. The potential solution of this global problem is either to destroy these hazardous chemicals completely which is a big challenge or to use/utilise them for beneficial uses. This recycling theme promotes a new window to turn the accumulated hazardous wastes in oil and gas industry into value added products. Figure 10 shows an overview of current challenges.

Figure 10

To meet the strict environmental regulations, sustainable and effective waste management remains a big challenge in oil and gas industry. Fortunately, new waste treatment or clean-up operation may eliminate this problem and in addition, we should explore a new window to turn these hazardous wastes into value added products (Adegbotolu et al., 2014). To utilise these pollutant materials which exist in wastes, it is very important to understand the sources of drilling fluid wastes, chemical composition, and characterisation of these wastes. Since oil based drilling fluids (OBFs) consist of diesel or mineral oil containing different types of polycyclic aromatic hydrocarbons (PAHs) and are also considered as a flammable hazard source, care consideration should be taken to design the cleaning or treatment processes (Xie et al., 2015).

Furthermore, although the separated liquids (water and oil condensates) are currently being reused in drilling fluids preparation and in some cases, the oil is used to provide power for the other equipment on the platform, it is important to note that, well conditions may vary and thus further analysis may be required to determine safest recycle or disposal options. Again, there may be the need for supplementary treatment due to the heavy metal content as well as high salts present in the original drilling waste in certain cases. This is imperative especially concerning the produced solids, which are currently being disposed off at landfill sites or used in the construction industry and as such a threat to human life.

The composition of drilling fluid waste and the importance of making this waste into resources which is not widely explored in the literature. Drilling fluid waste accumulation by its individual components might be a potential area where more research work needs to focus to optimise the use of individual drilling waste constituents in reuse or recycling operation.

Different mechanisms have been developed and continue to improve and aimed at treating drill cutting waste including non-biological treatment processes and disposal options and bioremediation technologies for treating drill cuttings (Veil, 2002 and Mokhalalati et al., 2000). However, the potential environmental impacts of spent drilling fluids and drill cuttings after treatment are still considered as serious health and safety concerning issues (Rozell et al., 2012).

Today, significant amount of drilling wastes accumulated during drilling operations are disposed off in the landfill or seabed without recovering the useful elements/compounds present in these wastes (Ball et al., 2012 and Xie et al., 2015). Treating these wastes to reuse and recycle them in different beneficial uses remains a significant challenge and any step to improve these processes are considered as sustainable and effective measures to reduce the environmental pollution in future (Xie et al., 2015; Maloney,and Yoxtheimer, 2012and Veil, 2002). For instance, the Waste to Want research being run at Centre for Advanced Engineering Materials at Robert Gordon University on the novel application of nanoclays extracted from spent oil based drilling fluids (drilling fluid) clean-up as nanofiller in the manufacture of nanocomposite materials offers new solutions (Adegbotolu et al., 2014 and Siddique et al., 2017). Previous studies by Adegbotolu et al. (2014) and Siddique et al. (2018, 2019a, 2019b) focused on using the produced solids as reinforcement for polymer composites. Produce the mineral powders (nanoclay) needed for use in the nanocomposite material industry. This will not only minimize the volume of drilling wastes disposed off at landfill sites but will also play a major role in reducing the carbon footprint of the oil and gas industry. To use the beneficiary elements or compounds present in drilling fluid waste, however, it is important to first analyse the composition and characterisation of this waste comprehensively.

6.1. EOR role in drilling fluid waste

Oil and gas production stage of field development is categorised into three phases on the basis of the energy or drive responsible for pushing the oil and gas from the reservoir into the well and up the tubing to the wellhead. These phases are the primary recovery, the secondary recovery, and the tertiary recovery phase. The primary recovery phase is characterised using the natural energy of the reservoir to drive the hydrocarbon fluid towards the wellbore. When a reservoir has produced for a period, then the natural energy of the reservoir depletes and is no longer able to support optimum or economic production rate from the reservoir. To maintain optimum or economic rate from the reservoir, the depleting reservoir pressure is supported by injecting water or gas through an injection well into the reservoir; this is the secondary recovery stage. At the end of the secondary recovery phase, the tertiary recovery phase or enhanced oil recovery (EOR) begins and is characterised by injection of fluids or chemicals alien to the reservoir to change or alter the flow properties of the reservoir fluids and/or the surface properties of the reservoir rock (Lake 2019). Fluid and rock properties usually targeted during EOR include relative permeability, wettability, viscosity, and density.

There are three main types of EOR; these include chemical flooding, gas injection and thermal recovery. As recoveries from primary and secondary production methods are usually between 20% – 40% of the original oil in place (OIIP) (IEA 2008), significant opportunities exist to increase the ultimate recoveries from oilfields to maximise oil and gas production. With EOR recoveries from oilfields can be increased to as much as between 30% and 60% (USA DOE). Figure 11 summarises the oil recovery mechanisms including EOR methods.

Figure 11

6.1.1 EOR Well Drilling Requirements

EOR methods are commonly used in onshore oil and gas projects as its use in offshore fields is constrained by a number of factors related to reservoir characteristics, environmental regulations, power limitation, well spacing and space availability on surface facilities (Kang, Lim and Huh 2014; Speight 2015). Figure 12 provides a comparison of the successful application of EOR in onshore and offshore fields from 1945 to 2010; the successful offshore application cases were from USA, UK North Sea, India and Angola (Kang, Lim and Huh 2014).

Figure 12

It is seen in the data shown in the Figure 13 that most of the successful EOR projects are concentrated in onshore fields. In view of the fact that drilling new wells or converting old wells into EOR injection wells will be required for EOR projects, it is only logical to conclude that drilling aspects will also place a lot of constraints on the use of EOR methods in offshore environments, where complex, non-conventional wells such as extended reach wells and multilateral wells are often the preferred option for economic and technical reasons. The volume of trapped oil in offshore fields globally that cannot be produced with primary or secondary production methods is still very huge and this appears to provide some sort of incentives to the upstream oil and gas industry to continue the ongoing initiatives aimed at evaluating and assessing technical, economic and environmental aspects of EOR application in offshore environments. It is therefore expected that the application trend of EOR in offshore environments will continue to rise in line with the trend in Figure 12 and Table 8.

Table 8

6.1.2 Future Projection of EOR Projects and Related Drilling Activities and Waste Generation

All types of EOR project involve the use of injection wells to inject chemicals, polymers, steam, gas, or water into the producing wells. Figure 13 shows the placement of CO_2 injection and production well.

Figure 13

Oftentimes, application of EOR requires the drilling of additional wells for effective placement of the EOR fluid or chemical "agent" not originally included in the initial field development plan.

In view of the current and projected increased demand for oil and gas to drive the global economy, the oil and gas industry will continue to look for ways to improve recoveries from their oilfields to be able to produce enough oil to fuel the ever-growing world econom135ies. EOR methods are expected to be a big part of the mix of approaches and technologies that will be used to deliver the increase in future oil production. A current study (Market Research Report 2019, MarketWatch 2020) focused on a period between 2019 and 2026 estimated Enhanced Oil Recovery market value to grow significantly at a compound annual growth of 6.8% over the study period. Based on the forecasted growth of EOR market, EOR projects in both onshore fields and offshore fields are expected to increase significantly. The expected increase in EOR projects with the requirement to drill additional wells for the EOR implementation would result in generation of more volume of drilling wastes which need to be managed.

6.2. Raw Materials Recovery

Current drill cuttings treatment typically focuses on the removal of oil contamination with a view towards disposal of the 'oil-free' solids, or in certain cases immobilisation of the solids into construction materials as a re-use option. Thermal treatment of the drilling wastes has generally been the preferred option prior to disposal and is targeted at the removal or recovery of the oil contamination without any focus on the potential to recover the metals inherent within such drilling wastes. The waste-mix residues are contaminated with water leachable metals and leaching has been shown to occur from treated waste drilling fluids deposited on landfills 40 years on (Breuer et al 2004). One of the potential route forwards is to extract raw materials recovery (increased yield and selectivity) from low grade and/or complex and variable primary and/or secondary resources:

6.3. Legal, cooperate responsibility and compliances issues

Although it is not in the scope of this work to analyse these regulations, they are presented to highlight the varying requirements of different countries even within the same continent. Further, the issues related with analytical tests compliance highlighted 1990s persist. These includes sampling procedures, measurements, and data interpretation of results.

Secondly, adoption of specific regulations in regions that do not have the requisite infrastructure to handle waste is futile. Plans to adopt regulations should involve specific plans that considering the early stage of development in certain countries giving a stepwise improvement plan. For example, it would not be feasible for a country like Ghana to adopt waste handling management principles present in Norway – but useful lessons can be learnt. Norway has the necessary infrastructure to handle waste volumes from cuttings that are transported to shore. In contrast, Ghana has limited onshore treatment facilities for drill cuttings according to Tullow (2009). Plans such as the government of Ghana tasking operating companies to export waste to countries where it can be treated should be adopted where necessary. This can serve as a temporary solution whilst the necessary treatment infrastructure is developed either onshore or offshore. Most regulations are put in place to ensure that drill cuttings are properly dealt with or handled. However, parties usually involved in the petroleum industry – operators and governments, try to reduce operational cost and would rather avoid responsibility. Regulations are structured to avoid dealing with waste because it is seen as a cheaper option

Again, in setting these regulations, stakeholders tend to add a socio-political feature to the decision-making. As stated earlier, economic, social and political factors influence these regulations. For instance, the toxicity limits for disposal determines the waste management strategy that will be adopted by operators in different countries. Stakeholders then consider different alternatives for treatment and disposal. However, the viability of these alternatives is determined by the stakeholders (Lahdelma et al., 2000). It is important to note however, that the different stakeholders have different values thus possible conflicts may arise. For some operators, in as much as corporate reputation is critical, cost of the waste treatment alternatives is an indispensable factor worth considering, even if the least expensive alternative does not necessarily reduce impact to the environment. Whereas for residents directly affected, the alternative with the least environmental impact would be of paramount interest.

Finally, the extensive economic benefit of oil and gas operations in any country is a deciding factor for the government as a stakeholder. The decision making involved in setting these regulations then becomes more of a power play between stakeholders and final regulations are usually biased in favour of certain stakeholders. Often, in developing countries, the regulations are usually biased in favour of the government of the time and operators. As stringent as some of these regulations may seem, it is important to note that no “safe limit” exists especially where human life is concerned (Rana, 2008) and perhaps cooperate society responsibility should prevail.

In terms of the regional developments, a number of African regional conventions (West Africa, North Africa, Southern Africa, and Eastern Africa) dealing with the protection of the environment in general could be enhanced on similar lines as the regulatory developments in the UK, and regional instruments from Europe (i.e. the EU Directives, and OSPAR Convention).

7 Conclusions

Waste drilling fluid contains many metal compounds including heavy metals, inorganic salts, hydrocarbons, biocides, hydrocarbons and solid/cuttings. Some of the metal's concentrations are significantly higher than naturally occurring concentrations, which makes the disposal of these wastes a critical environmental concern. Most of these metals (e.g. pick 2 or 3 from above) have a chronic damaging effect on the environment. When the bulk oil fraction of waste drilling fluids are separated and purified, residual organic compounds often remain tightly associated with solids in the remnant drilling fluid (fluids, or either of the clay or drill cuttings), requiring disposal as a hazardous substance. Methods for completely removing hydrocarbons from the solid phase, such as steam distillation, are energy-intensive and inefficient. Solvent-based methods of hydrocarbon separation from the solid phase merely compound the problem by the introduction of hazardous solvents. Combustion of the liquid hydrocarbon in emulsion requires very high operating temperatures and can be a source of air pollution. Combustion of liquid hydrocarbon when mixed with the solid phase is problematic and also requires the facility be licensed as an incinerator that has obvious environmental consequences.

The accumulated drilling fluid wastes in oil and gas industry is different in every operation site. The variations in drilling operations including using drilling fluid with different compositions and the variations in geological conditions make these waste streams so diverse that there is not any standard drilling fluid waste profile tool to identify the composition and character of the wastes. The scenario is even more complex in offshore drilling operation as the unique sediment characteristics, benthic community, and hydrodynamic regime also influence the drilling waste characteristics. 1Dangers posed by waste drilling fluids include: (i) health impact to humans: Health impacts arise via ingestion, inhalation and contact. This exposure could be due to work or drilling location exposure, air pollution, feeding on polluted crops and water; (ii) Socio economic impact: Disease and death of crops and animals such as fisheries lead to loss of livelihood for fish farmers, loss of fishing games and sport, loss of crops that rely on water bodies for farm irrigation; (iii) Ground water system pollution: Pollution of ground water due to unlined waste pits, leachate production from drilling waste landfill sites; (iv) Surface water pollution: This is due to dumping of fluid in water body; (v) The waste-mix residues are contaminated with water leachable metals. Leaching has been shown to occur from treated waste drilling fluids deposited on landfills 40 years on. Therefore, an isolation and inexpensive disposal method for waste drilling fluids is required; (vi) The environmental impact of oil and gas waste drilling fluid is poorly communicated to communities globally due to the presumed public resistance to oil field development and exploration activities and negative effect on oil and gas profits. Equally the current treatment processes are energy- and chemical-intensive leaving regulators with no practical solutions. Current drill cuttings treatment typically focuses on the removal of oil contamination with a view towards disposal of the 'oil-free' solids, or in certain cases immobilisation of the solids into construction materials as a re-use option. The thermal treatment of the drilling wastes has generally been the preferred option prior to disposal and is targeted at the removal or recovery of the oil contamination without any focus on the potential to recover the metals inherent within such drilling wastes.

Going forward there is need to: (i) Design a sustainable and viable drilling waste management plan/model, the first step is to identify the composition and nature of the pollutants in the wastes. Based on this information different waste treatment plan can be placed in operation such as, thermal treatment, thermo-mechanical treatment, biological treatment, encapsulation of pollutants. (ii) Meet the current strict environmental regulations with respect to disposal of this waste or to recycle or recover valuable components such as metals, identification of drilling waste composition and characterisation analysis as the obvious first step to move forward to the next stages of waste valorisation. (iii) Improved understanding of the composition of drilling fluid waste and the importance of making this waste into resources which is not widely explored in the literature. (iv) Improvement in current treatment measures to capability of producing pollutants free or environmentally safe discharge or producing pollutants free or eco-friendly solid waste. (v) The solution might be very difficult as these treatment processes involve space requirements, duration of treatment operation, operational cost, investment cost, monitoring requirement, expertise etc. These obligations open up a new era of research to use this waste as a raw material to make valuable products rather than incurring burden to the environment.

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Caption of Table and Figures

Tables

Table 1 NADM Classification Groups and Descriptions (Hock and Su Yean 2011)

Table 2 Types of Waste Discharges from Exploration and Production (Bashat, 2002)

Table 3 Concentration of metals in Water Based Fluids and Drill Cuttings from two offshore platforms in Southern California (Phillip et al., 1998).

Table 4 Elemental composition of typical water-based drilling fluid constituents (mg/Kg) (Onwukwe and Nwakaudu, 2012)

Table 5 Categorisation of different groups of pollutants in waste drilling fluids according to European Council Directive 76/464/EEC (DIRECTIVE HAT, 1976).

Table 6 Substitute drilling fluid materials (Source: Onwukwe and Nwakaudu 2012)

Table 7 End product quality after treatment as specified by supplier (Aquateam et al., 2014)

Table 8 EOR Projects in US from 1990 to 2014 (Oil and Gas Journal 2016)

Figures

Figure 1 Cuttings Discharged to Sea (top) and Waste Generated Offshore (Oil & Gas UK 2015b)

Figure 2 Example of drilling fluids waste pathways and application routes

Figure 3 Water based fluids composition (top) and non-aqueous drilling fluids compositions (bottom) (BERNIER et al., 2003)

Figure 4 Cuttings Movement in Drilling fluids (left) (Oil & Gas UK, 2015) a3 Drill cuttings in 1 cm scale (right) (Colliver and Carter, 2000)

Figure 5 Percentage of individual chemical constituents present in OBM and WBM discharge adapted from Hudgins (Hudgins and Charles, 1994).

Figure 6 Drilling waste management approaches (Zoveidavianpoor et al., 2012)

Figure 7 Particle size cut points for solids-control equipment (Jacques Whitford Stantec Limited, 2009 and Marinescu et al., 2007)

Figure 8 TCC Process (Thermtech, 2016)

Figure 9 TCC rotor with hammers, top (Schlumberger 2011) and the TCC Heat Generation and Milling, bottom (Thermtech 2016)

Figure 10 An overview of current opportunities and challenges in drilling fluid waste solutions

Figure 11 Classification of EOR Methods (Alusta et al 2011)

Figure 12 EOR application in onshore and offshore environments up to 2010 (Kang, Lim & Huh 2014)

Figure 13 CO_2 EOR Method (Source: Lawrence Livermore National Laboratory)

Table 2 NADM Classification Groups and Descriptions (Hock and Su Yean 2011)

Group	Base Fluid	Aromatic Content	Aromatic (%)	PAH (%)
I	Diesel and conventional mineral oil	High	>5	>0.35
II	Low toxicity mineral oil Enhanced Mineral oil	Medium	0.5-5.0	0.001-0.35
III	Synthetics (esters, olefins and paraffin)	Low to negligible	<0.5	<0.001

Table 2 Types of Waste Discharges from Exploration and Production (Bashat, 2002)

Aqueous Discharges	Solid waste	Atmospheric Emissions
Produced water	Tanking/piping sludge, waxes	Firefighting agents eg. Halons
Process water	Production chemicals	Refrigerants eg. CFCs
Hydro-test water	Industrial refuse	Vent gases
Contaminated rain/drainage water	Soil movements	Flare gases
Domestic sewage	Domestic refuse	Exhaust gases
		Fugitive gases

Table 3 Concentration of metals in Water Based Fluids and Drill Cuttings from two offshore platforms in Southern California (Phillip et al., 1998).

Metal	**Platform 1**		**Platform 2**	
(mg/kg dry wt) ppm	**Drilling Fluid**	**Cuttings**	**Drilling Fluid**	**Cuttings**
Barium	53,900	15,084	12,500	1,180
Silver	0.37	0.5	0.39	0.63
Arsenic	10	10	9.3	13
Cadmium	1.17	2.89	1.75	3.62
Chromium	91	104	84	94
Copper	24	70	24	56
Mercury	0.09	0.07	0.06	0.04
Nickel	39	47	42	17
Lead	23	356	40	32
Vanadium	76	100	46	---
Zinc	167	664	235	972

Table 4 Elemental composition of typical water-based drilling fluid constituents (mg/Kg) (Onwukwe and Nwakaudu, 2012)

Element	H_2O	Cutting	Barite	Clay	Lignite	Caustic
Aluminium	0.30	40400	40400	88600	6700	0.01
Arsenic	0.00	3.90	34.00	3.90	10.10	0.04
Barium	0.10	158.00	590000	640	640	0.26
Calcium	15.0	240000	7900	4700	16100	5400
Cadmium	0.00	0.08	6.00	0.50	0.20	0.00
Chromium	0.00	183	183	8.02	65.30	0.00
Cobalt	0.00	2.90	3.80	2.90	5.00	0.00
Copper	0.00	22	49.00	8.18	22.90	0.04
Iron	0.50	21900	21950	37500	7220	0.04
Lead	0.00	37	685	27.10	5.40	0.00
Magnesium	4.00	23300	3900	69800	5040	17800
Mercury	0.00	0.12	4.10	0.12	0.20	4.00
Nickel	0.00	15.00	3.00	15.00	11.60	0.09
Potassium	2.20	13500	660	2400	460	51400
Silicon	7.00	206000	70200	271000	2390	339
Sodium	6.00	3040	3040	11000	2400	500000
Strontium	0.07	312	540	60.50	1030	105

Table 5 Categorisation of different groups of pollutants in waste drilling fluids according to European Council Directive 76/464/EEC (DIRECTIVE HAT, 1976).

Type of pollutants	**Members of pollutant groups**
List I	Organohalogen compounds and substances Organophosphorus compounds Organotin compounds Carcinogenic substances Mercury and its compounds* Cadmium and its compounds* Persistent mineral oils and hydrocarbons of petroleum origin Persistent synthetic substances
List II	Certain metals, metalloids, and their compounds: 1) Zinc 2) Copper* 3) Nickel* 4) Chromium (Cr(VI)*) 5) Lead* 6) Selenium* 7) Arsenic* 8) Antimony* 9) Molybdenum 10) Titanium 11) Tin* 12) Barium 13) Beryllium 14) Boron 15) Uranium 16) Vanadium 17) Cobalt 18) Thalium* 19) Tellurium* 20) Silver Biocides and their derivatives Toxic or persistent organic compounds of silicon and its substances Inorganic compounds of phosphorus and elemental phosphorus Non persistent mineral oils and hydrocarbons of petroleum origin Cyanides and fluorides Substances causing oxygen imbalance such as ammonia, nitrites

*: Hazardous waste classified in according to Directive 2008/98/EC

Table 6 Substitute drilling fluid materials (Source: Onwukwe and Nwakaudu 2012)

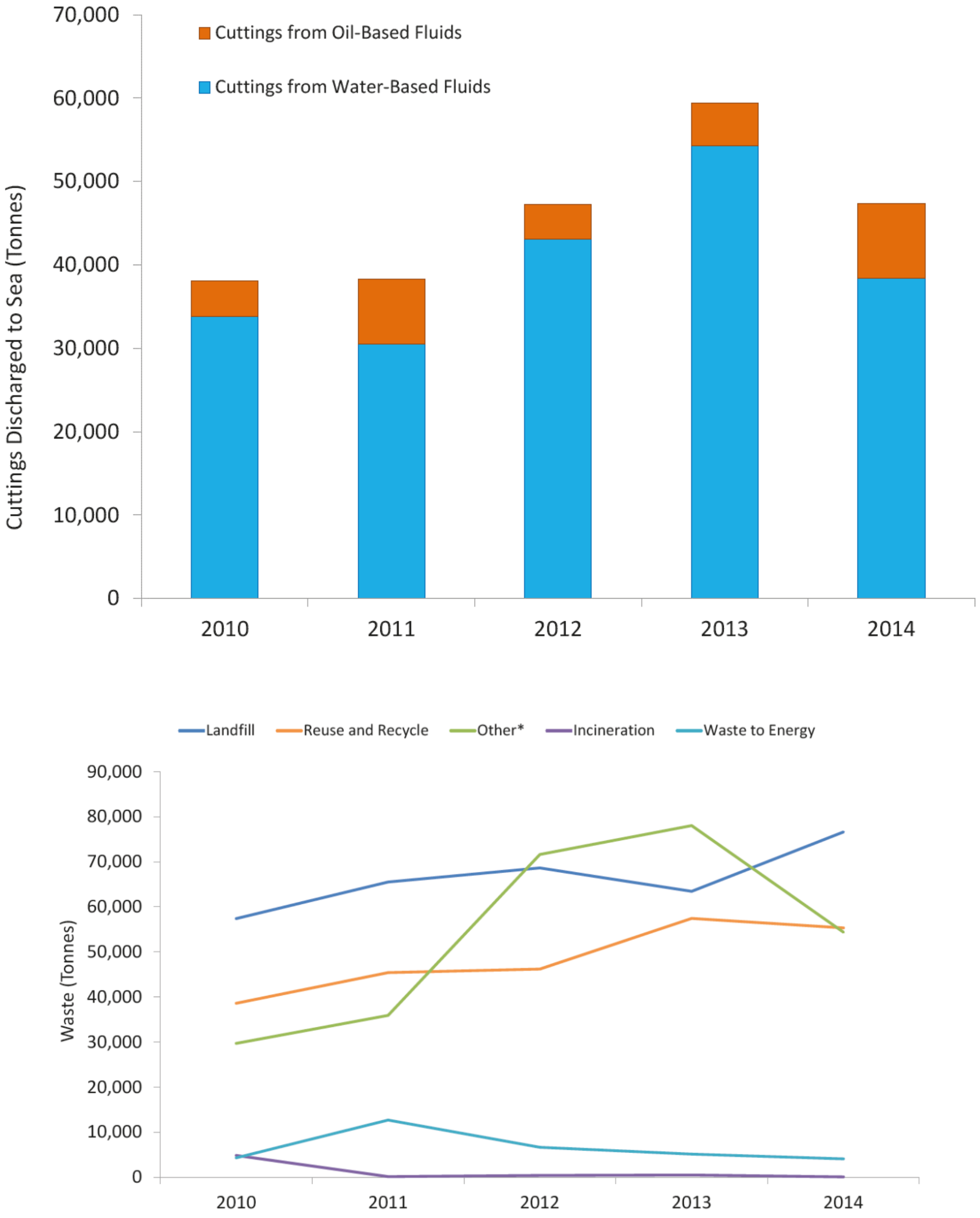
Additive	Toxic Component	Use	Substitute Material
Chrome Lignosulfonate/lignite	Chromium	Deflocculant	Polyacrylate and/or polyacrylamide polymer
Sodium chromate	Chromium	Corrosion control	Sulfites, phosphates and amines
Zinc chromate	Chromium	H_2S control	Non-chromium H2S scavengers
Lead-based pipe dope	Lead	Pipe thread sealant/lubricant	Unleaded pipe dope
Barite	Cadmium, Mercury, Barium, Lead	Fluids densifier	Choose barite from sources low in cadmium, mercury and Lead or use environmentally friendly weighting agents
Arsenic	Arsenic	Biocide	Isothiazolins, Carbonates and Gluteraldehydes

Table 7 End product quality after treatment as specified by supplier (Aquateam et al., 2014)

Description	Specification	Best result
Residual oil in treated cuttings (ppm)	<2000	200
Particles in recovered base oil (ppm)	<1000	<20
Boiling point reduction in recovered base oil (°C)	<5	0
Water content in recovered base oil (%)	<1	<0.5
Oil in water phase (ppm)	<1000	<50

Table 8 EOR Projects in US from 1990 to 2014 (Oil and Gas Journal 2016)

	1990	**1992**	**1994**	**1996**	**1998**	**2000**	**2002**	**2004**	**2006**	**2008**	**2010**	**2012**	**2014**
						Thermal							
Steam	137	119	109	105	92	86	55	46	40	43	45	48	48
Combustion in situ	8	8	5	8	7	5	6	7	12	12	12	11	12
Hot water	9	6	2	2	1	1	4	3	3	3	3	2	2
Total thermal	154	133	116	115	100	92	65	56	55	58	60	61	62
						Chemical							
Micellar-polymer	5	3	2										
Polymer	42	44	27	11	10	10	4	4	0	1	1		
Caustic/alkaline	2	2	1	1	1								
Surfactant	1									1	2	3	3
Total chemical	50	49	30	12	11	10	4	4	0	2	3	3	3
						Gas							
Hydrocarbon miscible/immiscible	23	25	15	14	11	6	7	8	13	13	12	13	14
CO2 miscible	52	52	54	60	66	63	66	70	79	101	103	112	127
CO2 immiscible	4	2	1	1	1	1	1	2	5	5	8	9	
Nitrogen	9	7	8	9	10	4	4	4	3	4	3	3	3
Flue gas (miscible and immiscible)	3	2											
Other	1	1											
Total gas	91	89	79	84	87	74	78	83	97	123	123	136	153
						Other							
Microbial		2	1	1	1								
Total other	0	2	1	1	1	0	0	0	0	0	0	0	0
Grand total	295	273	226	212	199	176	147	143	152	183	186	200	218



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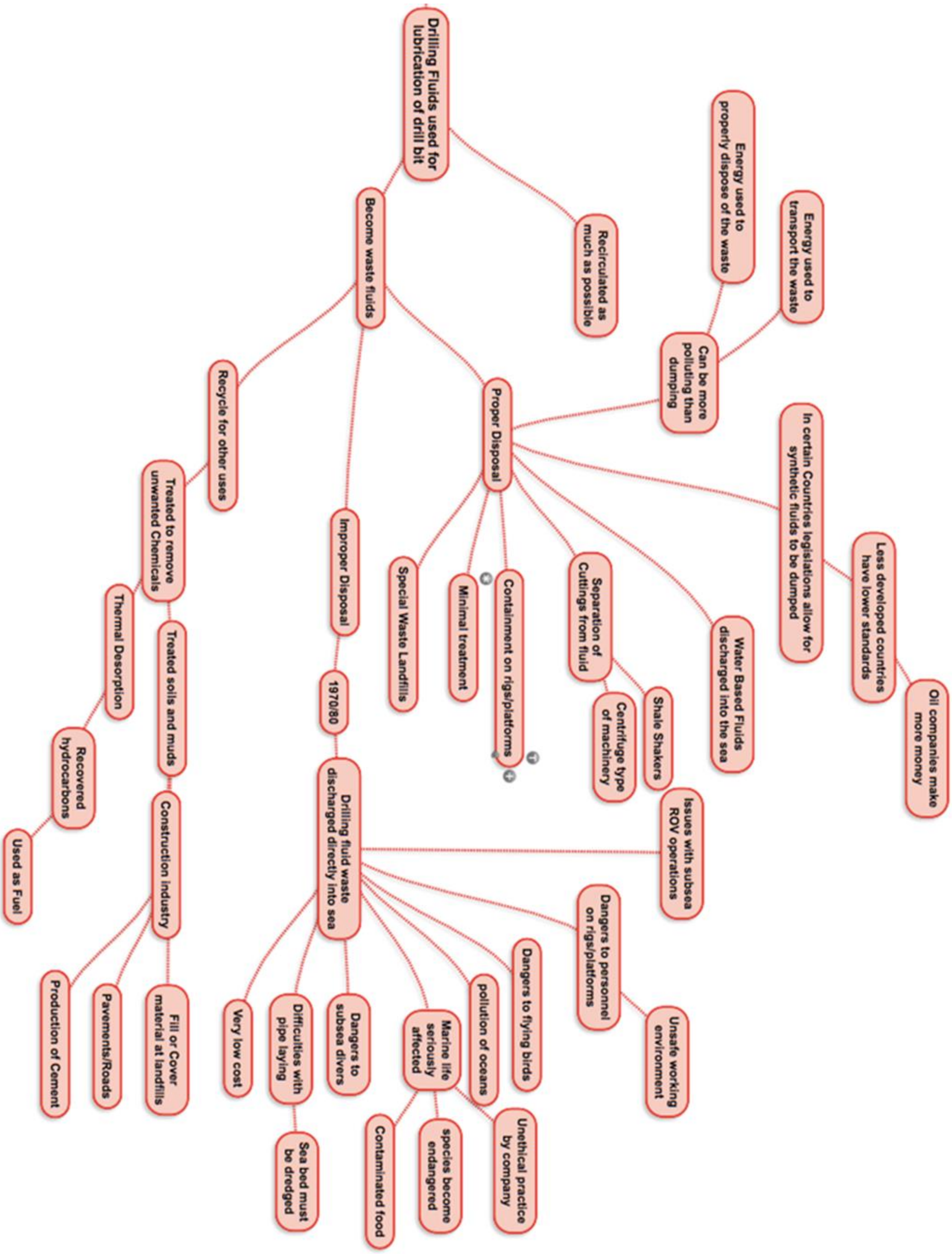

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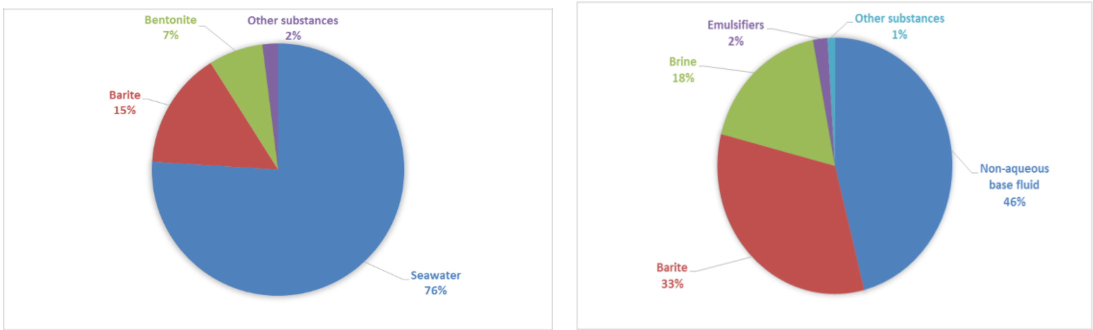

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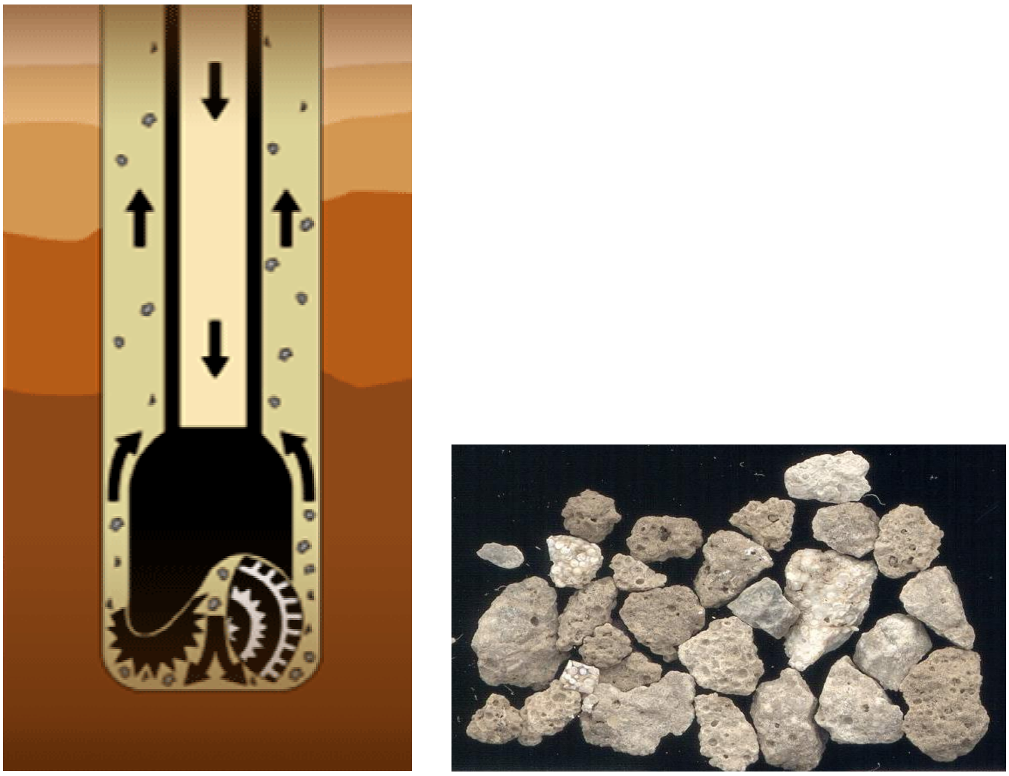

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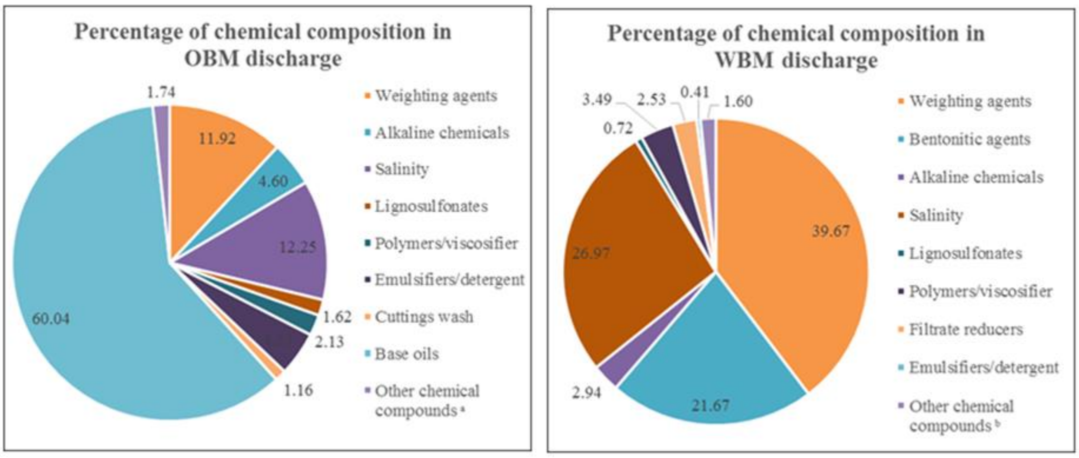

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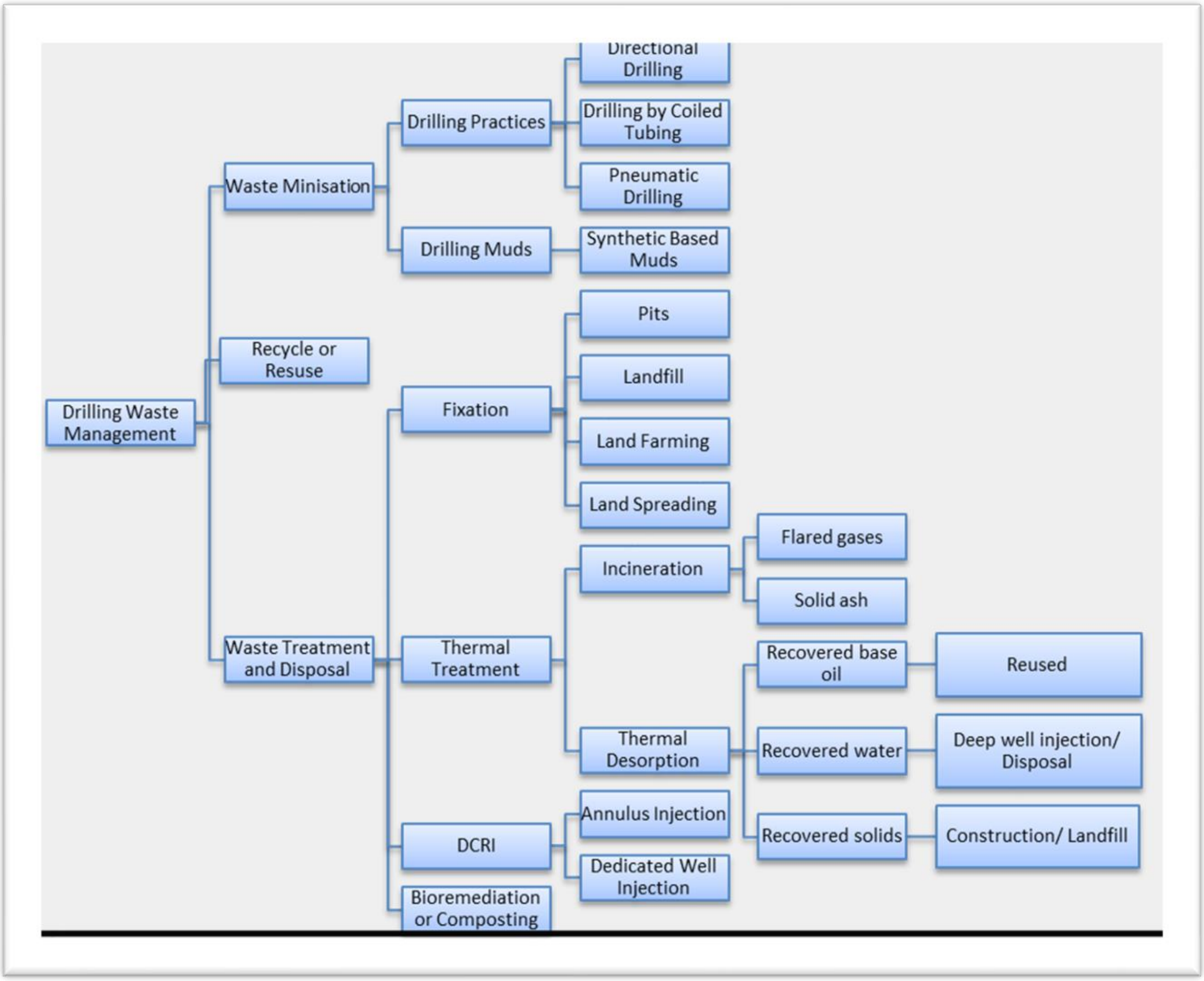

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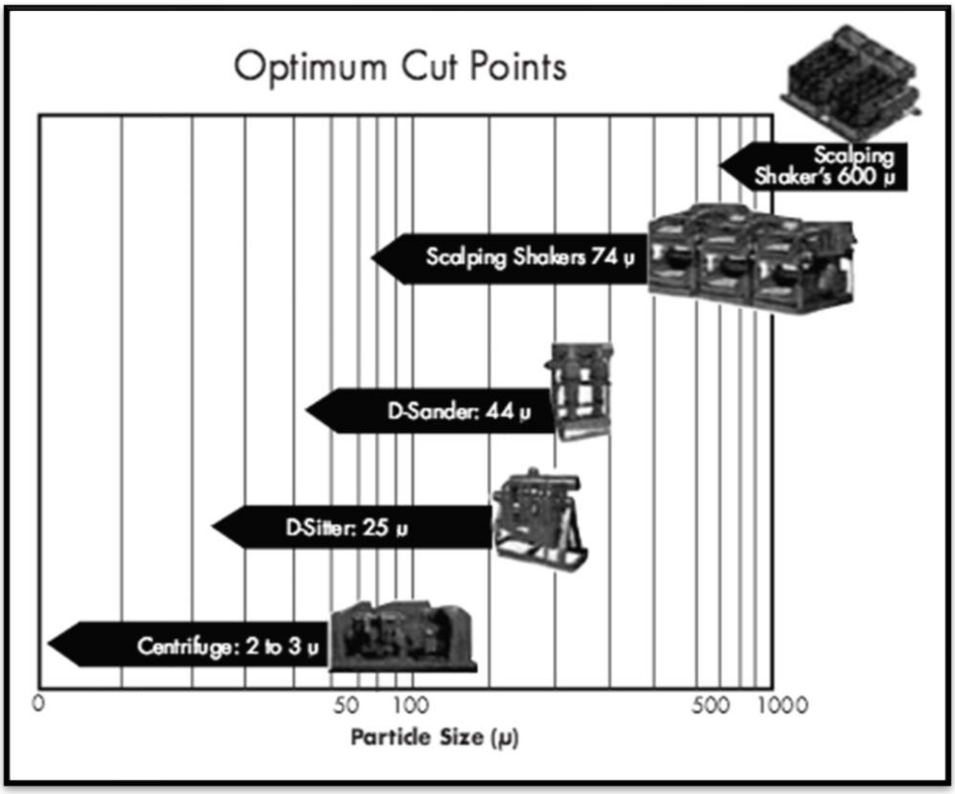

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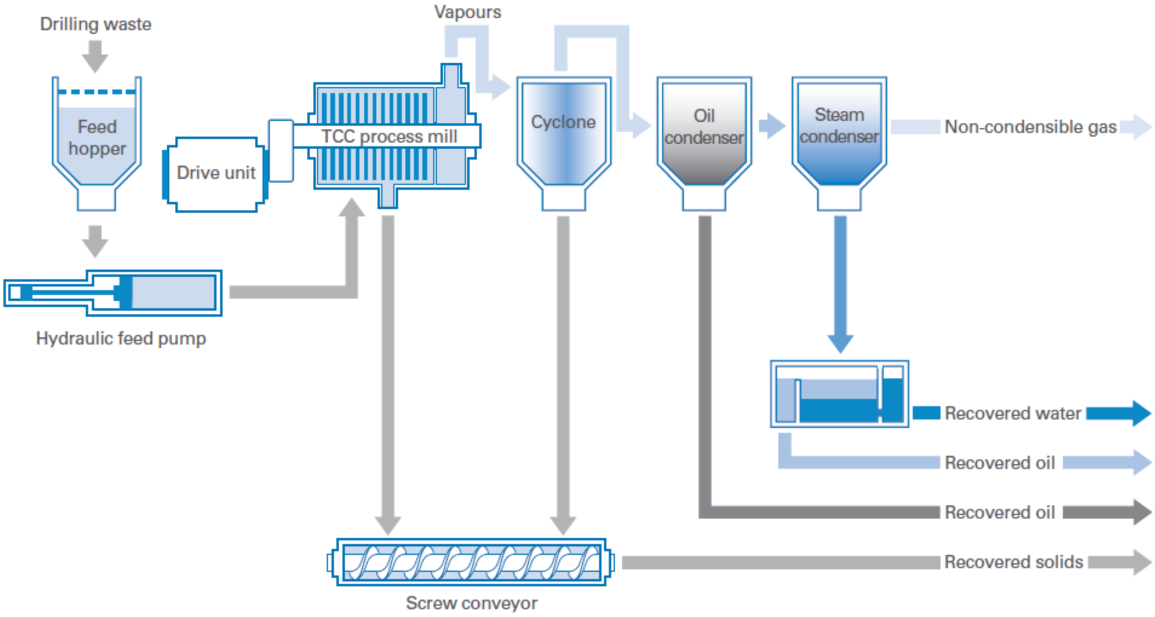
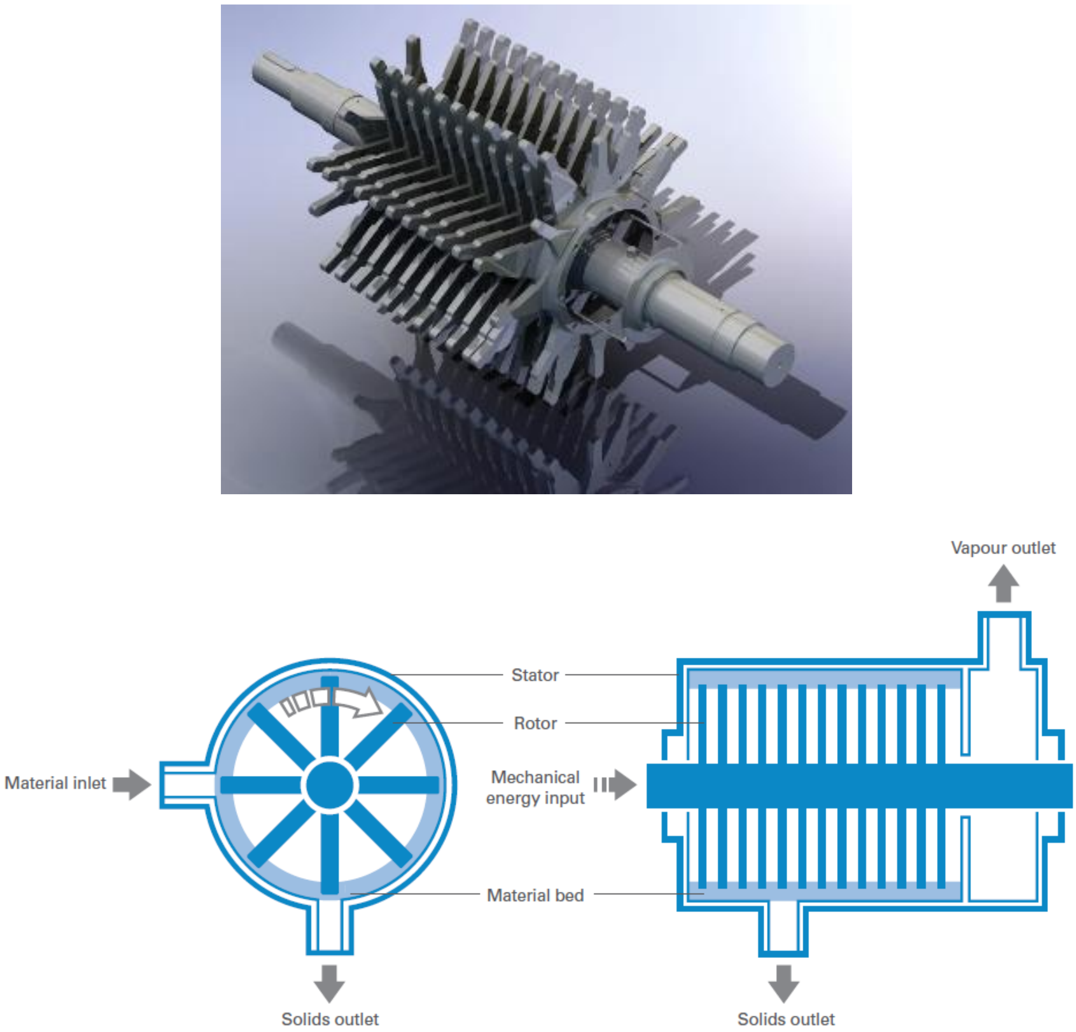


Figure 8 TCC Process (Thermtech, 2016)



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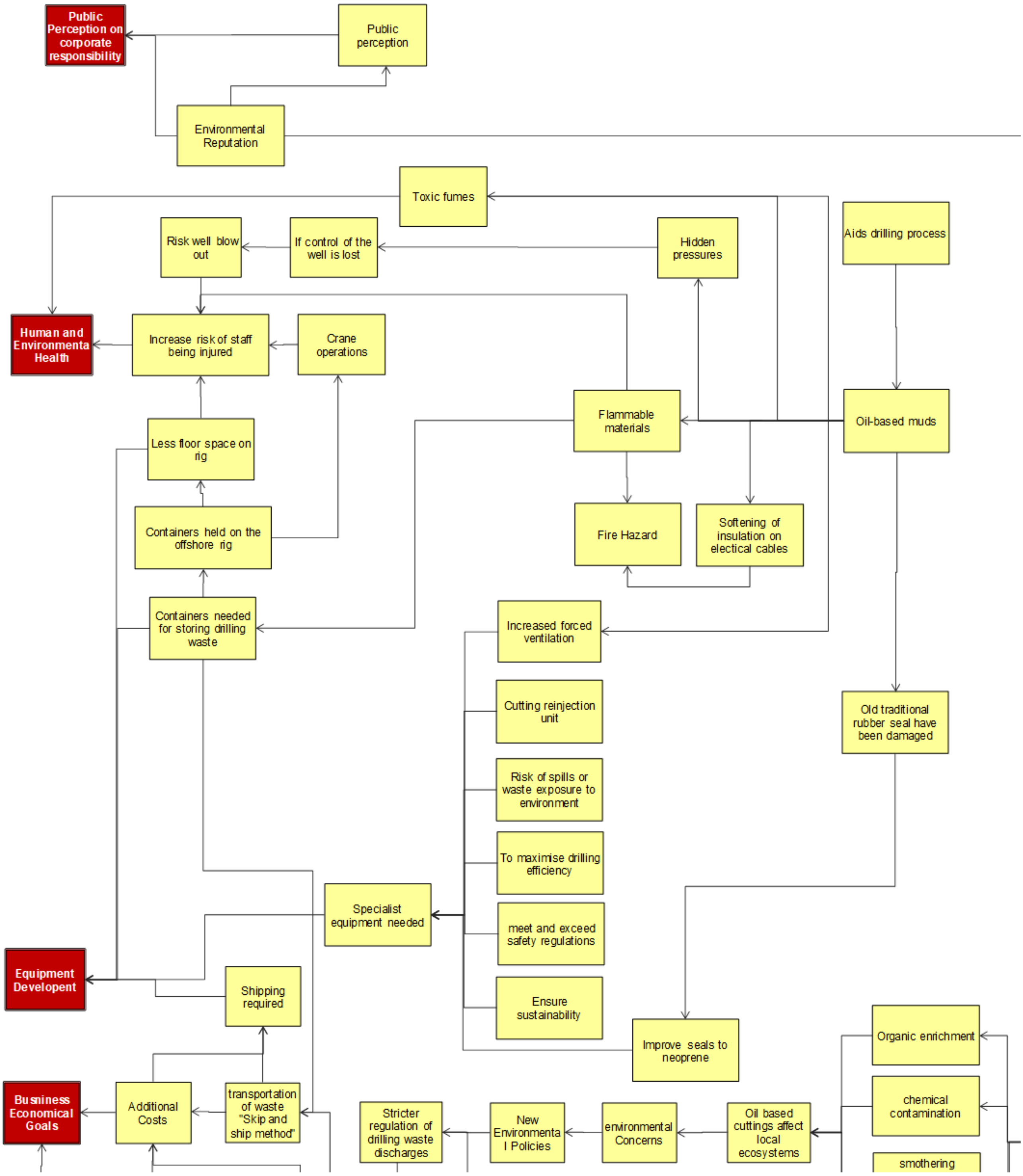

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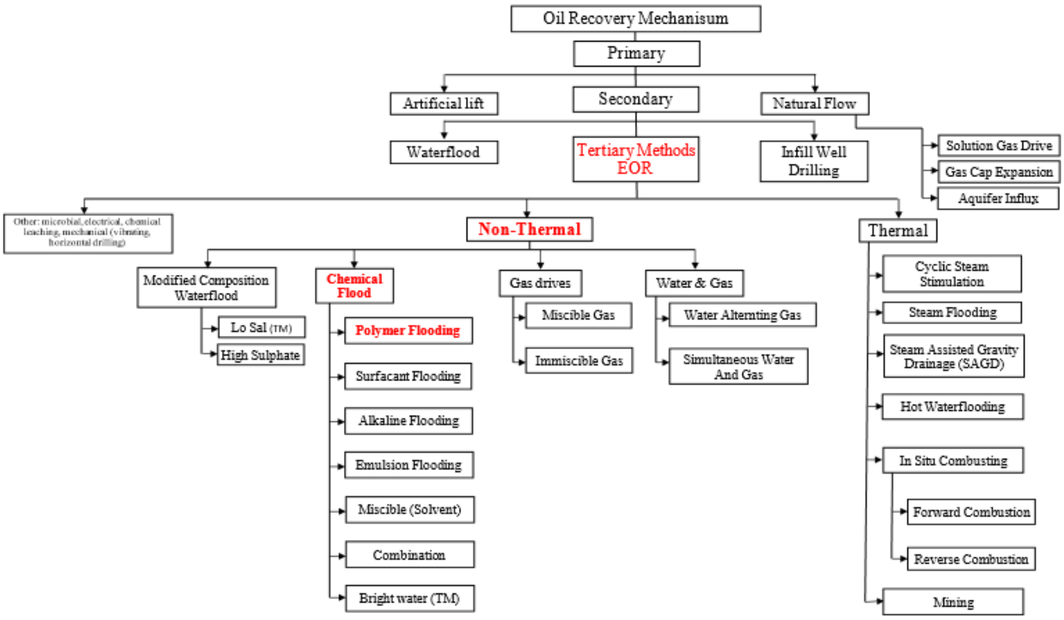

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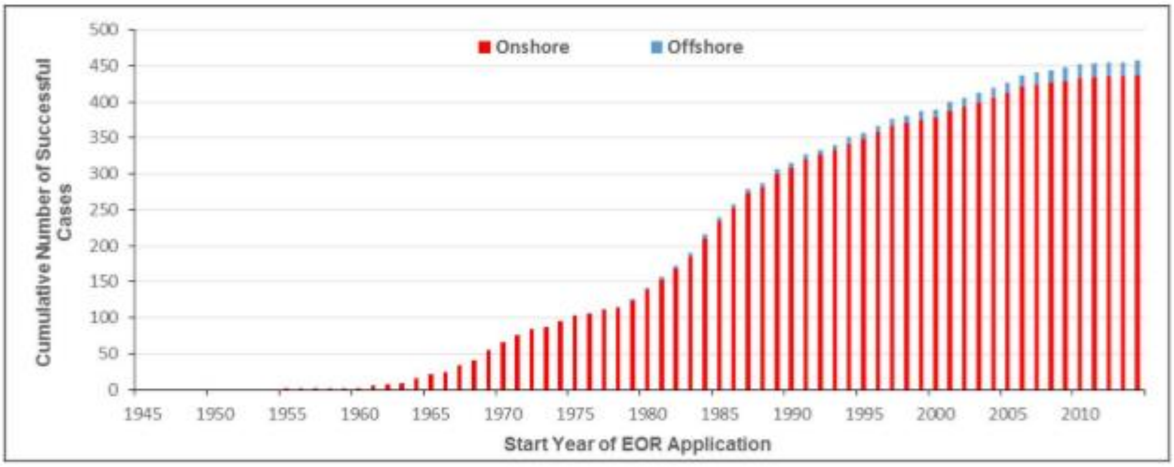

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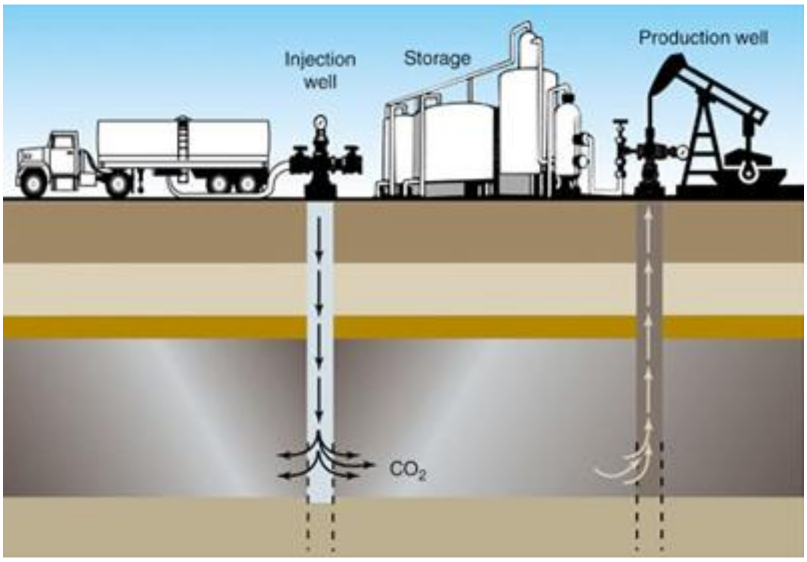

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