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# CHARACTERISTICS OF OIL BASED MUDS AND INFLUENCE ON THE ENVIRONMENT****

## 1. INTRODUCTION

The main categories of drilling fluids are water-based (WBM), oil-based (OBM) and synthetic-based (SBM) muds. The main purposes of using fluids in drilling operations are to cool and lubricate the drill bit, to stabilize the wellbore, to control subsurface pressure, formation pressure, well stability and corrosion, and to transport cuttings to the surface. To fulfill these functions drilling fluids are blends of several components.

To choose drilling fluids for a particular well, main attention should be on geological formations, drilling depth and physical and chemical properties of the fluid. Technical, economical and ecological aspects are important criteria in decision-making.

WBMs are commonly used mainly because of their advantages, such as an easy cleaning of drill cuttings, low cost of fluid materials, and low influence upon the environment compared to OBM [1]. However, WBM's have certain limitations, such as their influence upon stability of borehole walls related to rock hydration and lack of stability at higher temperatures. Tests of WBM and OBM stability (WBM and OBM) determined with the use of an optic analyzer Turbiscan Lab. Formulaction, conducted for a period of 24 h at 40°C, showed WBM more instable than OBM [2]. Figure 1 shows a profile of backscattering changes during analysis of WBM, clay-free mud (Fig. 1a) vs. OBM (Fig. 1b) scanned at 40°C.

Data presented in Figure 1a shows a considerable drop of backscattering at 40°C. The main instability effect for the analysed clay-free mud (WBM) is the phenomenon of sample clarification in the upper part of a measuring vessel. WBM is more instable than OBM.

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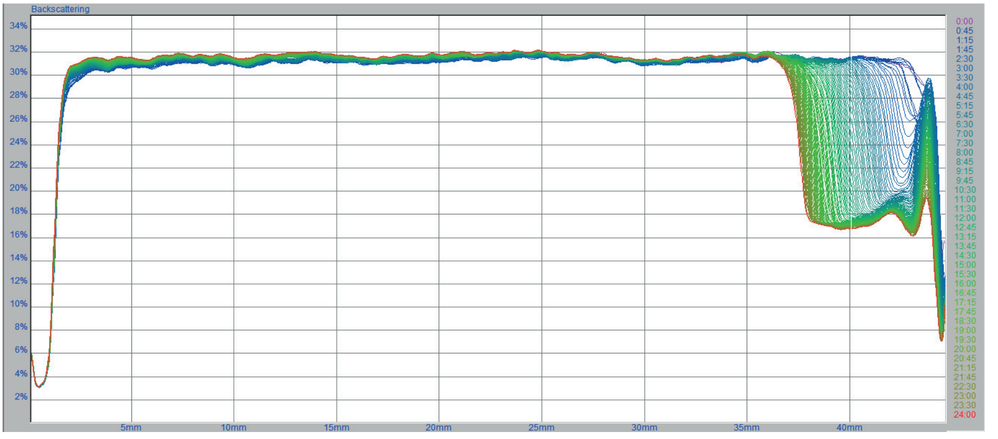
a)

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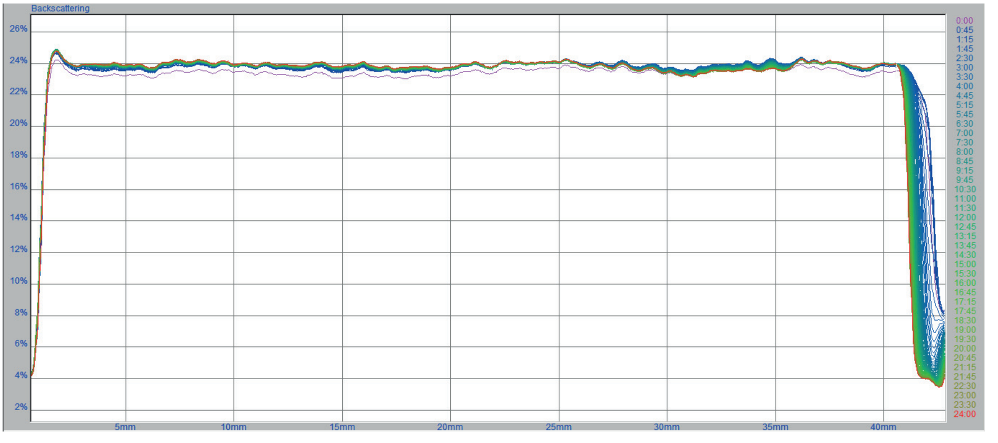


**Fig. 1.** Profile of backscattering during analysis of WBM (clay-free mud) vs. OBM at 40°C [2]

OBM are highly important in well drilling. WBM and SBM are not providing similar qualities. OBM ensure more efficient drilling due to the various desirable rheological properties. Since the 1930s, it has been recognized that better productivity is achieved by using oil rather than water as the base for drilling fluids. Oil is native to the formations and will not damage the pay zone by filtration to the same extent as foreign fluids such as water [3].

Unfortunately, OBM have higher initial cost and require more stringent environmental pollution controls and reduced effectiveness of some logging tools. Expenses for muds are 10–15% of total well cost [4]. However, such costs are still low compared to expenses for corrective measures in the case of using mud with poor properties, which could lead to drilling disruption with excessive time and cost.

Choice of drilling fluids for the Gulf of Mexico was a result of a decision-making process, accounting for technical, economical and ecological aspects in long-term perspective.

Use of WBM in the Gulf of Mexico would slow down the drilling process compared to OBM and SBM. Technical evaluation for drilling in deep-water eliminated WBM. Further environmental assessment indicated that risks of leakage would be significantly less using SBM rather than OBM [1].

Drilling with OBM generates drilling waste, which are classified as hazardous because of hydrocarbon contamination. Composition of drilling waste is complicated due to complex organic-mineral fractions. It is therefore necessary to treat the contaminated mud drilling waste properly. Zero discharge into the environment would be preferable option [5].

In this paper we describe the properties of oil based muds, hazardous effects of toxic compounds in OBM and evaluating treatment efficiency towards zero discharge.

## 2. COMPOSITION OF NON-AQUEOUS DRILLING FLUIDS

OBM was developed and introduced in the 1960s and addressed drilling problems such as:

- formation clays that react, swell or slough after exposure to WBM,
- increasing down-hole temperatures,
- stuck pipe, torque and drag,
- corrosion.

OBM are composed of base oil, water, additives and chemicals. In the early stages of development, diesel oil enriched with aromatics was used for OBM. However, toxicity assessments led to replacing diesel by mineral oil with a negligible amount of aromatics [6]. In the early 1980s research activities focused on lowering environmental impacts of synthetic-based fluids by replacing diesel oil with mineral oils. These fluids were highly refined crude oil products with lower toxicity than diesel oil, however, still contained high contents of aromatic hydrocarbons. Such a change from diesel to mineral oils became a new stage in drilling [6]. Table 1 summarizes the advantages and disadvantages of non-aqueous drilling fluids (NADF) [7].

Depending on the application, regulatory and environmental requirements, the base oil could be diesel, kerosene, low-toxic mineral oil or synthetic oils, such as esters, olefins or paraffins. A toxicity survey in the UK showed that toxicity of mineral oil is five times lower than diesel [6]. Less toxic types of mineral oil were also developed based on polynuclear aromatic concentrations. Mineral oils with no aromatics are available, negating toxic effects on the environment. However, the presence of aromatics are necessary for stable emulsions [6].

NADF (OBM and SBM) contain hazardous compounds. There are three main categories of toxic compounds associated with drilling waste [7]:

- metals: arsenic, barium, cadmium, chromium, copper, mercury, nickel, lead and zinc;
- natural organic compounds: BTEX (Benzen, Toluen, Ethylbenzene, Xylenes), 2–3-rings PAH, naphthalenes, aliphatic hydrocarbons, phenols;
- added chemicals – drilling fluids chemicals:
  - green/PLONOR (Pose Little or No Risk to the Environment),
  - non-PLONOR chemicals (yellow, red and black).

**Table 1**
Oil characterizations used for NADF [7]

| Base oil | Concentration aromatic hydrocarbons | Advantages | Disadvantages | Relative cost |
|---|---|---|---|---|
| Crude oil | >25% | Readily available<br>Inexpensive<br>Compatible with the formation | Unknown Chemical<br>Difficult to control<br>Fire hazard if low boiling point fraction present | Inexpen-sive |
| Diesel oil | 15–25% | Easy to control | Environmentally unacceptable<br>Dries out and irritates the skin | Expensive |
| Mineral oil (Naphthenes) | 1–20% | Environmentaly acceptable<br>Controllable properties | Expensive | Expensive |
| Mineral oil (Paraffin) | <1% | Environmentally acceptable<br>Controllable properties<br>Low Toxicity | Expensive | More expensive |
| Esters/ethers | 0% | Biodegradable<br>Low toxicity | Very expensive | Very expensive |

Added chemicals are strictly regulated and mostly "green" and "yellow" categories. However, chemicals of "red" and "black" categories are also evaluated from a safety perspective [7].

NADF is represented by mineral or synthetic oils with water and chemical additives. Typical compositions of aqueous and non-aqueous drilling fluids are presented in Figure 2.

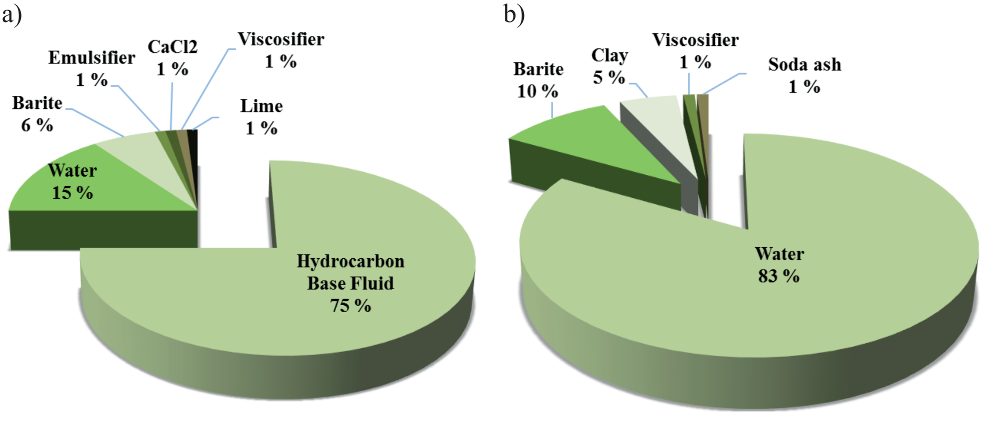


**Fig. 2.** Drilling fluid composition by volume [8]: a) non-aqueous drilling fluid; b) water-based fluid

However, OBM differ from WBM by more than their chemical compositions. OBM require installing additional equipment on the rig and necessitate measures for preventing bodily harm of the crew, limit fluid losses and eliminating fluid contamination of water [9].

The preparation of OBM is more challenging compared to WBM. Difficulties formulating drilling fluids are mainly from the presence of the water in the oil phase; i.e., generating an emulsion. Each formulated oil-based fluid has unique features and performance characteristics. Therefore, generalization and development of a unified procedure to formulate fluids of this type is not possible. Every formulation of the oil-based fluid is associated with preparing a dedicated mixing procedure. Individual components of the drilling fluid should be added in a specified order as it determines the fluid quality.

## 3. OBM CONSUMPTION

OBMs are only occasionally applied in Poland. However, this situation will likely change considering the advantages of their use. OBMs are applied when the technical properties of WBMs are insufficient. Some of the properties of OBMs are vital when drilling a very deep well, in troublesome geological formations (clay rocks and particularly shales), and long and horizontal wellbore sections in the oil producing formations. OBMs are particularly important for oil producing formations as it minimizes formation damage. WBMs have long contact time with the reservoir rocks and invading the reservoir may irreversibly worsen or even damage its productivity by reducing the formation porosity and permeability [10].

Disadvantages of applying OBM must considered; i.e., cost of ingredients as well as health and safety for the crew and the environment.

Use of OBM in Norway has long traditions. The first exploration well on the Norwegian Continental Shelf was drilled in 1966. Until 1980 diesel was used as the continuous phase in OBM drilling fluid. During the last ten years on the Norwegian Continental Shelf there has been an increase in WBM compared to OBM (Fig. 3), considered a „waste preventive actions" strategy [11].

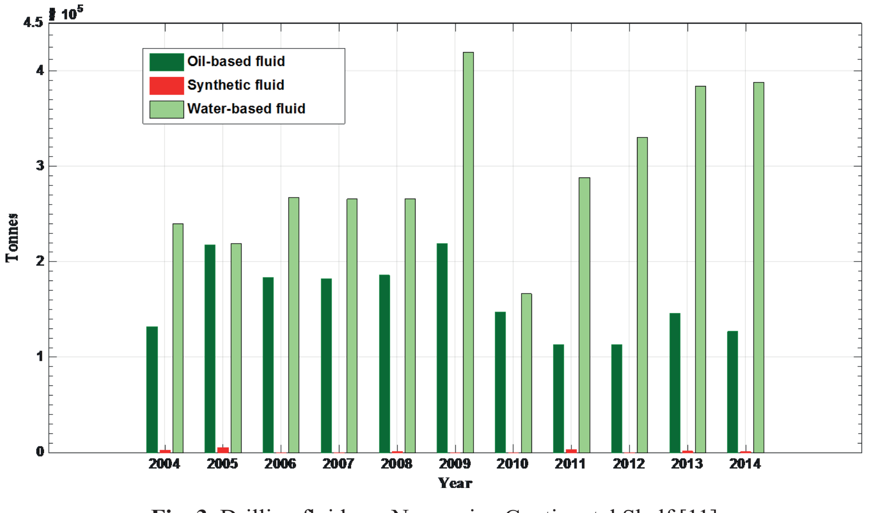


**Fig. 3.** Drilling fluids on Norwegian Continental Shelf [11]

However, a decrease of OBM could be due to the lack of drilling new wells. Oil & Gas UK reports exploration activity in 2014 has significantly decreased [12], 14 out of 25 planned wells were drilled. Also, 18 appraisal wells were drilled in 2014 compared to 29 in 2013. Such a decrease in exploration, drilling and production activities is a response to the fall of crude oil prices [13].

Exploring hydrocarbon deposits using OBM, generates drill cuttings and spent drilling fluids. Both are classified as hazardous waste because of their hydrocarbon content.

The volume of waste generated during drilling with OBM depends mostly on the length of wellbore sections, and the presence of side wells and horizontal sections. Average OBM drilling generates significantly less waste than WBM. Drilling with WBM produces 7,000–13,000 bbl of waste per well. Depending on well depth and diameter 1,400–2,800 bbl are drill cuttings. OBM is usually recycled leaving 2000–8000 bbl/well of drill cuttings for treatment [14].

## 4. BEST AVAILABLE TECHNOLOGIES FOR DRILLING WASTE

OBM and drilling waste are potential risks to land and marine ecosystems. Therefore, the Oslo-Paris convention for the protection of the marine environment of the North-East Atlantic OSPAR recommends assessing best available technologies (BAT) and best environmental practices (BEP) in relation to the management of oily waste, and ensuring the implementation of latest developments [15].

Waste minimization can be realized trough total fluid management and environmental impact reduction. Waste management, fluids and solids control are key processes for improving economics and minimizing the environmental impact of drilling [9].

An effective way of controlling the solid phase is the basis of an economic and ecological use of OBM. This statement results from two factors: the costs of such fluids and their utilization. A high cost of a base oil means that a proper cleaning of spent drilling fluids is more profitable than decreasing the respective amount of solids by diluting the fluid they contain. Thus, the best solution is removing the solid phase from the fluid before the solids begin to accumulate. A properly designed and utilized cleaning system ensures oil-based fluids to be reused many times.

Shale-shakers, hydrocyclones and centrifuges are important solids-control equipment [9], which separates solids from liquid. After solids-control stage, there are two common methods for secondary treatment of drill cuttings to reduce drilling fluid retained on cuttings (ROC): cuttings dryers and thermal desorption. The scheme of working cuttings dryers and view of drill cuttings before and after cuttings dryer are presented in Figure 4.

The strong disadvantage of cutting dryers is that they can not achieve the OSPAR requirement of 1% ROC [18]. Cuttings dryers were reported to reduce ROC from 11.8% to 2.1%. The advantage of cuttings dryers is recycling of fluids recovered from the dryer [18]. Another advantage is dramatic reduction in solid volume due to liquid and organic evaporation, which means more efficient logistic costs for transporting treated solids to disposal location [17]. Therefore, cuttings dryers are the best solution to reduce water in drill cuttings before thermal mechanical cuttings cleaner, which also improves TCC process efficiency.

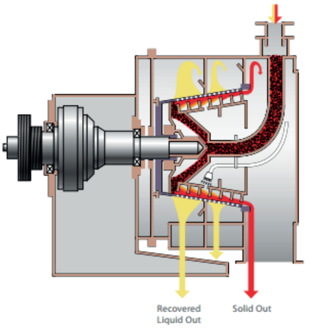


**Fig. 4.** Cuttings dryers [16] and drill cuttings before and after cuttings dryer [17]

Thermomechanical cuttings cleaner (TCC) is one of the BAT for drill cuttings treatment, which yields oil removal from cuttings below 1%. During TCC treatment of drilling waste, the liquid phase oil and water, evaporate and are recovered in separated chambers, while solids can be disposed to sea or land [20]. Thermal desorption achieves well below 1% ROC [19]. However, it implies logistical challenges and so far was implemented mainly onshore [18].

The analysis for oil and PAH from untreated and TCC-treated OBM cuttings is summarized in Table 2.

**Table 2**

Composition of untreated and TCC-treated oil base drill cuttings [20]

| Component | Concentration (mg/kg of dry matter) | |
|---|---|---|
| | Untreated OBM | TCC-treated OBM |
| Oil in sand | 160,000 | 960 |
| Dry matter | 66 | 84.6 |
| PAH 16: | | |
| Naphthalene | 5 | 0.043 |
| Acenaphthylene | 1.7 | <0.05 |
| Acenaphthelene | 3.3 | <0.01 |
| Fluorene | 2 | 0.038 |
| Phenanthrene | 2.1 | 0.13 |
| Anthracene | 0.37 | 0.014 |
| Fluoranthene | 0.26 | 0.021 |
| Pyrene | 1.2 | 0.061 |
| Benzo(α)anthracene | 0.26 | 0.028 |
| Chrysene | 0.3 | 0.046 |
| Benzo(b)fluoranthene | 0.15 | 0.041 |
| Benzo(k)fluoranthene | 0.017 | <0.01 |
| Benzo(α)pyrene | 0.12 | 0.031 |
| Dibenz(α,h)anthracene | 0.031 | 0.015 |
| Benzo(ghi)perylene | 0.16 | 0.098 |
| Indeno(1,2,3-cd)pyrene | 0.037 | 0.022 |
| Sum PAH 16 | 17 | 0.59 |

Results from TCC analysis show that required limit for oil on solids <1% in NCS is achieved. TCC treatment shows 99.4% of oil removal and 96.5% of PAH removal. The water and crushed cuttings after TCC process are cleaned to levels below Norwegian requirements for sea discharge, 30 mg/l oil in water and 1% oil by weight on cuttings, respectively. Also TCC – treated OBM satisfy the requirements for residual oil on solids [21].

## 5. TOXICITY OF OIL BASED DRILLING MUD

Different additives and pollutants from drilling operation with OBM, generate drilling waste because of their hazardous hydrocarbon content. The composition is complicated because they represent complex organic-mineral systems. 75% are hydrocarbons in OBM (Fig. 2) which makes the natural organic compounds such as BTEX, 2-3-rings PAH, naphthalenes, aliphatic hydrocarbons and phenols, an issue of high environmental concern [8]. Most hydrocarbon compounds are highly hazardous and cannot be discharged without treatment. Concentrations which may be harmful for the environment, were tested on organisms. Such concentrations for PAHs and BTEX are presented in Table 3, with a minimum exposure period of 96 hours and a maximum exposure period of 42 days.

**Table 3**

Toxicity levels of aromatic hydrocarbons in the aquatic environment [22]

| Compounds | | Endpoint | Trophic level | Concentration (μg/L) |
|---|---|---|---|---|
| BTEX | Benzene | NOEC* (20 days) | Crustacea (Male) | 170 |
| | Ethylbenzene | $LC_{50}$** (96 hours) | Crustacea (Male) | 490 |
| | Toluene | NOEC (21 days) | Crustacea (Female) | 1,000 |
| | Xylene | $LC_{50}$ (96 hours) | Fish (Female) | 1,200 |
| PAH | Naphthalene | NOEC (40 days) | Crustacea (Male) | 21 |
| | Phenanthrene | NOEC (60 days) | Fish (Female) | 1.5 |
| | Anthracene | NOEC (21 days) | Crustacea (Female) | 0.63 |
| | Crysene | NOEC (21 days) | Crustacea (Female) | 1.4 |
| | Benzo[a]pyrene | NOEC (42 days) | Fish (Female) | 6.3 |

* NOEC – No Observed Effect Concentration

** $LC_{50}$ – Lethal Concentration for 50% of tested organisms

As shown in Table 3, "no observed effect concentration" (NOEC) for PAH is low compared to NOEC for BTEX. Low NOEC means high toxicity of PAH, where lower concentrations and exposure time are needed for obtaining chronic or acute effects for organisms.

Harmfulness of OBM and WBM drill cuttings was preciously considered and investigated. However, this knowledge is still uncertain, because most investigations concern marine ecosystems and marine species, whereas drilling fluids generate problems also in terrestrial ecosystems [23].

The most hazardous OBM components for aquatic organisms are low-boiling aromatics. Additionally, the higher-boiling aromatic fractions are of high environmental interest due to their persistence in sediments, leading to enzyme induction, cellular dysfunctions, genetic alterations, and chronic effects on organisms [24].

To supplement this knowledge, bioassays were carried out on plant growth inhibition test with *Lepidium sativum*. Bioassays testing were carried out on the sample after the thermal desorption process (P-TCC) and on a sample of oil-based mud [25]. The samples were prepared by adding 0.1, 1.0, 10.0, 25.0 to 50 g of brown soil and 50.0 g of drilling fluid. View of the *L. sativum* growth on brown soil mixed with oil drilling fluid, sample P-O is shown in Figure 5 and with sample P-TCC in Figure 6.

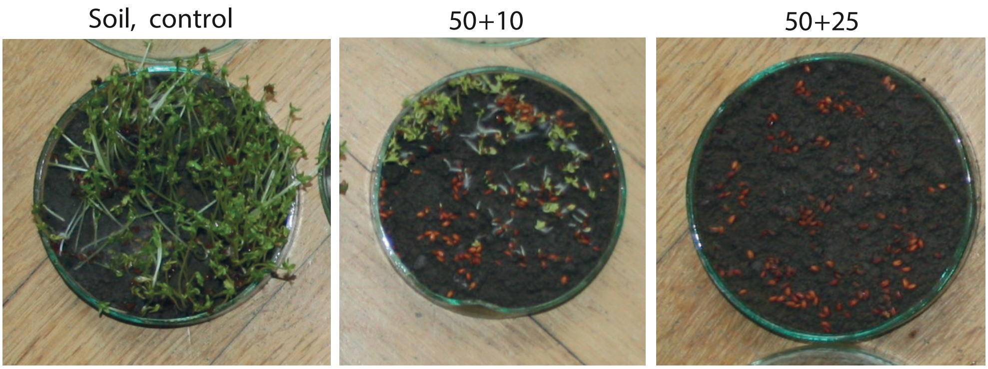


**Fig. 5.** *Lepidium sativum* growth on brown soil mixed with oil drilling fluid, sample P-O [25]

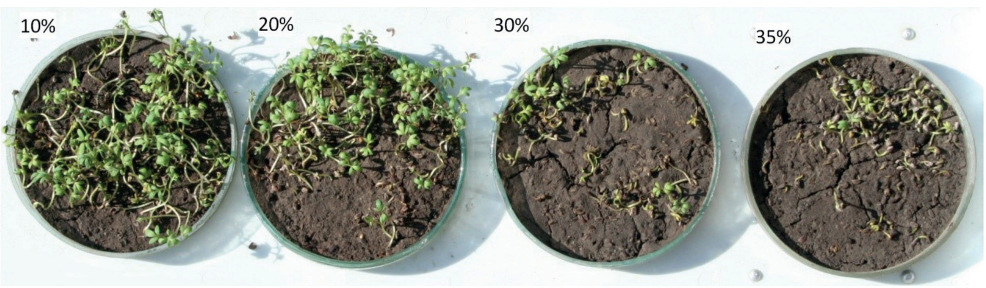


**Fig. 6.** *Lepidium sativum* growth on brown soil mixed with sample P-TCC [25]

Addition of 13.6% drilling mud is not toxic or does not inhibit growth of *L. sativum,* whereas the concentration 33.3% fully inhibits growth (Fig. 5). The $LC_{50}$ is 21.2% of the dry mass of drilling mud.

The samples after thermal desorption (P-TCC) were also tested with *L. sativum*. Germination is restrained but possible at 35% concentrations (Fig. 6). An admixture of up to 20% of dry mass has no apparent effect on the germination and growth of *L. sativum.* The calculated $LC_{50}$ for the P-TCC sample desorbed is $0.29 \pm 0.1$ as dilution (percent) of dry masses soil: sample.

Oil-based drilling mud was more toxic for growth of *L. sativum* ($LC_{50}$) than samples after thermal desorption; 21.2% and 29% respectively [25].

## 6. CONCLUSIONS

Sustainable waste management has become one of the biggest milestones for companies in the oil and gas industries. These goals can be reached by using environmental friendly chemicals and/or reusing and recycling the produced waste.

Strengthening of regulations for oil and gas industries leads to significant technological improvement in the form of BAT. TCC has proven to be an efficient technology for the treatment of drill cuttings. TCC shows potential for offshore implementation, simplifying waste treatment procedures without negative environmental impacts, eliminating drilling waste re-injection. Mineral oil with low content of hazardous components in OBM, as well as high efficiency BATs are strong indicators of progress towards zero discharge.

## REFERENCES


[1] SPE: *Drilling Fluids*, in: *Petroleum Engineering Handbook*. USA, 2006, pp. 112–113.

[2] Friedheim J., Candler J.: *The base fluid dilemma: what can we use and where can we use it?*. Texas, USA, 2008.

[3] Fadairo A. et al.: *New Technologies in the Oil and Gas Industry*, 2012.

[4] King Petroleum Service Ltd.: *Introduction to well engineering. Drilling fluids*, 2009. http://www.kingpetroleum.co.uk/training/wellEngHandout/training_chap09.php#&panel1-1.

[5] Schonacher D. et al.: *Meeting Zero Discharge Requirements in the Gulf of Mexico Using a Unique Cuttings Transport System.* San Antonio, Texas, 2003.

[6] Orszulik S.: *Environmental technology in the oil industry*. UK: Springer, 2016, p. 112.

[7] SINTEF: *Toxicity of drilling discharges. ERMS Report*, 2006.

[8] DACC: *An industrial recommended practice – IRP 14: Non Water Based Drilling Fluid*, vol. 14, 2014.

[9] *Drilling Fluid Processing*. Handbook, Elsevier, 2005.

[10] OGP: *Environmental aspects of the use and disposal of non-aqueous drilling fluids associated with offshore oil & gas operations*, 2003. http://www.ogp.org.uk/pubs/342.pdf [Access 28.03.2016].

[11] *Norwegian Oil and Gas Association*. Environmental Report. Facts and development trends, 2015.

[12] Oil & Gas UK: *Activity Survey*, 2015.

[13] Oil & Gas UK: *Economic Report*, 2015.

[14] Burke C.J., Veil J.: *Synthetic-based drilling fluids have many environmental pluses*. Oil & Gas Journal, 1995.

[15] OSPAR Commission: *Best Available Techniques (BAT) and Best Environmental Practice (BEP)*, 2015. http://www.ospar.org/work-areas/rsc/bat-bep [Access 16.04.2016].

[16] SCOMI Group: *The Extractor Cutting Dryers*, 2013. http://www.scomigroup.com.my/core/DWM/pdf/treatmentDisposal/Extractor_Cuttings_Dryer_1208.pdf [Access 30.03.2016].

[17] Halliburton: *Drilling waste management. Vertical cuttings dryer and centrifuge*, Halliburton, 2014. http://www.halliburton.com/public/bar/contents/Data_Sheets/web/Sales_Data_Sheets/H010844.pdf [Access 20.04.2016].

[18] Stantec: *Cuttings treatment technology evaluation. Report 166*, July 2009. http://www.esrfunds.org/pdf/166.pdf [Access 19.04.2016].
[19] Aquateam COWI: *Characterising thermal treated OBM drill cuttings. Sampling, characterisation, environmental analysis and risk assessment of offshore discharges*, 2014. https://www.norskoljeoggass.no/Global/NOROG-%20TCC%20treatment%20of%20OBM%20cuttings%20Final%20English%20version%20of%20report-July%202014.pdf [Access 9.03.2016].
[20] Hara C.: *Study of treated and untreated oil-based drilling waste exposure in Atlantic salmon* (*Salmo salar) using a biomarker approach: EROD and oxidative stress parameters*, Stavanger, Norway, 2014.
[21] *Rozporządzenie Ministra Środowiska z dnia 9 września 2002 r. w sprawie standardów jakości gleby oraz standardów jakości ziemi*. Dz.U. 2002, nr 165, poz. 1359.
[22] OGP: *Aromatics in produced water: occurrence, fate and effect and treatment*, 2002.
[23] IADC: *Drilling Manual*, 2000. http://210.31.208.121/jpkc/zuanjing/down/20104201543973499.pdf [Access 30.03.2016].
[24] Macdonald C., Lockhart L., Gilman A.: *Effect of oil and gas activities on the environment and human health*, in: *AMAP Assesment 2007: Oil and Gas Activities in the Arctic; Volume 2*. Oslo 2007, pp. 5.1–5.139.
[25] Jamrozik A., Gonet A., Fijał J., Terpiłowski K., Czekaj L.: *Analysis of waste mud stability*. AGH Drilling, Oil, Gas, vol. 31, no. 1, 2014, pp. 25–38.
[26] Health & Safety Executive: *Drilling fluids composition and use withing the UK Offshore drilling industry*. Offshore Technology Report OTO 199 089, 2000.
[27] OSPAR: *Background document on polycyclicaromatic hydrocarbons (PAHs)*, 2009. http://www.ospar.org/documents/dbase/publications/p00399/p00399_pahs%20update.pdf [Access 20.01.2015].
[28] ATSDR: *Polyaromatic Hydrocarbons (PAHs)*, 2013. http://www.atsdr.cdc.gov/csem/csem.asp?csem=13&po=8 [Access 20.01.2015].
[29] Leusch F., Bartkow M.: *A short primer on benzene, toluene, ethylbenzene and xylenes (BTEX) in the environment and in hydraulic fracturing fluids*, 2010.
[30] OSPAR: *Report on discharges, spills and emissions from offshore oil and gas installations*. OSPAR Commission, 2015.
[31] Oil & Gas UK: *The statutory regime*, 2014. http://oilandgasukenvironmentallegislation.co.uk/contents/pages/statutory.htm [Access 17.04.2016].
[32] ProSep: *CTour process*, 2014. http://prosep.com/wp-content/uploads/2014/03/CTour-Technology-Process-Letter.pdf [Access 16.04.2016].
[33] Statoil: *Annual Report 2011. Water management in Statoil*, 2011. http://www.statoil.com/annualReport2011/en/Sustainability/ClimateAndEnvironment/Pages/WaterManagementInStatoil.aspx [Access 16.04.2016].
[34] EPA: *Drinking water standards and health advisories table*, 2007. https://www3.epa.gov/region9/water/drinking/files/dwsha_0607.pdf [Access 18.04.2016].
[35] Alberta Energy Regulator: *Directive 050. Drilling Waste Management*, 6 April 2016. https://www.aer.ca/documents/directives/Directive050.pdf [Access 18.04.2016].
[36] IOGP: *Environmental performance indicators – Data 2013e*, 2014.
[37] International Association of Drilling Contractors: *IADC Drilling manual*, Houston 2000.