CLEANER PRODUCTION APPROACHES IN DRILLING-FLUIDS ENGINEERING

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CLEANER PRODUCTION APPROACHES IN DRILLING-FLUIDS ENGINEERING

ABSTRACT

Drilling-fluids or "mud", as commonly known in the oil and gas industries, are very instrumental from the early stage of spudding to the completion phase of a well development. Currently, majority of the drilling-fluids utilized are either water-based which is prepared by mixing various types of chemicals on the offshore drilling rig itself, or synthetic oil-based which is recycled from previous drilling campaign. Drilling-fluids residues from dead volume of mud tanks, drilled cuttings and contaminated drilling-fluids from various operations are usually discharged directly to the sea. In addition, many of the support operations and practices in managing drilling fluids are less environmentally friendly. These practices may cause seawater pollution, which is hazardous to the micro aquatic life and overall marine environment. Therefore, in this study, an overall assessment was conducted for the full life cycle of drilling-fluids management to identify possible greening opportunities using cleaner production strategy. Subsequently, cleaner production (CP) options were generated and evaluated in the perspective of carbon footprint. From this initiative, a general guideline that can be used to green drilling-fluid related operations were developed in order to reduce contamination of marine environment. To meet the objectives, a CP audit was conducted in an offshore rig site which was executing a drilling operation from top section to reservoir section. Based on the analysis, carbon footprint could be reduced from 48.0 kg to 39.3 kg of carbon dioxide (CO_2) / footage drilled with all the CP options proposed in all four intervals. This is equivalent to 18.2 % of reduction from total of 520.9 MT CO_2 emitted throughout the drilling operations without considering any CP strategies.

Meanwhile, batch drilling technics could be considered as the finest CP option among all. The contribution of batch drilling can be significantly observed via optimization of fluids volume and materials in first and fourth interval.

Keywords: drilling-fluids, seawater pollution, cleaner production, carbon footprint

PENDEKATAN PENGELUARAN BERSIH DALAM KEJURUTERAAN BENDALIR PENGGERUDIAN

ABSTRAK

Bendalir penggerudian atau "lumpur", seperti yang biasa dikenali dalam perindustrian minyak dan gas, memainkan peranan penting dari tahap awal penggerudian hingga he tahap akhir dalam perkembangan sesebuah telaga minyak. Pada masa ini, sebilangan besar bendalir penggerudian yang digunakan adalah berasaskan air yang dihasilkan dengan mencampurkan pelbagai jenis bahan kimia di dalam kemudahan pelantar minyak, atau berasaskan minyak sintetik yang dikitar semula dari kempen penggerudian yang sebelumnya. Sisa bendalir penggerudian dari tangki, serpihan atau sisa-sisa gerudi dari telaga minyak dan bendalir penggerudian yang tercemar daripada pelbagai operasi selalunya dialirkan terus ke dalam laut. Selain itu, banyak operasi sampingan dalam menguruskan bendalir penggerudian adalah kurang mesra alam. Amalan ini boleh menyebabkan pencemaran laut yang membahayakan kehidupan akuatik mikro dan persekitaran lautan secara keseluruhan. Oleh yang demikian, dalam kajian ini, penilaian keseluruhan telah dijalankan terhadap seluruh jangka hayat pengurusan bendalir penggerudian bagi mengenal pasti peluang pedekatan yang lebih hijau dengan menggunakan strategi pengeluaran bersih. Kemudian, strategi pengeluaran bersih yang sesuai akan dipilih dan dinilai dari segi jejak karbon. Melalui inisiatif ini, panduan umum yang lebih mesra alam dapat dijana bagi operasi yang melibatkan bendalir penggerudian supaya dapat mengurangkan kadar pencemaran laut. Untuk memenuhi objektif tersebut, audit pengeluaran bersih dijalankan di sebuah lokasi pelantar minyak yang melakukan operasi penggerudian dari seksyen permukaan ke seksyen takungan gas. Berdasarkan analisis, jejak karbon boleh dikurangkan daripada 48.0 kg ke 39.3 kg karbon dioksida (CO_2) / kaki gerudian dengan semua strategi pengeluaran bersih yang dicadangkan dalam kesemua empat seksyen. Ini bersamaan dengan pengurangan 18.2 % daripada jumlah 520.9 MT CO_2 yang dijana sepanjang operasi penggerudian tanpa mempertimbangkan strategi pengeluaran bersih. Sementara itu, teknik penggerudian secara kelompok boleh dianggap sebagai strategi pengeluaran bersih yang terbaik di antara kesemuanya. Sumbangan daripada penggerudian secara kelompok dapat dilihat secara ketara melalui pengoptimuman isi padu bendalir dan bahan dalam seksyen pertama dan keempat.

Kata kunci: bendalir penggerudian, pencemaran laut, pengeluaran bersih, jejak karbon

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LIST OF SYMBOLS AND ABBREVIATIONS

BOD	:	Biological Oxygen Demand
CDS	:	Casing Drive System
CFP	:	Carbon Footprint
CH_4	:	Methane
CO_2	:	Carbon Dioxide
CO_2 eq	:	Carbon Dioxide Equivalent
COD	:	Chemical Oxygen Demand
CP	:	Cleaner Production
CwD	:	Casing while Drilling
DWM	:	Drilling Waste Management
EEZ	:	Exclusive Economic Zone
EEZA	:	Exclusive Economic Zone Act, 1984
EIA	:	Environmental Impact Assessment
EQA	:	Environmental Quality Act, 1974
FAME	:	Fatty Acid Methyl Esther
GHGs	:	Greenhouse Gases
GHK	:	Good Housekeeping
GWP	:	Global Warming Potential Index
H_2S	:	Hydrogen Sulfide (H_2S).
HFCs	:	Hydrofluorocarbons
LAM	:	Light Annular Mud
LCM	:	Loss Circulation Material

MEMAC	:	Marine Emergency Mutual Aid Centre
MMT CO_2 eq	:	Million Metric Ton CO_2 equivalent
MPD	:	Managed Pressure Drilling
N_2O	:	Nitrous Oxide
NAF	:	Non-Aqueous Drilling-Fluid
NDF	:	Non-Damaging Fluids
OBM	:	Oil Base Mud (OBM)
OIM	:	Offshore Installation Manager
OSPAR	:	Oil Spill Prevention, Administration and Response
PFCs	:	Perfluorocarbons
PHB	:	Pre-hydrated Bentonite
PMCD	:	Pressurized Mud Cap Drilling
ppb	:	part per billion
PPE	:	Personal Protective Equipment
ppm	:	part per million
ROC	:	Retention on Cuttings
SCE	:	Solid Control Equipment
SF_6	:	Sulphur Hexafluoride
SOBM	:	Synthetic Oil Base Mud
TDS	:	Top Drive System
TSS	:	Total Suspended Solid
UNEP	:	United Nations Environment Program
WBM	:	Water Base Mud

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Background

For more than hundred years, burning fossil fuels have generated most of the energy required to power our industries, homes and vehicles. There are so many breakthrough technologies and innovations in renewal energy nowadays, however fossil fuel still provides about eighty percent of our energy demand (Denchak, 2018). Fossil fuel forms from composed organic materials which is trapped under high pressure and temperature beneath the rock for millions of years deep down the earth's surface. With current existing technology, drilling could be the most convenient way of accessing them. Process of extracting fossil fuel from reservoirs located beneath earth's ocean is defined as offshore drilling, while fossil fuel extraction from mainland is defined as onshore drilling.

Offshore operations have been the biggest contributor in petroleum production in Malaysia though there are few onshore operations took place in the last one decade. Drilling operations in Malaysia usually practiced with two types of drilling fluids, which are aqueous drilling fluids and non-aqueous drilling fluids. Aqueous drilling fluids basically uses water as the base fluid thus generally known as Water Base Mud (WBM). Non-aqueous drilling fluids are often referred as Oil Base Mud (OBM) or Synthetic Oil Base Mud (SOBM). SOBM uses paraffin type base oil like Saraline 185V, Sarapar 147 or Escaid 110 as base fluid while OBM uses distilled crude oil like diesel to run their drilling-fluids system. The usage of OBM eventually been substituted with SOBM due to high toxicity content. Paraffin type base oil has been preferred due to the fact that it produces less harm for aquatic lives. By early 90s the usage of OBM is no longer permitted by the drilling operators in Malaysia for their drilling operations.

WBM are generally prepared in the rig site itself. In the event where the campaign requires high volume of continuous supply of WBM, the drilling-fluids will be supplied from the supply base. For SOBM, the reclaimed drilling-fluids from previous drilling campaign will be stored in supply base. Upon the requisition, the fluids from storage will be transferred to the drilling rig sites via the supply vessels. Subsequently, the received SOBM will be reconditioned and treated in rig site itself to fulfill the requirement of well programs.

Petronas Activity Outlook (2021-2023) had reported that 23 drilling rigs was operational in first half of 2020. The number of the operational rigs declined towards the end of 2020 due to global oil price plunge and COVID-19 pandemic. However, it is expected that a total of 22 drilling rigs will be operational by this year, and the numbers might not decline so much towards 2022 and 2023. These figures reflect directly to the numbers of projected well and the usage of drilling-fluids for the next 3 years.

Contaminated drilling-fluids and its residue are usually discharged directly to the seawater. Fluid contamination in most of the scenarios are unavoidable due to the various operations at the rig site. Operations such as well fluids displacements, casing cementations, dead volumes in the tanks and drilled cuttings management are among the main contributor of drilling-fluids discharge to the sea. Therefore, an overall assessment to identify the drilling-fluids discharged throughout the drilling operations to the well completion is required. Possibility of applying cleaner production strategy will be also explored within the boundary of drilling-fluids engineering in the rig site.

1.2 Problem statement

The usage of drilling-fluid is essential from early stage of spudding to completion of a well. Considering its critical function in drilling activities, drilling-fluid is usually prepared excessively to overcome any unforeseen situations like total or partial loss circulations. All this unutilized WBM are usually discharged during the change-over to another fluids system. As for SOBM system, it will be mobilized back to the storage tanks at onshore facilities. SOBM is often categorized as less toxic and easily biodegradable, thus in certain scenarios, direct discharge could be convenient and cost effective in the industry. Even so, SOBM residues from dead volume of mud tanks, drilled cuttings with traces of SOBM and contaminated SOBM from various operations could still be the biggest contributor in seawater pollution in offshore drilling activities. In addition, many of the support operations and practices in managing drilling fluids are less environmentally friendly. All this routine procedure in a long run could create a hazardous environment to micro aquatic life and disrupt overall marine ecology. Pollution caused by drilling-fluids might not be completely prevented, but adoption of cleaner production strategies could minimize these contaminants to more reasonable acceptance. Cleaner production (CP) implementation in oilfield industry is very commonly carried out, yet studies focused on drilling-fluids engineering and its management in offshore rig facilities have not been carried out thoroughly. Therefore, a research will be conducted in a rig facility operating in Malaysian offshore to improve the process and operations of drilling-fluids through cleaner production approaches.

1.3 Research questions

i. What are the current issues with drilling-fluids management contributing to seawater pollution?

ii. How does CP implementation minimize drilling-fluids related environment impact?

iii. How the effectiveness CP strategies in drilling-fluids engineering is measured in the perspective of Carbon Footprint?

1.4 Aim of the study

The aim of the study is to apply CP strategies for greener drilling-fluids management and related process to reduce seawater pollution in offshore drilling operations.

1.5 Objectives of the study

The objectives of this study are:

i. To identify the various operations causing the drilling-fluids discharge in rig site.

ii. To evaluate possible greening opportunities using cleaner production strategy in drilling-fluids management.

iii. To determine Carbon Footprint reduction before and after Cleaner Production implementation.

1.6 Scope of the study

The study is conducted to assess the drilling-fluids management in a drilling rig operating in offshore Malaysia. The scope of the research was focused on the usage and management of drilling-fluids from early stage of spudding the well to completion of reservoir section drilling. This will include all the operations involving various type of drilling-fluids used for all four intervals. System boundary of fluids and waste management are focused within the drilling rig premise, however fluids movements back and forth between onshore storage facility and the rig site are also surveilled.

1.7 Significant of the study

The findings from this study are important to identify the area of improvement which could be taken to improvise the management of drilling-fluids in reducing seawater pollution. The study could also evaluate various drilling operations which could be contributing most of the drilling-fluids discharge to the environment. The guidelines from this study could be used as Cleaner Production options by drilling operators and mud companies so that seawater pollution could be eliminated or minimized as low as reasonably practical.

1.8 Dissertation outline

In nutshell, this study consist of 5 chapters as follows:

i. Chapter 1 – Introduction

This chapter covers the background of the research a brief information on types of drilling-fluids which is being used in drilling operations, components of drilling-fluids causing the sea pollution, the current management of drilling-fluids and projected usage of drilling-fluids and waste generations in 3 years' time. Besides, this chapter discusses problem statement, aim and objectives of the study and scope of the study.

ii. Chapter 2 – Literature review

This chapter discusses previous and current findings on drilling-fluids and how waste generations been polluting the sea. Apart from legal requirements in controlling the release of contaminants to the environment, this chapter also reviews on current practice of fluids and waste management in Malaysia and middle east. Discussions on cleaner production and carbon footprint have also been highlighted here.

iii. Chapter 3 – Research Methodology

This chapter explains the various techniques and methods used in gathering data and information which is relevant to this study. Among the method used includes site visits, interviews and CP audit at the rig site. All the information gathered are analyzed for the possible CP implementation. Carbon dioxide emission factors for the elements in drilling-fluids are determined by computer software and previous studies.

iv. Chapter 4 – Results and Discussion

This chapter involves results obtained by implementing of CP strategies in drilling-fluids engineering. All the CP options proposed will be further analysis and discussed in this chapter. The effectiveness of CP options was measured by carbon footprint quantification. The barriers and challenges on the implementation are also reviewed accordingly.

v. Chapter 5 – Conclusion and Recommendation

This chapter summarizes overall findings from CP approaches in drilling-fluids engineering while assessing if the initial objective was met. Suggestions and recommendation for future studies being highlighted in another segment of this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews previous study towards the applications drilling-fluids in oilfield industry. Seawater pollution could be hazardous to the micro aquatic life and overall marine environment. An overview of seawater pollution and how this could be related to drilling activities are also being discussed here. Drilling-fluids management might differ from one region to another region, hence the studies conducted on drilling-fluids management and the practice in Malaysian operations are being highlighted here. Drilled cuttings from the drilling operations is an important factor to consider in seawater pollution. Thus, previous studies on drilling waste management could an important reference as well. The implementation of CP is what most of the industries seeking nowadays. CP approaches are considered less costly to implement and operate, subsequently providing cost reductions on usage of raw materials, energy and waste disposal. Meanwhile carbon footprint could be used to evaluate the greenness of a product throughout its life cycle. Therefore, the literature reviews on CP and carbon footprint could be essential for this research.

All these previous studies could be helpful in identifying the necessary research which should be further pursued to resolve the issue pertaining in drilling-fluids engineering.

2.2 Drilling-fluids and functions

Drilling-fluids was used all the way from early 1900s to suspend the cuttings from the drilled hole (Bridges & Robinson, 2020). As the technology evolved, drilling-fluids were circulated, and drilled cuttings (pieces of formation) are continuously removed from the system during the drilling operations. Drilling-fluids soon became an integral factor in determining the success of any drilling operations. It is being considered as “blood flow” of drilling till now. Any failure in drilling operations will be inspected in the perspective of drilling-fluids first before focusing on other mechanical factors. Therefore, drilling fluids need to be carefully engineered and designed according to the chemical and physical properties of the formation. Drilling-fluids are engineered to carry out wide range of functions during the drilling operations. According to Williamson (2013), among the important functions are:

i. Controlling formation pressure to avoid kick or well blowout.
ii. Maintain the temperature and lubricate the drilling bit.
iii. Carry out the drill cuttings deep from the formation to the surface.
iv. Acts as medium to transmit hydraulic energy for the movements of drilling bits and downhole tools.
v. Maintaining the wellbore stability by regulating the density so that the well do not collapse.
vi. To assist on studies on the types of formation being drilled so that same techniques could be applied for drilling wells on the same field.

2.3 Drilling-fluids impact to the environment

Seawater which covers more than 70% of earth's surface provides important services to human populations from regulating earth's temperature, dissolve oxygen to enable terrestrial and aquatic animals to survive and also absorbing excessive carbon dioxide from anthropogenic activities.

Seawater pollution due to rapid development in certain countries are alarming. According to Kumar et al. (2020), rapid marine pollution was observed in coastal environment due to uncontrolled industrial development in India for the past 10 years. Most of the pollutants in coastal environment appears from mismanagement of the plastic materials. A team of researchers from United States and Australia had discovered that China and Indonesia are the biggest contributor of plastic wastes which had polluting global waters (McCarthy, 2020). In the same study conducted by Jenna Jambeck an environmental engineer, Malaysia was ranked 8th in the world for their mismanagement of plastic wastes. The study which was done in 2010 estimates about 0.14 to 0.37 million tonnes of plastic wastes could have ended up in the sea. Subsequently, these figures led Malaysia as the 5th global plastic polluter of the oceans (*Malaysia, 5th Global Plastic Polluter of the Oceans,* 2019).

Table 2.1: The Countries Polluting The Oceans The Most, 2010

Annual metric tons of mismanaged plastic waste and total amount ending up in global waters		
Country	Mismanaged plastic waste (MT)	Plastic marine debris (MT)
China	8.8	3.53
Indonesia	3.2	1.29
Philippines	1.9	0.75
Vietnam	1.8	0.73
Sri Lanka	1.6	0.64

Generated in 2010 (selected countries)
Source: The Wall Street Journal

Apart from plastic waste mismanagement, other contributing factors to seawater pollutions are industrial waste discharge, agrochemical runoff and oil spillages from tankers. Although spillages and discharge incidents from offshore drilling operations are rarely reported or not significant, more attention must be given on the drilling-fluids and its waste generation which could be the hidden contributor of seawater pollution.

The most common mode of disposal for drilled cuttings and contaminated drilling fluids generated during various drilling operations is direct discharge. Direct discharging drilling waste is cost effective and simplifies the operations. Direct discharge is necessary when drilling with WBM due to large quantity of waste generated with this activity. Apart from generating cuttings and associated fluid, drilling with WBM generates relatively large volumes of waste fluid. This is mainly due to the intolerance of WBM with fine drilled solids buildup in the circulation system. If the low gravity solids (fine drilled solids) are more than 5% by volume, the rate of penetration will be adversely affected. If the content is greater than 10% by volume, it could be difficult to control the desired physical and chemical property of WBM. Due to the instability of WBM with low gravity solids buildup, “dump and dilute” method may be adopted, depending on the judgment of fluids engineer. Dumping this dirty or contaminated fluid may create eight times the amount of drilling waste created by the drilling cuttings.

Drilling activities involving SOBM do contributes seawater pollution as well. Although direct discharge of any sort SOBM are not allowed, discharge of drilled cuttings with SOBM are still permitted. This is however done after cuttings are treated with sequences of solid control equipment and SOBM being reclaimed back to the system. Apart from this scenario, a significant amount of SOBM could be also discharged during the well fluid displacements, mud tank cleanings and also during the casing cementation jobs.

Increasing attention has been paid to environmental risks posed by drilling operations in recent years. Recent studies find that there may be some long-term liability associated with discharging, even if water-based fluid is used. According to Nguyen et al. (2021) microbial activities were being distorted due to agitation of the seabed surrounding the borehole through deposition of drilled cuttings and residual drilling mud. The components in spent drilling-fluids which have been causing the pollution are biocides, oil, reservoir stimulation fluids, corrosion inhibitors, traces of crude oil and also other drilling mud chemicals (Onwukwe & Nwakaudu, 2012). In a deep water well explorations (water depths more than 200 meters), the trace of WBM and SOBM could be seen over 2 kilometers radius. Ecological impacts on the micro aquatic life on the seabed could be commonly seen from 200 to 300 meters radius from the source (Cordes et al., 2016). This will not only kill the marine lives, but also contaminate fish and shellfish which could be life-threatening to the consumers.

2.4 Legal requirements for offshore discharges

In most of the oil and gas producing countries, stringent environment laws have been enforced with the drilling fluids and drilling wastes. Although requirements from each country could differs, international and regional convention which include drilling activities such as OSPAR (Oil Spill Prevention, Administration and Response), MEMAC (Marine Emergency Mutual Aid Centre) and Barcelona Convention are being used as guideline for their operations. Reviewing from the regulations around the world, the usage of OBM is not preferred due to its high toxicity and hazardous impact to the marine environment (Ismail et al., 2017).

Legal requirements for drilling fluids and its waste management are very subjective and totally depending on the collaboration of the operating company and local environmental authority. In most cases, operating companies will set their environmental policy standards higher than the minimum requirements from local environmental law. Oil and gas companies operating in Malaysia showed pro-activeness in environmental preservation by self-regulating against their own company standards which are adopted from other regions and best industry practice. This is important to maintain their approach to oilfield industry, prioritizing safety and minimizing impact towards nature and environment. According to Shell Global Environmental Standard, discharge of OBM to the sea is not permitted under any circumstances. OBM must be recycled and reclaimed. Meanwhile, the discharge of low toxicity SOBM is permitted under certain scenarios with strict allowance. The treated drilled cuttings with the residue of SOBM is permitted, but the solid control equipments must be efficient to provide retention on cuttings (ROC) below 6.0% by weight. Offshore operations in Malaysia which is governed by Exclusive Economic Zone (EEZ) had specified the discharge oil contaminated effluent should not exceed the concentration 100 ppm. Petronas had taken an extra mile to adopt more stringent specification of 40 ppm and future targetted limits within the region of 10 ppm. Petronas, as national oil company has also developed a guideline for upstream operations in Malaysia entitled Petronas Procedures and Guidelines for Upstream Activities. This guideline gives a generic requirement for the usage of drilling fluids and drilling waste management and discharge. Oil and gas companies operating in Malaysia under the umbrella of Petronas are required to follow these guidelines without any compromise.

Any offshore operation that is 12 nautical miles away from Malaysian water territory is not governed by Environmental Quality Act, 1974 (EQA). However, Environmental

Impact Assessment (EIA) is still required from oil and gas operators by Petronas before project approval. There is no particular law or regulation affiliated with oil and gas operations in Malaysian waters. EQA and Exclusive Economic Zone Act, 1984 (EEZA) are basically general environmental law in Malaysia, which is being adopted by all other industries (Ismail et al., 2017).

Table 2.2: Comparison between Malaysian regulations with international conventions

Type of Drilling Fluid	Malaysia Regulations and Guidelines	OSPAR Convention	MEMAC Convention	Barcelona Convention
WBM	WBM is allowed for usage. Cuttings must be washed properly before disposal to sea.	WBM is allowed for usage. Discharge of WBM is allowed.	WBM is allowed for usage. Discharge of WBM without persistent toxins is allowed.	WBM is allowed for usage. Discharge must be at specific and approved site.
OBM	Low toxicity OBM is not encouraged (minimized), and only for specific hole problem. Sea disposal is not allowed.	OBM discharge is not allowed.	OBM is not allowed for usage, unless approved. Discharge is not allowed at offshore.	OBM is allowed for usage, with prove of low toxicity and approved permits by authority.
SOBM	Low toxicity SOBM is allowed for usage. Sea discharge is not allowed.	SOBM discharge is not allowed. SOBM cuttings discharge authorized based on BAT.	SOBM discharge is not allowed. SOBM cuttings discharge must be with approval from authority.	Not specified.

2.5 Drilling-fluids management

A non-comprehensive WBM system normally used to drill top section of the formation (*Drilling Fluid: Type and Function,* 2015). Pre-hydrated bentonite and spud-mud will be mixed and stored in the mud tanks at the rig site. Usually, top formation is drilled with seawater, and the cuttings drilled will be swept with high viscosity pre-hydrated gel and dumped at the seabed itself (*Spud Mud and Operation,* 2018). Upon reaching the targeted depth of the top section, the well is displaced with spud mud. All the excessive WBM will be discharged to create space for the different mud system to drill the intermediate section. Offshore rigs are designed with limited space for mud volume, thus discharge of previous WBM system could not be avoided. A significant amount of WBM could be also discharged during the mud tank cleanings due to the dead volumes.

Usually, intermediate sections will be drilled with high performance WBM or SOBM. The selection mud system is basically depending on the formation or previous experience. If formation which projected to drill is reactive clay, SOBM will be preferred system. However, if the rig is not capable of handling the solid control equipment dedicated to treat drilling cuttings with SOBM, then high-performance polymer mud (WBM) will be considered (Pino et al., 2018). Considering all this factors, the operating companies will have the final say on the selection of drilling-fluids system. Usually, WBM will be mixed and prepared in rig site facilities. Different strategies are approached if the drilling operations requires SOBM system. Reclaimed SOBM from previous drilling campaign will be stored in facilities or supply base onshore. Upon the requisition, SOBM will be transported to the drilling rigs via supply vessels. SOBM stored in mud tanks is then finetuned and treated with the chemicals as per specifications in drilling programs.

Finally, reservoir sections will be drilled using non-damaging fluids (NDF). Application of NDF control formation damages thus, the content of barite (Barium Sulfate) as weighting agent are avoided (Mandal et al., 2006). Usually, NDF are water base fluids but in certain circumstances like unstable shale formation or long horizontal well design, NDF with synthetic oil base fluids are preferred.

Table 2.3: Drilling-fluids options with selected drilling section

Section	**Type of Drilling-Fluids** **Option 1**	**Section**	**Type of Drilling-Fluids** **Option 2**
Surface Section Interval 1 (26" – 36" hole)	Seawater / Pre-hydrated Bentonite	Surface Section Interval 1 (23" hole)	Seawater / Pre-hydrated Bentonite
Intermediate Section 1 Interval 2 (17 1/2" hole)	Potassium Chloride + Polymer Mud	Intermediate Section 1 Interval 2 (16" hole)	Synthetic Oil Base Mud
Intermediate Section 2 Interval 3 (12 1/4" hole)	Potassium Chloride + Polymer Mud	Intermediate Section 2 Interval 3 (12 1/4" hole)	Synthetic Oil Base Mud
Reservoir Section Interval 4 (5 1/2" – 8 1/2" hole)	Carbonate + Polymer Mud	Reservoir Section Interval 4 (5 1/2" – 8 1/2" hole)	Carbonate + Polymer Mud Carbonate + Synthetic Oil Base Mud
Water Base Mud (WBM)			
Synthetic Oil Base Mud (SOBM)			

During the drilling operations, drilling-fluid will be pumped from mud tanks to the top drive, and all the way to the drill bit. The hydraulic pressure from the fluids will rotate the bottom hole assembly and fluids will be jetted out via the nozzles in the bits. Drilling-fluids will move in the annular path between the wellbore and drill string, carrying the drilled cuttings to the surface (Ahammad Sharif et al., 2017). This mixture is then screened out in shale shakers, and the fluids will be recovered back to the mud tanks. Mud is continuously tested and treated during the entire process of drilling operations to the targeted depth. Upon casing cementation, excessive WBM are usually discharged on the sea. If the drilling operation utilize SOBM for its fluids system, excessive SOBM will be mobilized back to onshore storage facilities.

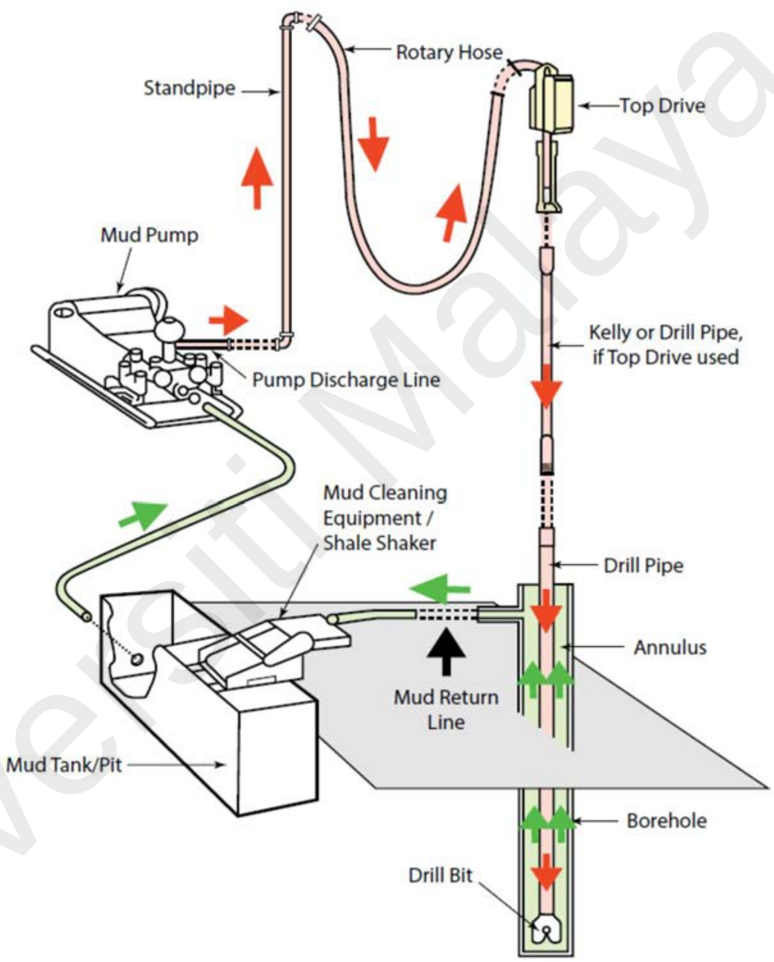


Figure 2.1: Circulating System of Drilling-Fluids (Biyanto et al., 2018)

2.5.1 Drilling-fluids management during the lost circulation

In certain critical situations like total losses, time could be essential factor. Well must be continuously fill with fluid to sustain the formation pressure. Failure of doing this could lead to well kick followed by more serious situations like well blowout. To encounter this situation while drilling in possible total loss zones, Pressurized Mud Cap Drilling (PMCD) could be always the favorable option (Dipura et al., 2018). Huge amount of sacrificial WBM or Light Annular Mud (LAM) will be readily prepared in onshore storage facilities. If it permits, supply vessels and mud tanks in the rig site will be stocked with these fluids as well to minimize waiting time. However, if the drilling operations never encounter any total losses scenarios, all these sacrificial fluids are discharged to the sea.

2.6 Drilling waste management

Generation of drilling cuttings is totally unavoidable in any drilling operations. Depending on the depth and diameter of the wellbore, the volume of drilling wastes generated from each well is different. Typically, each well can generate few thousand barrels of drill cuttings and discharging them directly to the ocean probably the most cost effective an operationally safe option. This could be suitable for drill cuttings with WBM as they require no treatment prior to discharge. As for drill cuttings with SOBM, they are required to go through series of treatment before being discharged into the sea (Ahammad Sharif et al., 2017). Drilling waste management (DWM) is all about cutting discharges while drilling with SOBM. The main function of DWM is to recover SOBM as much as possible while disposing the cuttings generated during the drilling operations. This process is executed via solid control equipment like shale shakers, centrifuges and cuttings dryer.

The drilled cuttings with drilling fluids (SOBM) from the wellbore will move upward in the annulus to the surface. This mixture of fluids and solids will be diverted to shale shakers to go through first treatment process. Shale shakers use vibrations and series of screen mesh to separate drill cuttings from the drilling fluids. The filtered fluid will be recycled to the circulation system, while drilled cuttings will be conveyed to cutting dryers for the second treatment process.

Drilled cuttings will be processed in cutting dryer comprises a circular screen rotating at high speed. Dry cuttings are discharged at the screen bottom and fall by gravity into the "water flushed" trough and dumped overboard. Depending on the efficiency of the equipment, dry cuttings discharged are typically <5% oil content by wet weight (MI SWACO, 2019). The fluids phase from cutting dryer will go through further treatment / centrifugations and returned to mud pits for reuse. The solids from centrifuges will be also discharged overboard.

Certain countries and operators impose more stringent environment law on drilling wastes management. As an example, ADCO in Abu Dhabi emphasize "zero discharge" policy, where all the SOBM drill cuttings collected and mobilized to thermal desorption treatment plant. These treatment plants will be located in the center of major oil producing field, thereby reducing hauling distance (Al-Suwaidi et al., 2004). Referring to Ataya (2008), same approaches will be carried out at offshore, where drill cuttings are transported to onshore treatment facility, or re-injected back into wellbore or annulus of the well.

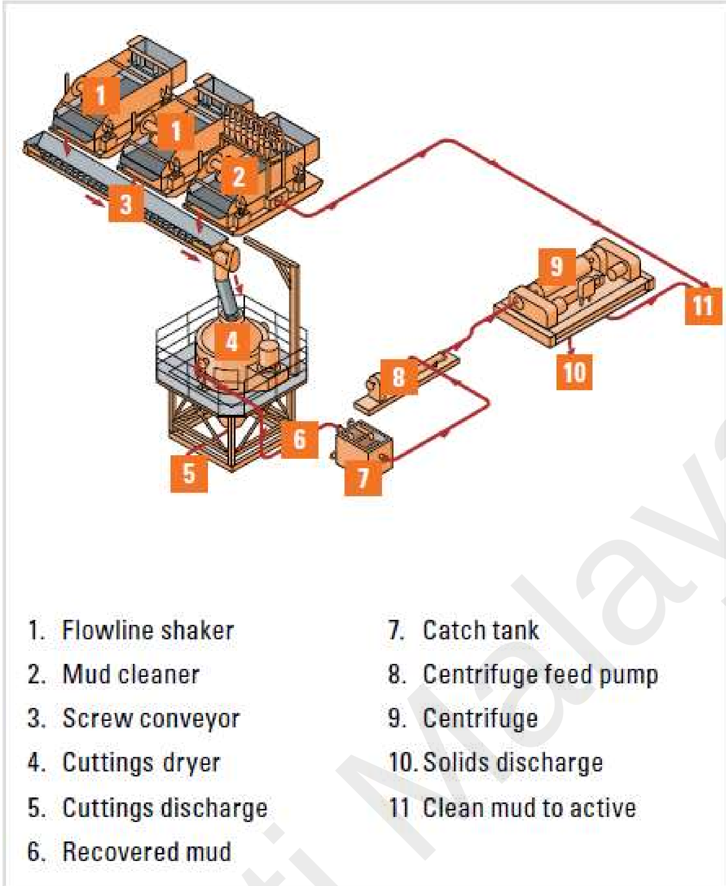


Figure 2.2: Typical setups of solid control equipment in drilling rigs (MI Swaco, 2019)

2.6.1 Drilling waste management in Malaysia

In Malaysia, drill cuttings are permitted to be dumped overboard. However, this is done after drill cuttings are treated with sequences of solid control equipment on board. If the value of retention on cuttings is not attained as per operating company's specification, the drill cuttings will be processed and treated again before being able to be dumped overboard.

2.6.2 Sampling and analysis of drilling cuttings

Evaluating retention on cutting is an analysis of drilling waste specifically intended to measure the amount of base fluid (oil) from cuttings generated during a drilling operation. Samplings will be taken at dry solid discharge from cutting dryer and centrifuges. The value of ROC will be determined by retort test method. Basically, samples are taken in daily basis (every 12 hours) during drilling operations, from the discharge of every solid control equipment.

Retort test method which is being used for this analysis determines percentage weight of base oil over solids discharged from the solid control equipment. Briefly, a known mass of cuttings is heated in the retort chamber to vaporize the liquids associated with the sample. The base fluid and water vapors are then condensed, collected, and measured in a precision graduated receiver (U.S. Environmental Protection Agency, 2011).

i. Determination of the Amount of Non-Aqueous Drilling-Fluid (NAF) Base Fluid from Drill Cuttings by a Retort Chamber (Derived from API Recommended Practice 13B-2) (EPA Method 1674)

a. Clean and dry the retort assembly and condenser. Pack the retort body with steel wool. Apply lubricant/sealant to threads of retort cup and retort stem.
b. Total mass of the retort cup, lid, and retort body with steel wool is weighed and recorded as mass (A), grams.
c. Collect the cutting samples from representing solid control equipment. Partially fill the retort cup with cuttings and place the lid on the cup.
d. Install the retort cup (with lid) onto the retort body. Weigh and record the total mass as (B), grams.
e. Attach the condenser and place the retort assembly into the heating jacket.

f. The mass of the clean and dry liquid receiver is weighed and recorded as mass (C), grams.

g. Place the receiver below condenser outlet. Turn on the retort. Allow it to run a minimum of 1 hour.

h. Remove the liquid receiver. Allow it to cool. Record the volume of water recovered as (V), cm^3.

i. Weigh and record the mass of the receiver and its liquid contents (oil plus water) as mass (D), grams.

j. Turn off the retort. Remove the retort assembly and condenser from the heating jacket and allow them to cool. Remove the condenser.

k. The mass of the cooled retort assembly without the condenser is weighed and recorded as mass (E), grams.

ii. Calculations

a. Calculate the mass of oil (SOBM base fluid) from the cuttings as follows:

Mass of the wet cuttings sample (M_w) equals the mass of the retort assembly with the wet cuttings sample (B) minus the mass of the empty retort assembly (A).

$M_w \quad = B - A$

Mass of the dry retorted cuttings (M_D) equals the mass of the cooled retort assembly (E) minus the mass of the empty retort assembly (A).

$M_D \quad = E - A$

Mass of the SOBM base fluid (M_{BF}) equals the mass of the liquid receiver with its contents (D) minus the sum of the mass of the dry receiver (C) and the mass of the water (V).

$M_{BF} \quad = D-(C+V)$

Note: Assuming the density of water is 1 g/cm^3, the volume of water is equivalent to the mass of the water.

b. Mass balance requirement:

The sum of M_D, M_{BF}, and V shall be within 5% of the mass of the wet sample.

$(M_D + M_{BF} + V)/M_w \quad = 0.95 \text{ to } 1.05$

If this criterion is not meet, the procedure should be repeated again.

c. Reporting oil from cuttings:

Assume that all oil recovered is SOBM base fluid. The mass percent base fluid retained on the cuttings ($\%BF_i$) for the sampled discharge "i" is equal to 100 times the mass of the base fluid (M_{BF}) divided by the mass of the wet cuttings sample (M_w).

$ROC, \%BF_i \quad = (M_{BF}/M_w) \times 100$

If percentage of ROC is more than 6.0% by weight, DWM representatives should pay more concentrations on the efficiency of their solid control equipment.

Discharging small volume of SOBM (*i.e.*, displaced interfaces, contamination during cementing operations, accumulated solids in sand traps, pit clean-out solids, or centrifuge discharges while cutting mud weight) will not be counted in sampling interval. So, for this case:

a. Mass percent for base fluid retained on the cuttings ($\%BF_{SVD}$) for each small volume discharges are measured; or
b. Use a default value of 25% base fluid retained on the cuttings.

2.7 Cleaner Production

In reference to United Nations Environment Program (UNEP), Cleaner Production or CP defined as continuous application of an integrated, preventative environmental strategy to processes, products and services to increase eco-efficiency and reduce risks to humans and the environment" (UNEP, 1997). The strategies of CP must be seen in a wider perspective. It is a “win-win” situation where environment is conserved while improving operation efficiency of the industry (El-Haggar, 2007). According to Rahim and Abdul Raman (2017), a simple CP implementation focusing on energy conservation in recycled plastic resins production plant could potentially reduce its carbon dioxide emission by 0.11 kg/kg resin produced. The concept of CP encourages the industries to look into possible reduction of waste in every stage of process rather than costly end-of-pipe treatment. This reduces long term liabilities which companies can face many years after waste generation and disposal at a given site. The implementation of CP could be easy and requires little capital invested by which recovered in short period of time. Systematic implementation of CP in any industries will not only increases profitability but also leads to more efficient usage of raw materials and energy. This will directly lowers production costs and provides a rapid return on any capital or operating investments.

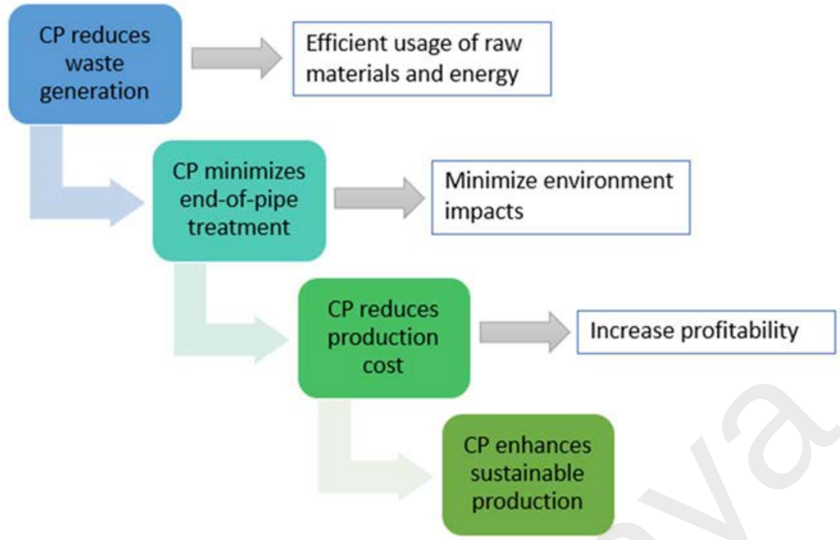


Figure 2.3: Benefits of CP implementation in industry

2.7.1 Cleaner Production strategies

Applying strategies of CP in any industry could be inexpensive. It can be a simple as implementation of good housekeeping (GHK) in production process. According to Khuriyati et al. (2015), wastewater produced from washing production equipment in a cracker company exceeds the quality standard to the environment. However, implementation of GHK by cleaning the waste on the production equipment before washing remarkably improves the environmental performance in Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and Total Suspended Solid (TSS) by 76.67%, 84%, and 40% respectively. Furthermore, the water usage for washing reduced 22.04%.

Another CP strategy which could adopted by industries is substitution of input material. From a research conducted by Sirait (2018), wastewater from Celatik batik industry contains contaminants far larger than the threshold of water quality standard. Cleaner production option was therefore utilized, where chemical dyes are substituted with natural dyes. Environmental performance in terms of BOD, COD, and TSS are significantly reduced with the substitution of input material strategies.

The change of technology could be also explored as a strategy for cleaner production. As per Sangeeth Kumar and Gokulachandran (2015), emission of welding fumes can be prevented by installing local exhaust ventilation with a proper design. They had further explained on-site recovery could be another option to explore as CP strategies. As an example, in-situ water treatment plant shall be established for the purpose of water reuse.

Other alternatives such us efficient usage of energy and raw material could be elemental strategies which could be promote CP. Apart from conserving electricity, the utilization of renewal energy utilization could be more effective CP approach. Meanwhile, efficient usage of raw material could produce less waste generation, thus end-of-pipe treatments could be minimized. In an advanced CP approach, product modification can be also considered. The concept of product modification involves altering product's characteristic in order to obtain minimal environmental impacts of the product during or after its use (disposal).

2.7.2 CP practice in drilling-fluids management

CP always encourages industry to recycle and reduce pollutants at the source rather than end-of-pipe treatment and dispose of them to the environment. This strategy is always preferred in managing pollutants and often regarded as highest priority in "environmental management options hierarchy" in preventing pollution. In such case, few approaches have been implemented in drilling-fluids management in the rig site.

Towards the end of first interval drilling or surface section, WBM are usually discharged in the sea to allocate incoming SOBM from onshore supply base. Incoming SOBM will be treated with additives and utilized to drill second and third interval. Upon reaching the targeted depth and casing cementations, certain oil companies will initiate the fluids engineers to treat the SOBM, before loading it to the supply vessels. Supply vessels will then mobilize this fluid back to onshore supply base, to be stored and recycled again for the next drilling campaign.

In most of the well, NDF will be used as preferred fluid to drill fourth interval or reservoir section. This will be followed by well fluid displacement with salt solution or completion brine. Brine is usually built from inorganic salts of chlorides and bromides or salts of formic acid (Crumpton, 2018) which contributes to high operational cost. Therefore, brine salvaged from this section are usually reused in another drilling campaign. Sometimes, salvaged calcium chloride brine is reused to treat the SOBM to improve the shale inhibition.

In Kingdom of Saudi Arabia (KSA), huge amount sacrificial WBM will readily prepared to encounter total losses scenario at offshore wells. Drilling operations in KSA is solemnly controlled by Saudi Aramco, thus sacrificial WBM in one rig will be shared and mobilized to another rig within the same region depending on the severeness of total lost circulation scenario. This enhances the concept of efficient usage of raw materials, hence reduces significant amount of waste generation towards the end of drilling campaign.

2.7.3 Greener chemicals in drilling-fluids

The technology of drilling-fluids does not evolve so much for the last 50 years. A typical drilling-fluids shall contain base fluid (water or oil), viscosifiers and weighting agent. In advanced engineering, fluid loss chemicals, emulsifiers, shale inhibitors and other additives are added to enhance the performance of drilling-fluids. The opportunity of introducing green chemicals in drilling fluids have been always explored, and this must be carefully engineered to such an extent that the performance of the drilling-fluids is not jeopardized.

i. Oil base drilling fluids

The usage of diesel and crude oil in drilling-fluids is no longer permitted due to high toxicity exposure to the environment (Caenn et al., 2011). In early 1990s most of oil base drilling mud formulation are designed with synthetic base oil, or mineral oil. Mineral oil like Sarapah, Escaid and Saraline could cost higher operational cost, but it is considered as green chemical which could be discharged to the environment under certain circumstances.

ii. Lignosulfonate

Lignosulfonate is largely consumed as plasticizer in making concrete and cement production. In water base drilling-fluids, lignosulfonates are being used as thinner to reduce the viscosity. Chromium based lignosulfonates were widely used in drilling industry more than 30 years ago. Throughout the studies, drilling industry had accepted the fact that additives containing hexavalent chromium are hazardous to the environment. Hence the usage if chromium lignosulfonate as additives in drilling-fluids was discontinued (Park, 1988). The heavy metal content is removed, and currently chrome-free lignosulfonate are widely used as thinning agent in drilling-fluids.

iii. Asbestos

Asbestos is widely used in industries in 1960's due to its resistance to fire and durability against high temperature. Due to its chronic effects, little had known about the hazards of asbestos fiber back then. The usage of asbestos even introduced as additives in drilling-fluids. Flosal, an additive which is used in drilling fluids contain 85% – 95% asbestos. Exists in a white fibrous powder, Flosal was commonly used to adjust the viscosity drilling-fluids (*Drilling Mud From Long Ago and Mesothelioma*, 2021). U.S. government banned the usage of asbestos by 1970s, however offshore oil companies considered the law inapplicable for them. The usage of asbestos type additives in drilling-fluids were continued until at least 1989 (*Drilling Rig Workers and Engineers at Risk of Asbestos Exposure*, 2021). The usage of asbestos is completely eliminated from drilling fluids or any sort of addittives in today's drilling industry. Organic clay as viscocifier became common additive in synthetic base drilling fluids. From laboratory tests conducted by Li et al. (2014), organic clay prove to be effective in increasing the viscosity and reducing the fluid loss synthetic base drilling-fluids. Organic clay's performances were better than additives of the same kind at home and abroad. Furthermore, the results shows that organic clay have good compatibility with other additives used in synthetic based drilling-fluids.

2.8 Carbon Footprint in oil and gas industry

As per Kyoto Protocol, six main greenhouse gases (GHGs) which are causing climate change are identified as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). Thus, carbon footprint (CFP) can be defined as total emission of GHG of a product or services over its entire lifecycle and the impact created to the environment. CO_2 and CH_4 are generally considered as main culprit of climate change in recent years.

The increase of these GHGs often related to anthropogenic activities for the last 60 years due to the vast industrialization. According to Lindsey (2020) global atmospheric CO_2 was recorded at 409.8 ± 0.1 part per million (ppm) in 2019 sets as a new record high. It was an increase of 2.5 ± 0.1 ppm from 2018, equivalent to the increment between 2017 and 2018. The major cause for this increase was because the burning of fossil fuel for energy generation. Meanwhile, the global growth rate of atmospheric CO_2 in 1960s was just around 0.6 ± 0.1 ppm per year.

Estimated one third of global methane emission to atmosphere comes from organic decomposition of bacteria. Another 20 % to 25 % of methane emission contributed by agriculture and fossil fuel burning respectively. Recent study by Jackson et. al (2020) suggested that's global average methane concentration reached the region of 1875 parts per billion (ppb) at the end of 2019 which is more than two-and-a-half times pre-industrial levels.

Emission of GHGs in oilfield can be divided into exploration, production, transportation and refining. Drilling-fluids management is primarily associated with exploration; hence this study is focused on the GHGs emission in exploration. From the data collected since 1990, U.S Environmental Protection Agency (2021) had reported that the emission of CH_4 in petroleum system decreased by 91 % in 2019. However, emissions of CO_2 from exploration in 2019 were 5.8 times higher than in 1990. In natural gas system, CH_4 emission from explorations decreased 87 % from 1990 to 2019. CO_2 emission which was also recorded on the same period of duration shows the declining trend of 42 % due to decrease in flaring operations.

Table 2.4: Total Greenhouse Gas Emissions (CO_2, CH_4, N_2O) from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2015	2016	2017	2018	2019
Exploration	3.4	4.9	4.3	1.7	1.9	3.1	2.2
Production	50.8	43.2	66.0	55.9	59.0	67.3	75.1
Transportation	0.2	0.1	0.2	0.2	0.2	0.2	0.2
Crude Refining	4.0	4.5	4.9	4.8	4.6	4.5	5.9
Total	**58.3**	**52.7**	**75.5**	**62.7**	**65.7**	**75.1**	**83.5**

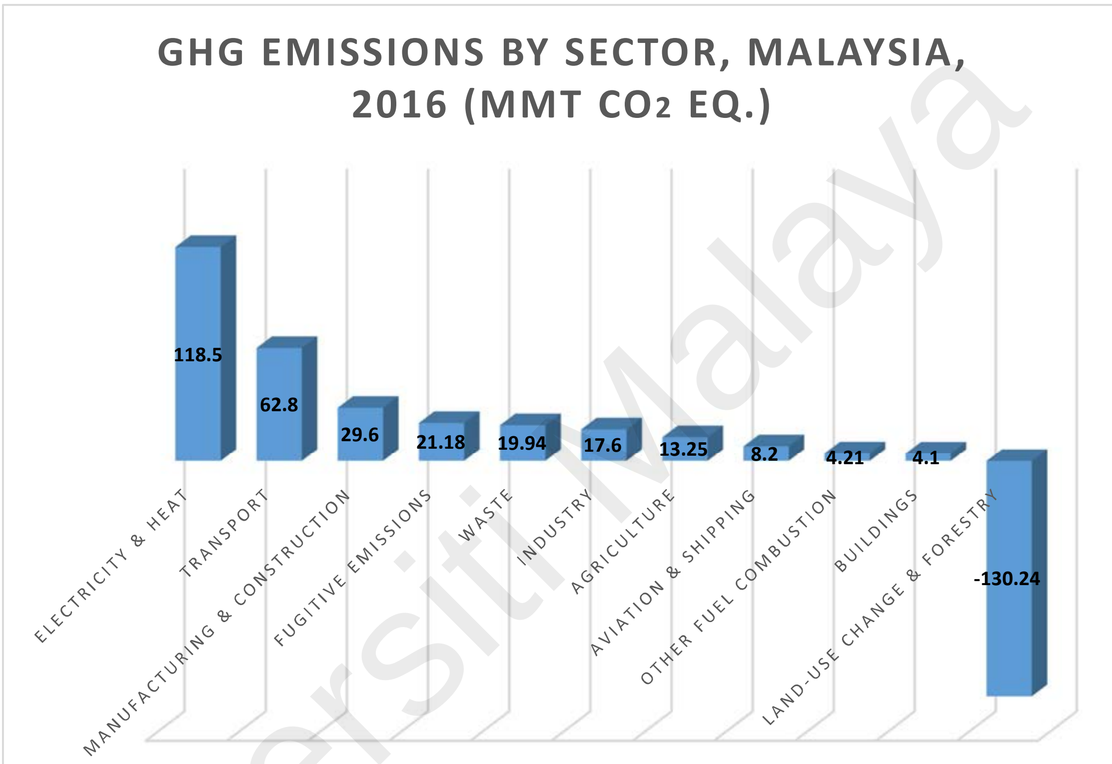
Note: Totals may not sum due to independent rounding.
Source: United States Environmental Protection Agency

Table 2.5: Total Greenhouse Gas Emissions (CO_2, CH_4, N_2O) from Natural Gas Systems (MMT CO_2 Eq.)

Stage	1990	2005	2015	2016	2017	2018	2019
Exploration	4.4	11.9	1.3	0.9	1.7	1.2	0.8
Production	62.7	84.7	95.8	93.5	95.5	98.9	103.1
Processing	49.7	30.4	32.0	33.2	34.5	35.2	37.2
Transmission and Storage	57.4	36.2	34.4	34.8	32.9	35.3	38.2
Distribution	45.5	25.6	14.4	14.3	14.2	14.1	14.0
Total	**219.7**	**188.9**	**177.8**	**176.8**	**178.8**	**184.7**	**193.3**

Note: Totals may not sum due to independent rounding.
Source: United States Environmental Protection Agency

Accurate quantity of GHGs emission in oil and gas exploration in Malaysia could not be determined due to lack of studies. However, through data compilations from 1990, Ritchie and Roserd (2020) suggested that electricity and heat productions in 2016 being the largest contributor of GHGs emission at 118.5 million metric ton CO_2 equivalent (MMT CO_2 eq). This is followed by emission by transportations and manufacturing at 62.8 and 29.6 MMT CO_2 eq respectively. GHGs emission by industries which could include the entire segments of oilfield are on sixth with 17.6 MMT CO_2 eq.



Source: CAIT Climate Data Explorer via Climate Watch

Figure 2.4: Greenhouse gas emissions by sector in Malaysia 2016

2.9 Summary of literature review

Drilling-fluids plays a vital role in drilling operations. While providing hydrostatic pressure to sustain formation pressure, circulation of the fluid lifts out the drill cuttings out from the formation. More advanced engineering was explored to enhance the performance of drilling-fluids. Thus, additives were engineered and introduced into the fluids according to the behavior of the wellbore formation. However, recent studies revealed that some of these additives could lead to serious environment impact and adverse to human health, thus toxic components from these additives are removed. In some cases, the usage of these chemicals is completely eliminated. Options of applying greener chemicals must be explored more to enhance the concept of CP in drilling-fluids management.

Seawater pollution has always been major concern on drilling operations at offshore. Stringent environment law was adopted by all the operating companies however discharge of drill cuttings and contaminated drilling-fluids are still allowed. This is however can be only proceeded under certain circumstance with scrutinized sampling and analysis which is set by operating companies. Applying CP strategies could further minimize these direct discharges to the ocean, hence understanding drilling-fluids and drilling waste management could be beneficial. Efficient usage of materials and on-site recovery of fluids and waste need to be further studied in perspective of CP. Although end-of-pipe could be the least option preferred, the feasibility of utilizing pre-treated drill cuttings for other industrial purposes in Malaysia need to be explored.

Identifying carbon footprint of a process or product could be beneficial to locate the area need to be focused for CP implementation. Although data collected in 2016 suggesting CFP by industrial sector emits 17.6 MMT CO_2 eq, it does not specifically identify the CFP of the oilfield industry in Malaysia. Further focusing CFP on division of exploration, production, transportation and refining could determine where exactly we are in terms of GHGs emission in oilfield industry.

In summary, plenty of efforts in reducing seawater pollutions have been actively imposed in offshore drilling operations. Nevertheless, there are still room for improvements and lack of transparency especially in activities involving drilling-fluids and its waste generation. Therefore, a study is required to analyze possible inefficiency in drilling-fluids management and how implementing CP strategies could further green the operations in rig site.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter summarizes specific procedures or technique used to conduct the study. Further explanations on how the necessary data was retrieved, processed and analyzed to achieve the stated objective will be reviewed here. Subsequently, all the data will be interpreted and further discussed in Chapter 4 (Result and Discussion).

The data obtain in this research were generated from case study of a gas reservoir well drilled in Sarawak offshore. This particular well was chosen based on its drilling operations, which includes all the drilling intervals from top section to the reservoir section, using various type of mud system. However, information from other wells drilled in region of middle east is also used as comparison.

Before leaving to the field site, an approval to conduct this research in the rig facility was obtained from the client company in charge. The choice of rig was influenced by its active participation in drilling activities, completing an average of 6 to 8 wells in yearly basis. The rig facility hires huge number of personnel for its operations, who works 12 hours in shift basis. Other factors considered in choosing this rig facility are based on the followings:

i. Huge capacity of drilling-fluids storage.
ii. The rig's capability of handling various drilling fluids, e.g., WBM, SOBM and brine.
iii. The rig's capability in handling drill cuttings with SOBM.
iv. Good safety culture and safety records.

A cleaner production audit was conducted in the rig site to acquire a comprehensive overview of drilling-fluid engineering in order to achieve the main objective of the audit including waste reduction and efficient consumption of resource and energy. Overall process of drilling-fluids management was observed from fluids loaded from supply boat to fluids discharged back to supply boat. The observation also includes the mud built and waste generated in the rig site, which means the system boundary of fluids and waste management set within the drilling rig premise. Fluids and waste discharged from each process is quantified and subsequent GHGs generation is calculated. The main methodology for this research is highlighted as per below:

i. Site visit to the rig site.
ii. Conduct interview to identify the current situation in drilling-fluids and waste management.
iii. Carry out CP audit.
iv. Identify area of probable CP implementation.
v. Generation of CP option.
vi. Carbon footprint evaluation.

3.2 Methodology flowchart

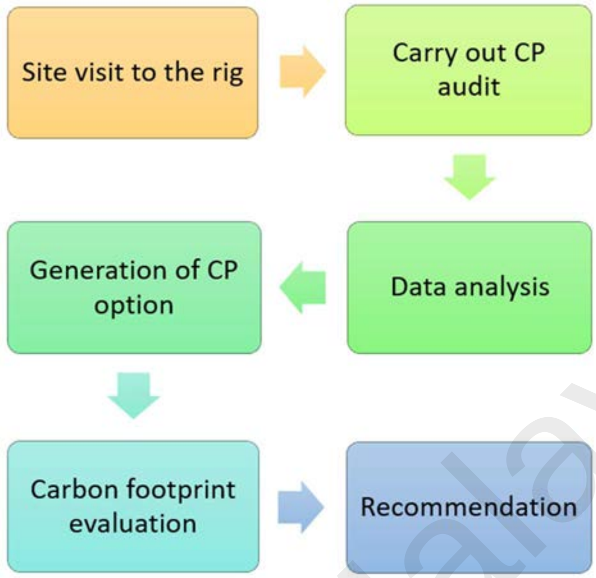


Figure 3.1: Methodology flowchart

3.3 Site visit to the rig

Time would be a limitation factor during the site visit to the rig, hence a detailed work plan and time schedule for activities was drafted in advance. Site visit must be carried out on the right timing of drilling operations, therefore good communication with the drilling engineer and drilling supervisor is essential. The first step upon arrival of the rig facility was safety orientation and initial meetings with Offshore Installation Manager (OIM) and client representatives. Further orientation was carried by safety office onboard so that emergency exits and lifeboats are familiarized. All the in-house rules and regulations of the rig facility were strictly adhered without any compromise. To ensure the safety of the new person on board, assessor was always accompanied by authorized personnel in the area. But before this could take place, all the entry permits were obtained, approved and verified by OIM, client representative and safety officer.

Throughout the site visit, a walk-through assessment was carried out to get some rough ideas on what need to be focused. A good observation could be essential to get the understanding on how drilling-fluids are managed. During the walk-through, informal interviews among the workers were conducted to enhance the knowledge on how things are operated and what was their principal subjects of concern. It is important to gain an early rapport and trust among these individuals, to start with a positive note so that they will clearly understand that the audit is an improvement strategy, not a policing tool. Subsequently, all these evaluations are used to improvise CP audit plans.

3.4 Cleaner Production audit

It is important to prepare audit plans and develop audit protocols in advance so that invaluable time during the CP assessment is well utilized. These audit techniques were further improvised upon walk-through, hence led the focus to those areas which require more concern.

Cleaner production audit is a crucial foundation for CP strategy implementation. This audit was designed to identify and provide information about the opportunities in drilling-fluids engineering, which could be utilized in reducing environmental impact. This is done by exploring resource conservation and reduction on waste generation while maximizing profitability (Department of Environment, Malaysia, 2007). CP audit was initiated by developing CP audit checklist. The structured checklist comprises the following aspects:

i. Source, quantities and type of waste generated.
ii. Information on unit operation, raw materials, final product, energy usage and waste generated.

iii. Identify process efficiencies and area of process control.

iv. Identify the area of poor housekeeping.

v. Evaluate the existing end-of-pipe treatment.

Formal interview is another useful tool which could be used to assist in CP audit. However, it is important to explain the interviewee on how the data obtained is used during the audit and emphasize the confidentiality on the information given. This may greatly affect the response of the person without prejudice. Interviews were carried out with the area supervisors to get in-depth information on:

i. Overall practice in drilling-fluids engineering.

ii. Incidents of drilling-fluids spillages to the ocean.

iii. Information on drilling-fluids discharge from each process.

iv. Information on drill cuttings discharge during the drilling.

v. Current practice drilling-storage and mud tank cleaning.

vi. Information on solid control equipment or waste treatment facilities.

vii. Information on drilling-fluids contamination.

viii. Known hazards of material to human and environment.

3.5 Data analysis and generation of CP option

From all the useful information and data obtained during the site visit, interviews and CP audit, data analysis is done to evaluate the proposed CP implementation in necessary area. The CP options are designed accordingly in the consideration of safety of the worker, risks of hazardous chemical exposure, risks to the existing process control and environmental merit. Other human factor issues like ergonomics and workers approach towards CP was also evaluated in implementing the options. Subsequently, carbon footprint before and after implementing the CP were used as tool to measure the effectiveness of CP option.

3.6 Carbon dioxide emission factor

Emission of GHGs usually calculated by determining the emission amount of each GHG components like carbon dioxide, methane and nitrous oxide. However, the term "carbon dioxide equivalent" (CO_2 eq) is used as standard to describe GHGs in a common unit. In another word, CO_2 eq can be defined as quantity of carbon dioxide which could cause equivalent impact as GHGs to global warming. CO_2 eq could be calculated by multiplying amount of GHGs with its Global Warming Potential Index (GWP) (Brander & Davis, 2012).

Table 3.1: Global Warming Potentials (IPCC Fourth Assessment Report, 2021)

Species	Chemical formula	Global Warming Potential (100-year time horizon)
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	NO_2	298

3.6.1 Carbon dioxide emission factor with SimaPro

In this study, SimaPro software was used to obtain CO_2 emission factor of each additive in preparation of specific drilling fluids. The method used for the analysis was IPCC 2013 GWP 100a, suggested the most suitable to analyze carbon emission.

Table 3.2: CO_2 emission factor of various chemicals used in WBM and SOBM system (SimaPro – Analysis Method: IPCC 2013 GWP 100a)

WBM Additives		**SOBM Additives**	
Chemical / Material	**CO_2 Emission Factor (kg CO_2/kg)**	**Chemical / Material**	**CO_2 Emission Factor (kg CO_2/kg)**
Water	0.00024	Base oil (Paraffin)	0.743
Soda Ash (Sodium Carbonate)	1.030	Emulsifier (Fatty Acid)	4.400
Caustic Soda (Sodium Hydroxide)	0.861	Water	0.00024
Fluid loss control (Starch)	0.996	Calcium Chloride	0.760
Barite (Barium Sulphate)	1.120	Lime (Calcium Hydroxide)	0.0716
Viscosifier (Bentonite clay)	0.047	Viscosifier (Bentonite clay)	0.047
Sodium Chloride	0.238	Fluid loss control (Natural Asphalt)	0.0178
Calcium Carbonate	1.730	Barite (Barium Sulphate)	1.120
Magnesium Oxide	1.110		
Sodium Bicarbonate	1.31		

LCM materials such as Kwikseal usually blended with granular, flake and fibrous materials from plastic, woodchips and nut shells. Thus, the carbon dioxide emission factor for Kwikseal was calculated based on estimated percentage composition of its elements.

Table 3.3: CO_2 emission factor for Kwikseal with SimaPro analysis

Material	Kwikseal		
Type	Lost control additives for WBM and SOBM		
Reference	SimaPro – Analysis Method: IPCC 2013 GWP 100a		
Components	**CO_2 Emission Factor (kg CO_2/kg)**	**Composition (% by weight)**	**CO_2 Emission Factor by Composition (kg CO_2/kg)**
Polyethylene terephthalate waste	0.279	5.0	0.01395
Woodchips	0.187	95.0	0.17765
Carbon dioxide emission factor for Kwikseal (kg CO_2/kg)			0.19160

All the additives for drilling-fluids are packed according to the safety of the consumers. Usually, high quality paper bags or polypropylene woven bags are used as packaging material for dry chemical, with weight capacity of 25 kg while dry bulk chemicals are mobilized in polypropylene woven bag, with weight capacity of 1 MT. All these packaging wastes are considered as hazardous waste from the rig site, therefore sent for waste treatment plant in Kuching. Assuming all the hazardous wastes incinerated in the plant, carbon emission factor for 1 kg hazardous waste is determined from SimaPro analysis.

Table 3.4: CO_2 emission factor for hazardous waste with SimaPro analysis

Material	Packaging wastes from offshore rig
Type of treatment	Hazardous waste incineration
Reference	SimaPro – Analysis Method: IPCC 2013 GWP 100a
CO_2 Emission Factor (kg CO_2/kg)	2.63

3.6.2 Carbon dioxide emission factor from journals

Few organic chemicals used in formulating drilling-fluids are unique, therefore CO_2 emission factors for these chemicals and are not available in SimaPro. For this case, the factors are obtained from previous studies from other researchers. Chemicals in the studies might not represent the exact composition of additives used in drilling-fluids. However, the choice was justified based on its functionality and similar purpose for other industries which could be incorporated with drilling-fluids.

CO_2 emission factor for viscosifier or guar gum was obtained from an experimental trial conducted in 2012 in two guar farms in Sicily, Southern Italy (Gresta et al., 2014). Meanwhile, the factors for biocide are obtained from another study which was conducted to determine the carbon footprint for rain-fed watermelon production in Northern Iran (Mohammadi-Barsari et al., 2016).

Table 3.5: CO_2 emission factor of chemicals obtained from journals

Chemical / Material	Type	Reference	CO_2 Emission Factor (kg CO_2/kg)
Viscosifier (Guar gum)	WBM/NDF additives	Gresta et al., 2014	1.2733
Biocide	WBM/NDF additives	Mohammadi-Barsari et al., 2016	5.0938

Packaging materials used for liquid chemicals are normally 55 gallons steel or plastic drums. Usually, used drums are transported back to onshore and will be taken care by third party company for cleaning and reconditioning. According to Rietveld and Hegger (2014), carbon footprint for steel drum and plastic drum reconditioning are 20.907 kg CO_2 / drum and 20.862 kg CO_2 / drum respectively.

3.7 General safety

Safety is the prime concern at rig sites during the CP audits, thus it is important to follow in-house safety rules without any compromise. During the site visit, all the possible physical and mechanical hazards are identified. Personal protective equipment (PPE) are worn all the time at work area. In area with high noise exposure, double hearing protection are done. Work and entry permits must be approved by safety officer, OIM and company representative before entering hazardous area. Buddy system is implemented in areas where more than one person needed for monitoring and physical assistance. Plus, assessor must always be aware of type emergency alarms, emergency exits and location of the lifeboats.

All the data and information for this study was collected before Malaysia was hit by waves of Covid-19 pandemic. But with the current situation, stricter measures were taken to ensure the safety of the workers at the rig site. Any personnel assigned to the rig are required to undergo 2 weeks quarantine prior to their travel. A swab test was also taken during this period of time to ensure they are free from the virus.

CHAPTER 4: RESULT AND DISCUSSION

4.0 Introduction

Well-KLM is a gas reservoir located at Sarawak offshore. Simultaneously with other wells in the same field, development of this well intend to supply natural gas to an offshore integrated processing complex before being piped onshore to the LNG complex in Bintulu. This well is programmed to be completed within 40.3 days from the start of rig-up activities.

All the information and data obtained during the site visit and CP audit are analyzed for the possible CP strategies during drilling operations in perspective of drilling-fluids engineering and management. All these strategies were prioritized for optimum usage of materials and minimization of wastage. Preparing just the right volume of drilling-fluids for the operations could be the best solution material optimization, however this could end up in huge failure if it is not diligently planned. Contingency volumes were the main factor contributing to the high waste generations of drilling-fluids. But from the perspective of safety, the importance of these volumes should not be simply neglected during the CP implementation.

In those areas where the above strategies were not feasible, other strategies like change of technology or process design were explored. The usage of more environmentally friendly or greener chemicals could be an added advantage in reducing the end-of-pipe treatment, however these materials must not incapacitate the performance of the drilling-fluids. Few chemicals used during the preparations of the drilling-fluids might cause serious injuries to the personnel, thus the usage of alternative chemicals was considered. The possible adoption of CP strategies was also explored from the perspective of waste generated from packaging materials. In certain work practices, even a simple approach of good housekeeping could contribute to efficient CP application.

Electricity in the rig were generated from diesel generators and centralized for the entire rig facilities, therefore carbon footprint for energy usage could not be determined accurately especially in fluids preparations and management. So, the efficiency on proposed CP options were measured by calculating the carbon footprint on the material usages and waste generated before and after the implementation.

4.1 Type of chemicals and its function in drilling-fluids system

Drilling-fluids are mixture derived from natural chemical compound which was used to remove the cuttings deep down the well bore to the surface. At the same time, this fluid provides hydrostatic pressure to prevent well collapse and control the formation pressure. As more study conducted to understand the behavior of the formation, other synthetic and inorganic additives added into the fluids system to cover wider range of functionality according to the composition of formation. As an example, drilling formation of reactive clay with conventional WBM system could lead to the issues of bit balling and gumbo (sticky, swelling clay formation). To encounter this issue, polymers and inhibitors are added to encapsulate shale surface with a film that incapacitate dispersion and disintegration. The function of each chemicals plays an elemental role in drilling-fluids performance, subsequently enhancing the drilling operations. Some of these chemicals or its elements could be hazardous to human and environment. Thus, implementing CP strategies was seen in perspective of materials substitution, material elimination or usage of the other alternative greener chemicals. For non-hazardous chemicals, other CP options such as reduction in packaging materials, material optimizations and good housekeeping can be considered as areas of improvement. The chemical functions and its usages vary on the type of drilling-fluids and its interval, therefore the CP strategies are discussed as per the intervals of drilling operation.

4.2 Drilling operation intervals with various drilling-fluid systems

The possible application of CP options was studied in all four intervals of drilling operation according to changes in drilling-fluids system during the drilling operation. The first interval was drilling top section of 23 inches hole with seawater and high viscosity bentonite gel. Upon reaching the targeted depth the open hole was backreamed whilst displacing its content with spud mud. The second interval was drilling intermediate section of 16 inches hole with SOBM. Upon reaching the targeted depth, casing was run in and set to the desired depth. Similar operation steps executed during the third interval which is drilling intermediate section of 12.25 inches hole with conditioned SOBM salvaged from previous interval. Finally, the fourth interval of drilling operation whereby 8.5 inches hole was drilled in reservoir section with water based NDF. After reaching the final targeted depth, existing NDF in the well was displaced by aqueous salt solution or brine for completion activities. All the fluids operations in each of the intervals are discussed further and possible implementation of CP strategies explored thoroughly by intervals.

4.3 Identification of CP options in first interval

The top section of 23 inches was drilled from 546 ft to 2314 ft with seawater and pre-hydrated bentonite (PHB). 18.625 inches casing was run in and cemented at the depth of

2239 ft. A total of 4 days was taken from the rigging up activities to the completion of this section. Total volume WBM prepared for this interval was 4848 bbls. From this volume, 1745 bbls were used to sweep the drilled cuttings from the wellbore to the surface and another 1083 bbls were utilized as spud mud prior to casing operations. The balance volume of 2020 bbls were dumped or discharged directly to the sea after casing cementation. Therefore, total mud usage of this interval can be summarized as 2.74 bbls per footage drilled or 1212 bbls per day. As per Table 4.1, carbon emission of 1 bbl WBM is estimated at 26.2 kg CO_2. If usage of WBM is analyzed from the aspect of carbon emission, 71.7 kg of CO_2 is emitted per footage drilled or 31.7 MT of CO_2 is emitted per day. Overall process flow for top section drilling of 23 inches and the management of drilling-fluid and drill cuttings are shown in Figure 4.1.

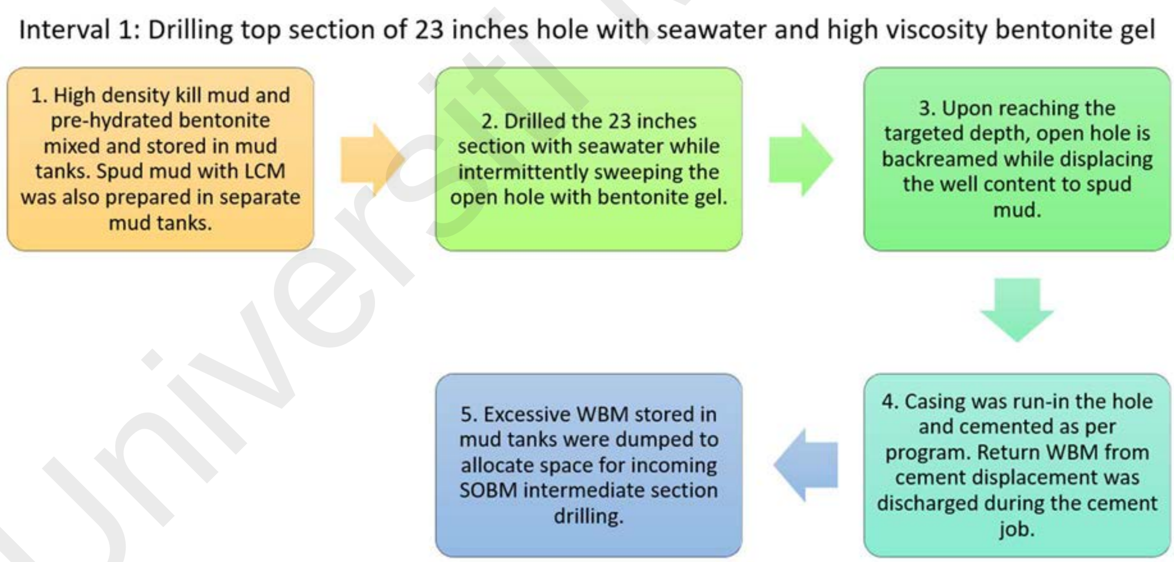


Figure 4.1: Interval 1 – Drilling top section of 23 inches hole with various WBM

4.3.1 Optimization of WBM volume and material usage

The projected PHB to be used while drilling top section is just about 1700 bbls. Instead, an extra 645 bbls were prepared making a total volume of 2345 bbls of PHB. PHB was diluted with seawater before it could be used as sweeping agent for cutting removals. Without viscosity, drilling with seawater do not have the ability to suspend the cuttings and bring the cuttings out to surface. So frequent pumping of PHB was required to sweep the cuttings out, which was contributing a large volume of wastages. This could be solved if the drilling operation is executed in closed system, where the drilling-fluid pumped is recycled back into system. One of the main problems here could be the sand content built up in the system. But with appropriate utilization of the solid control equipment like desanders, centrifuges and finer mesh in shale shakers, this could be avoided. Dump and dilute strategies could also be used the minimize sand intrusions into the mud system.

4.3.1.1 Utilizing kill mud for spud mud without LCM additives

Kill-mud is usually prepared for the contingency to overcome shallow gas scenarios while drilling top section. Upon reaching the targeted depth, kill mud shall be diluted for the purpose of spud mud preparation. But this practice this is not feasible due to time constraint. Hole back-reaming took place immediately after reaching targeted depth and this requires spud mud spiked with 20 lb/bbl of loss circulation material (LCM). Practically mixing spud mud with this high concentration will require huge amount of LCM and time. So, for this section, spud mud was being prepared in advance. 1020 bbls kill mud prepared prior to drilling was dumped upon completing casing cementation of 23 inches section. This huge number of wastages could be avoided if LCM is not required for the spud mud. Usually, well will be monitored for losses after reaching the targeted depth. If the well is not facing any significant losses, the usage of LCM might not be needed after all. Thus, kill mud could be easily diluted in a short period of time and utilized as spud mud. Table 4.1 shows various type of WBM prepared and its carbon footprint throughout first interval drilling.

Table 4.1: Type of WBM prepared and its carbon footprint in first interval

Chemical	Total chemical usage (kg)	CO_2 emission factor (kg CO_2/kg)	Total CO_2 emission (kg)
Estimated carbon footprint for PHB			
Caustic soda	475	0.861	409.0
Soda ash	475	1.03	489.3
Bentonite	45000	0.047	2115.0
Viscosifier	225	1.2733	286.5
Drill water	337052.4	0.00024	80.9
Total CO_2 emission, (kg CO_2)			3380.6
Total volume PHB mixed			2345
CO_2 emission, (kg CO_2 / bbl)			1.4
Estimated carbon footprint for kill mud			
Chemical	Total chemical usage (kg)	CO_2 emission factor (kg CO_2/kg)	Total CO_2 emission (kg)
Caustic soda	200	0.861	172.2
Soda ash	75	1.03	77.3
Viscosifier	750	1.2733	955.0
Barite	68000	1.12	76160.0
Total CO_2 emission, (kg CO_2)			77364.4
Total volume kill mud mixed			1020
CO_2 emission, (kg CO_2 / bbl)			75.8
Estimated carbon footprint for spud mud			
Chemical	Total chemical usage (kg)	CO_2 emission factor (kg CO_2/kg)	Total CO_2 emission (kg)
Caustic soda	300	0.861	258.3
Soda ash	100	1.03	103.0
Viscosifier	975	1.2733	1241.5
Barite	38000	1.12	42560.0
Kwikseal	10500	0.1916	2011.8
Total CO_2 emission, (kg CO_2)			46174.6
Total volume spud mud mixed			1483
CO_2 emission, (kg CO_2 / bbl)			31.1
Total CO_2 emission from various WBM, (kg CO_2)			**126919.6**
Total volume WBM mixed			**4848**
CO_2 emission, (kg CO_2 / bbl)			**26.2**

Surface losses due to hole cleaning is unavoidable, but with proper planning, other dumping or discharges of WBM directly to the sea could be reduced. Table 4.2 will further visualize the reduction on carbon footprint with the optimization of WBM volume and materials.

Table 4.2: Estimated carbon footprint before and after optimization of volume and materials

Estimated carbon footprint for various WBM used in first interval			
	Volume mixed (bbls)	CO_2 emission, (kg CO_2 / bbl)	Total CO_2 emission (kg)
PHB	2345	1.442	3380.6
Kill mud	1020	75.847	77364.4
Spud mud	1483	31.136	46174.6
Total CO_2 emission, (kg CO_2)			126919.6
Total volume WBM mixed			4848
CO_2 emission, (kg CO_2 / bbl)			26.2
Estimated carbon footprint with optimization of volume and material usage			
	Volume mixed (bbls)	CO_2 emission, (kg CO_2 / bbl)	Total CO_2 emission (kg)
PHB	2345	1.442	3380.6
Kill mud	493	75.847	37392.8
Diluted kill mud	527	75.847	39971.6
Chemicals	Total chemical usage (kg)	CO_2 emission factor (kg CO_2/kg)	Total CO_2 emission (kg)
Caustic soda	200	0.861	172.2
Soda ash	75	1.03	77.3
Viscosifier	650	1.2733	827.6
Total CO_2 emission, (kg CO_2)			81822.1
Total volume WBM mixed			4321
CO_2 emission, (kg CO_2 / bbl)			18.9

As per table above, a reduction of 45.1 MT in carbon emission is achievable if all the kill mud utilized as spud mud, without LCM additives. More significant carbon reduction could be observed if drilling operations are executed in closed-loop fluid circulation concurrently with dump and dilute techniques. Assuming this strategy conserves about 50 %

of total volume PHB built for 23 inches section, 1.7 MT of CO_2 emission could be reduced further. As conclusion, by strictly adhering strategies of volume and material optimization, CO_2 emission could be brought down from 126.9 MT to 80.1 MT, which is equivalent to 36.9 % reduction. However, these CP options need to be evaluated thoroughly to ensure the rig productive time is not affected. Time required for kill mud dilution and equipment abrasion due to sand built-up in system would be an essential factor to consider.

4.3.1.2 Volume and material optimization with batch drilling

Another strategy of volume and material optimization which could be applied in first interval is batch drilling. Batch drilling is an operation where 2 or more wells drilled sequentially, within same platform, sections by same sections. 2 main advantages of this type of drilling are operation efficiency and logistic convenience (Panhar & Rahmadona, 2015). In the aspect of drilling-fluids management, batch drilling optimizes fluids volume and material consumptions in a significant way. As an example, all the excessive WBM on 23 inches section from the first well could be refilled and utilized in the second well and subsequent well for the same section. Therefore, dumping or direct discharge of excess is not necessary till the last well of batch drilling. By evaluating the same well design for 3 wells for batch drilling, average carbon footprint per well can be estimated as per Table 4.3.

Table 4.3: Estimated carbon footprint of WBM in batch drilling

Estimated carbon footprint for various WBM in single well drilling			
	Volume mixed (bbls)	CO_2 emission, (kg CO_2 / bbl)	Total CO_2 emission (kg)
PHB	2345	1.442	3380.6
Kill mud	1020	75.847	77364.4
Spud mud	1483	31.136	46174.6
Total CO_2 emission, (kg CO_2) per well			126919.6
Total volume WBM mixed			4848
CO_2 emission, (kg CO_2 / bbl)			26.2

Estimated carbon footprint for batch drilling					
	Volume mixed (bbls)			CO_2 emission, (kg CO_2 / bbl)	Total CO_2 emission (kg)
Well	Well -KLM	Well-ABC	Well-XYX		
PHB	2345	2345	645	1.442	7691.1
Kill mud	1020			75.847	77364.4
Spud mud	1483	783		31.136	70554.0
Spud mud additives			956	N/A	1077.1
Total CO_2 emission, (kg CO_2)					156686.6
Average CO_2 emission, (kg CO_2) per well					52228.9
Total volume WBM mixed					9577
CO_2 emission, (kg CO_2 / bbl)					16.4

Drilling experience from Well-KLM and Well-ABC can be used as reference while drilling Well-XYZ. With the consultations from the experts and drilling engineers in town, kill mud can be directly used as if there is no sign of shallow gas in first 2 wells. Moreover, if there no seepage losses from the first 2 well, the usage of Kwikseal as LCM could be prevented. Following all these strategies, total CO_2 emission for all the three well in batch drilling is estimated 156.7 MT, averaging 52.2 MT of emission per well. Compared to a single well drilling, batch drilling could reduce the carbon emission by 58.8 % per well. While observing significant reduction on drilling-fluids wastage with batch drilling, optimization of mud additives contributes directly to less waste generation from packaging materials.

4.3.2 Identification of CP options in caustic soda handing

pH of drill water used to mix pre-hydrated bentonite has significant effect on its hydration. The pH of drill water must be slightly alkaline in the range of 8.5 to 9.5 before bentonite is added. Usually, caustic soda or sodium hydroxide is used for the pH control in this system. Caustic soda is considered as strong base and naturally a very corrosive material. It can cause serious burn to the respiratory tract, skin, eyes and gastrointestinal tract. The degree of injury however depends upon dose, duration and how the mixing job is carried out. Spillages of caustic soda could also create toxic environment for marine lives. Increase in pH can kill the fish and development of juvenile fish. It will strip off fish's slime coat, cause damages to their gills, eyes, skin and weaken the disposal of metabolic wastes (Lenntech, 2021).

4.3.2.1 Alternative greener chemicals

Among the alternative chemicals that can be used to raise the pH of solutions are calcium hydroxide, magnesium hydroxide or sodium carbonate (Burt Process Equipment, 2019). Sodium carbonate, which is known as weak base is neither the most soluble nor the strongest one. Excessive sodium carbonate will never produce a strong reaction like other strong bases, thus making it safer to be utilized in so many industries. Meanwhile, calcium hydroxide is widely used as flocculant in sewage treatment and to raise the pH of fresh water in treatment plants.

To raise the alkalinity in water-based drilling-fluids, amount required from these chemicals could be more than caustic soda. However, these chemicals could be more environmentally friendly and handling these chemicals could be easier during the mixing.

Usually, chemicals like magnesium oxide and sodium carbonate are supplied in 25 kg sacks. Due to its mild reactivity with atmospheric humidity, these powdered chemicals can be easily mixed through mixing hopper. At the same time, mixing these chemicals do not require any special PPEs and can be done by one person. Spillages from these chemicals could be easily contained and recycle for the same applications. Another advantage which can be seen by utilizing these chemicals is its costs. Although the cost of magnesium oxide is slightly higher, chemicals like calcium hydroxide and sodium carbonate could cost lesser than caustic soda.

4.3.2.2 Good operating practice

Batch mixer was provided on the top of mud tank for purpose of caustic soda mixing. However, conventional way of handling and mixing are still preferred due to its convenience. Few suggested that the batch mixer was not user friendly and requires more physical strain. Unfortunately, this had been exposing workers with more hazardous conditions like inhalation of fumes and physical contact with the chemicals. A batch mixer should be located at the chemical storage area to minimize the manual handling of the caustic soda cans. This batch mixer should be automated, convenient for residue cleaning and easy maintenance. Corrosive fume, spillages, splashes and direct chemical contacts could be easily prevented with the technique of good operation practice. The figures below show the conventional way of handling and mixing caustic soda in the mud tanks.

Caustic cans were carried to desired mud tank.

Figure 4.2: Caustic soda handling (Step 1)

Caustic flakes were poured on the top of the gratings of mud tank

Figure 4.3: Caustic soda handling (Step 2)

Caustic flakes were sprayed with water to disolve into the mud tank

Figure 4.4: Caustic soda handling (Step 3)

4.3.2.3 Reduction in packaging wastes

Caustic soda was supplied in 25 kg polypropylene sacks, secured in steel cans. Upon clearing the contents, these empty sacks with caustic residues were kept back inside the can, secured and disposed together with other wastes in chemical storage area. A volume of 1385 bbls pre-hydrated bentonite was mixed alongside with 1020 bbls of kill mud for top section drilling. Mixing these large volumes of WBM requires an amount of 925 kg of caustic soda, which is equivalent to disposal of 37 empty cans each weighing 0.8 kg. Waste from packaging material could be reduced if caustic soda solutions being supplied in 1.0 m^3 IBC tanks. While reducing the amount packaging material, handling of caustic soda could be easier during the mixing. The empty IBC with caustic residues could be transported back and re-used for the caustic solution storages.

4.3.2.4 Good housekeeping

Another possible CP option considered here was good housekeeping while handling the waste generated from packaging materials. By placing the empty cans of caustic soda mixed with other wastes, the entire waste was considered as hazardous waste. Hazardous wastes usually go through more meticulous treatment and its disposal are more costly if compared to non-hazardous waste. Therefore, segregation of all these cans could be helpful in reducing end-of-pipe treatment and the cost of waste management. The simple technique of segregation requires little work force and could be easily executed, however without the commitments from the workers, this CP strategy will never be successful.

4.3.3 Change of technology

Casing while drilling (CwD) is technology where drilling is executed with casing as a drill string. The system consists of a drillable bit located at the bottom of casing string, which is extended till the surface. Small equipment modifications are required before proceeding with CwD. Top drive system (TDS), usually used for conventional drilling is replaced with casing drive system (CDS) to hold the weight of casing string and apply torque required while drilling. The utilization of CDS and power slips speeds up casing connection, hence minimize the rig operation while promoting better rig floor safety (Patel et al., 2018).

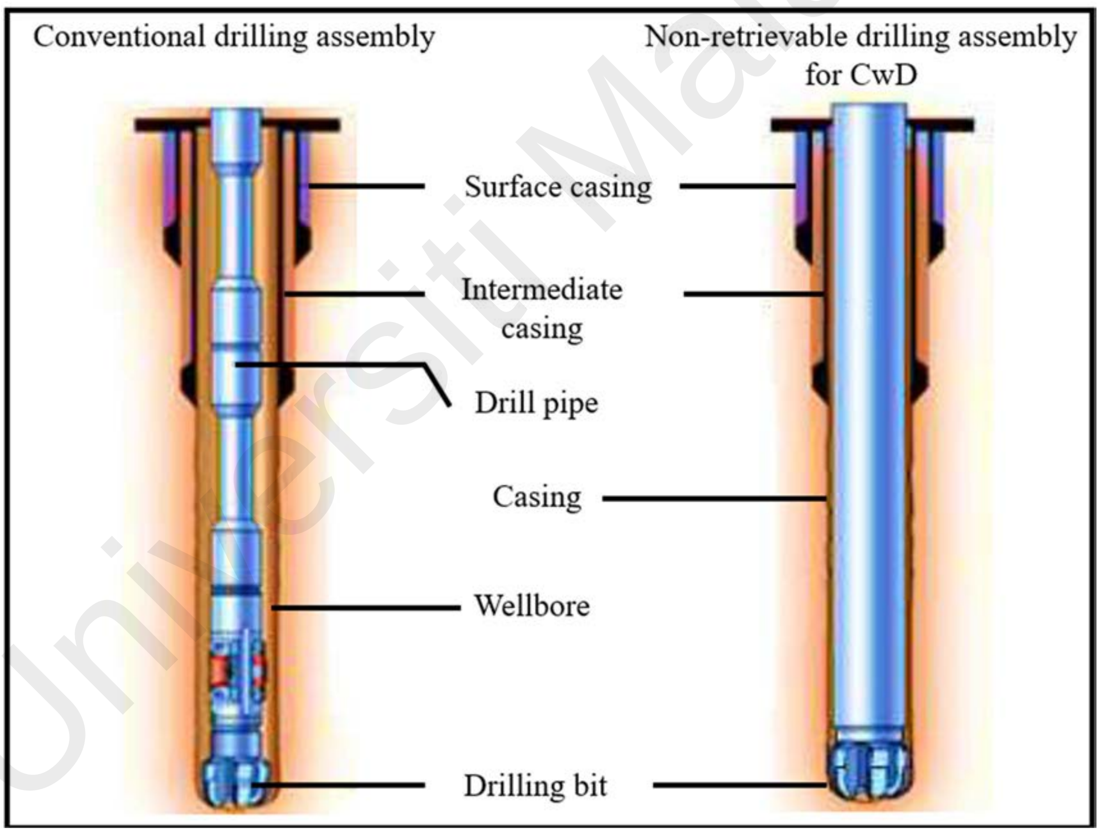


Figure 4.5: Configurations in conventional drilling and casing while drilling (modified from Patel et al., 2018)

Due to the limitation of CwD that it can only drill a straight hole with no directional control, the utilization of the system is very suitable for top section drilling. CwD will still require seawater for drilling, pre-hydrated bentonite for intermittent sweeps and kill mud contingency. However, the usage of spud mud and LCM additives can be completely avoided, therefore reducing overall carbon footprint of top section drilling.

4.3.4 Waste reduction from packaging materials

Kwikseal and viscosifier were supplied in 25 kg paper sacks while soda ash was supplied in 25 kg polypropylene sacks. The consumption of Kwikseal contributes more than 50% by weight of total waste generated by packaging materials in 23 inches section drilling. This huge amount of waste generation could be minimized by changing the packaging material from paper bags to polypropylene jumbo bags, which could accommodate 1000 kg weight of material. Amount of soda ash and viscosifier are relatively small and to preserve the quality of these chemicals, the packaging material and its size should remain as it is. Waste generated by caustic cans could also be reduced if it is being supplied in concentrated solution in IBC tanks as per discussed previously. In most scenarios, these IBC tanks could be recycled few times for the same usage purposes, hence was not considered as waste generation. Table 4.4 shows a reduction of 163.6 kg in CO_2 emission, which is achievable by implementing these strategies. Changes in packaging material while optimizing its safe working load could result in significant reduction in carbon footprint of packaging wastes. Less of amount of packaging materials also reduces the physical strain and other ergonomic risk which could be suffered from repetitive actions while mixing these additives.

Table 4.4: Estimated carbon footprint from packaging material before and after waste reduction strategies

Material	Packaging material	Weight of packaging material (kg)	Hazardous Waste generated (pcs)	Hazardous Waste generated (kg)
Estimated carbon footprint for waste generated from packaging materials (23 inches section)				
Material	Packaging material	Weight of packaging material (kg)	Hazardous Waste generated (pcs)	Hazardous Waste generated (kg)
Caustic Soda	Steel can	0.80	39	31.2
Soda Ash	Polypropylene sack	0.07	26	1.8
Kwikseal	Paper bag	0.10	420	42.0
Viscosifier	Paper bag	0.10	78	7.8
Total hazardous waste generated from packaging materials				82.8
Total CO_2 emission from packaging material (kg CO_2) [CO_2 emission factor of hazardous waste (kg CO_2 / kg) x hazardous wastes generated (kg)]				217.8
Estimated carbon footprint with waste reduction strategies				
Material	Packaging material type	Weight of packaging material (kg)	Hazardous Waste generated (pcs)	Hazardous Waste generated (kg)
Caustic Soda	IBC tank	57	-	-
Soda Ash	Polypropylene sack	0.07	26	1.8
Kwikseal	Polypropylene jumbo bag	1.10	10	11.0
Viscosifier	Paper bag	0.10	78	7.8
Total hazardous waste generated from packaging materials				20.6
Total CO_2 emission from packaging material (kg CO_2) [CO_2 emission factor of hazardous waste (kg CO_2 / kg) x hazardous wastes generated (kg)]				54.2

4.4 Identification of CP options in second and third interval

The intermediate section of 16 inches and 12.25 inches was drilled with SOBM system. 16 inches section was drilled from 2314 ft to 5551 ft and cased with 13.375 inches casing to depth of 5533 ft. A total of 5 days was taken from the making up 16 inches bottom hole assembly to completion of this section. Total volume SOBM received and mixed for this interval was 3240 bbls. From this volume, 958 bbls were reported as surface losses from fluids and drill cuttings treatment with solid control equipment. Small volume discharged to the seawater due to fluid contamination is also counted as surface losses. The balance volume of 2282 bbls were salvaged and transferred to the third interval drilling. Hence, total mud usage of this interval can be summarized as 0.30 bbls per footage drilled or 191.6 bbls per day. As per Table 4.5, carbon emission of 1 bbl SOBM is estimated at 147 kg CO_2. If usage of SOBM is analyzed from the aspect of carbon emission, 43.5 kg of CO_2 is emitted per footage drilled or 28.1 MT of CO_2 is emitted per day. Overall process flow for intermediate section drilling of 16 inches and the management of drilling-fluid and drill cuttings is shown in Figure 4.6.

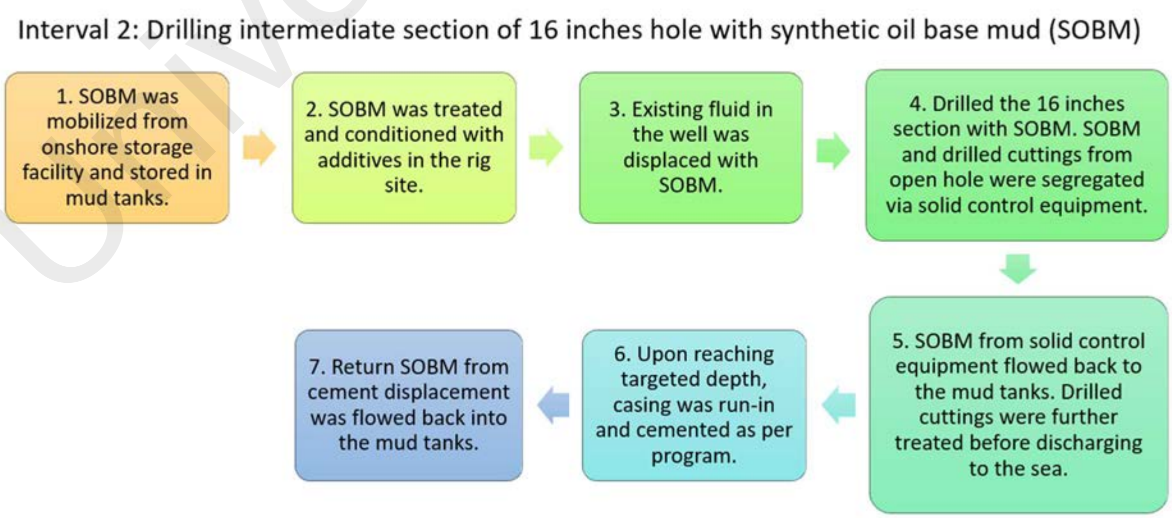


Figure 4.6: Interval 2 – Drilling intermediate section of 16 inches hole with SOBM

The third interval of 12.25 inches was drilled from 5551 ft to 8564 ft. 10.25 x 9.625 inches casing was run in, set and cemented at the depth of 8551 ft. A total of 5 days was taken from the making up 12.25 inches bottom hole assembly to completion of this section. Total volume SOBM salvaged from previous interval and fresh SOBM mixed for this interval was 3048 bbls. From this volume, 866 bbls were reported as surface losses, mostly from solid control equipment. Surface losses also includes volume left in the hole from cementing operation and mud tank cleaning upon the end of section completion. 2182 bbls of SOBM salvaged from this section were backloaded to onshore storage facility. Thus, total mud usage of this interval can be summarized as 0.29 bbls per footage drilled or 173.2 bbls per day. As per Table 4.6, carbon emission of 1 bbl SOBM is estimated at 175 kg CO_2. If usage of SOBM is analyzed from the aspect of carbon emission, 50.2 kg of CO_2 is emitted per footage drilled or 30.3 MT of CO_2 is emitted per day. Overall process flow for intermediate section drilling of 12.25 inches and the management of drilling-fluid and drill cuttings is shown in Figure 4.7.

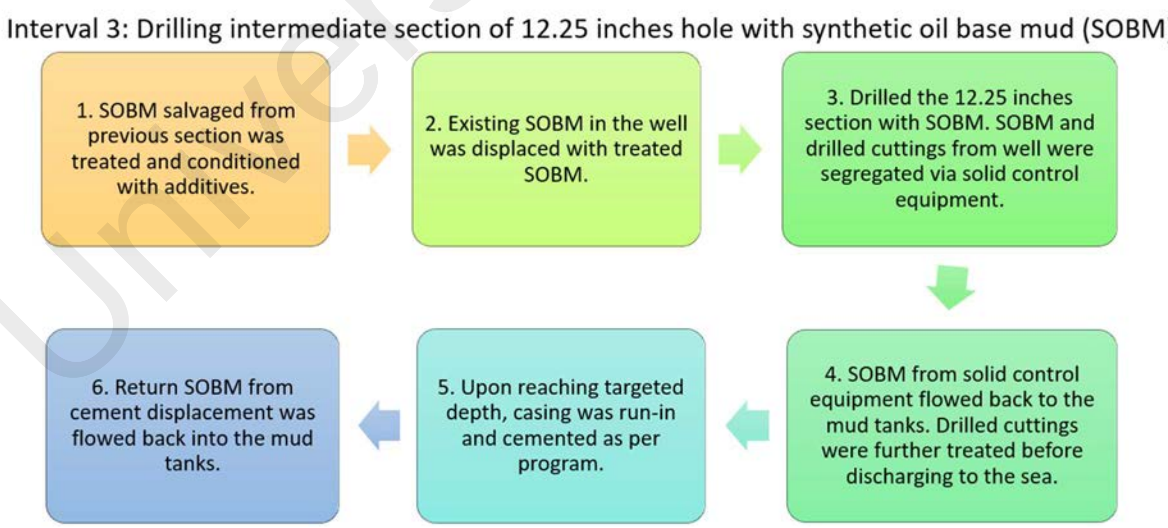


Figure 4.7: Interval 3 – Drilling intermediate section of 12.25 inches hole with SOBM

4.4.1 Identification of CP options in base oil usage

Drilling-fluid system with diesel as its base fluid was traditional oil base mud way before 1990s. Beside proven excellent performance during the drilling operations, oil base mud was extensively used because diesel was inexpensive and widely obtainable fossil fuel. Oil base mud was used to drill various type of formation like shale, gypsum, salt and other complex formation. Besides, the ability of oil base mud to sustain degradation in high pressure and temperature making it preferable choice of mud. But due to its high toxicity content, diesel is replaced with other mineral oil like paraffin which has lesser impact on health and environment.

Types of mineral oils currently utilized as base fluid for SOBM are Saraline 185V, Escaid 110 and Sarapar 147, depending on by-production of operating company. These base oils are known as higher alkanes from a mineral source, usually derived from distillate of petroleum. To build SOBM, base oil was mixed with brine solution with emulsifiers to produce a stable emulsion preventing the separation of oil and water. Usually, the ratio of base oil to water are designed in the region of 75:25 or 80:20, depending on the requirements by operating company.

4.4.1.1 Alternative greener chemical

Although paraffin type base oil is considered as green chemical, recent studies suggested that drilling-fluids or drill cuttings with the element of paraffin could still harm the environment in certain degrees. A substitution material recently considered was usage of vegetable oil as base fluid for drilling-fluids. In a study conducted by Said and El-Sayed (2018), fatty acid methyl esther (FAME) or biodiesel synthesised from palm oil can be successfully used as a base fluid for a high-performance flat rheology drilling fluid. The viscocity of biodiesel could be a barrier, however this could be easily overcomed by proper engineering of drilling-fluids formulations. In another study conducted by Ismail et al. (2014), vegetable oils such as corn oil, palm oil, rice bran oil are converted to biodiesel through transesterification. The synthesized biodiesel was suggested as greener option to replace sarapar or diesel as base fluid to formulate SOBM. Although inability to tolerate excessive solid loading due to high rheology property been seen as main limitation, biodiesel considered to cause no harm to aquatic lifes with respects to its level of toxicity and degradration rate. The analysis of the study suggested ester based drilling-fluids achieved 60 % of degration over the period of 28 days, while diesel and sarapar based drilling fluids only achieved 30 % of degradation over the same duration. Although biodiesel can be seen as environmentally friendly in so many ways, the carbon footprint of biodiesel production are suggesting a contradicting result. In a research conducted by Wahyono et al. (2020), carbon footprint of 1 MT biodiesel produced from palm oil is reported at 2882 CO_2 eq, which is equivalent to 2.882 kg CO_2 / kg. The life cycle analysis in this study was carried in comprehensive method, which includes carbon footprint from oil palm plantations and palm oil production as inputs. Meanwhile, paraffin production as per analyzed in SimaPro, indicates a carbon footprint of 0.743 kg CO_2 / kg, which is 74.2 % lower than carbon footprint of biodiesel.

4.4.1.2 Product modification

SOBM system designed to drill second interval and third interval contains 75:25 oil water ratio. The possibility of reducing the oil ratio can be explored to minimize the harmful effect to the environment from drilling-fluids and its residues on drill cuttings. In a study conducted by Sheer et al. (2019), 12.25 inches section of a well in Southeast Kuwait was drilled with diesel base mud, with 60:40 oil water ratio. Although slight increase in rheology observed in mud properties, the section was successfully drilled to the targeted depth without any issues. The formulation with lower oil water ratio requires more chemicals to maintain the quality of drilling fluids on its interaction with formation, however reduction in base oil volume eventually reduces the total cost of drilling-fluids and minimize the amount of toxicity dumped into the environment.

With the product modification from 75:25 to 60:40 oil water ratio, carbon footprint of SOBM could be reduced from 147 kg CO_2 / bbl to 138 kg CO_2 / bbl. About 8.1 MT of carbon dioxide emission can be conserved, which is equivalent to 5.7 % of carbon footprint reduction while drilling 16 inches section.

Similar results could be observed by analyzing drilling-fluid's carbon emissions in 12.25 inches section. With the product modification from 75:25 to 60:40 oil water ratio, about 6.9 MT of carbon dioxide emission can be conserved, which is equivalent to 4.5 % of carbon footprint reduction. Simultaneously, carbon footprint of SOBM could be reduced from 175 kg CO_2 / bbl to 167 kg CO_2 / bbl with this formulation.

Table 4.5: Estimated carbon footprint of SOBM in 16 inches section with 75:25 and 60:40 oil water ratio

Interval 2 (16 inches section)			
Drilling-fluid consumed (bbls)		958	
Drilling-fluids density (SG)		1.2	
Drilling-fluid oil water ratio		75:25	
Chemicals	Chemical Used (kg)	CO_2 emission factor (kg CO_2/kg)	Total CO_2 emission (kg)
Base Oil	72932	0.743	54188
Emulsifier	1434	4.4	6308
Water	32292	0.00024	8
Calcium Chloride	10862	0.76	8255
Lime	1303	0.0716	93
Viscosifier	869	0.047	41
Fluid lost control	1303	0.0178	23
Barite	58485	1.12	65504
Calcium Carbonate	3476	1.73	6013
Total CO_2 emission, (kg CO_2)			140433
CO_2 emission, (kg CO_2 / bbl)			147
Drilling-fluid oil water ratio		60:40	
Chemicals	Chemical Used (kg)	CO_2 emission factor (kg CO_2/kg)	Total CO_2 emission (kg)
Base Oil	58461	0.743	43437
Emulsifier	3476	4.4	15293
Water	51333	0.00024	12
Calcium Chloride	13034	0.76	9906
Lime	1303	0.0716	93
Viscosifier	217	0.047	10
Fluid lost control	391	0.0178	7
Barite	50767	1.12	56859
Calcium Carbonate	3910	1.73	6765
Total CO_2 emission, (kg CO_2)			132382
CO_2 emission, (kg CO_2 / bbl)			138

Table 4.6: Estimated carbon footprint of SOBM in 12.25 inches section with 75:25 and 60:40 oil water ratio

Interval 3 (12.25 inches section)			
Drilling-fluid consumed (bbls)	866		
Drilling-fluids density (SG)	1.34		
Drilling-fluid oil water ratio	75:25		
Chemicals	Chemical Used (kg)	CO_2 emission factor (kg CO_2/kg)	Total CO_2 emission (kg)
Base Oil	62788	0.743	46652
Emulsifier	1296	4.4	5703
Water	27539	0.00024	7
Calcium Chloride	9819	0.76	7462
Lime	1178	0.0716	84
Viscosifier	785	0.047	37
Fluid lost control	1178	0.0178	21
Barite	75936	1.12	85048
Calcium Carbonate	3927	1.73	6794
Total CO_2 emission, (kg CO_2)			151808
CO_2 emission, (kg CO_2 / bbl)			175
Drilling-fluid oil water ratio	60:40		
Chemicals	Chemical Used (kg)	CO_2 emission factor (kg CO_2/kg)	Total CO_2 emission (kg)
Base Oil	50231	0.743	37321
Emulsifier	3142	4.4	13825
Water	44062	0.00024	11
Calcium Chloride	11782	0.76	8955
Lime	1178	0.0716	84
Viscosifier	196	0.047	9
Fluid lost control	353	0.0178	6
Barite	69570	1.12	77918
Calcium Carbonate	3927	1.73	6794
Total CO_2 emission, (kg CO_2)			144923
CO_2 emission, (kg CO_2 / bbl)			167

4.4.2 Waste reduction from packaging materials

Generally, the concentration of lime is maintained above 2 lb/bbl to neutralize formation gases such CO_2 and hydrogen sulfide (H_2S). As such, the lime's concentration tends to deplete after certain period. Regular addition is necessary done while drilling and circulation to maintain its content based on daily mud analysis. Meanwhile calcium chloride concentration was maintained between 28 – 30 % (by weight) with regular addition into active system. This is to maintain the salinity of water phase in SOBM for shale inhibition. Therefore, majority of waste from packaging materials were generated from the usage of lime and calcium chloride. Other packaging waste are generated from drum chemicals of emulsifiers and some small portions from chemicals like viscosifiers and fluid lost control chemicals. Lime was supplied in 25 kg paper sacks while calcium chloride was supplied in 25 kg polypropylene sacks. In order to minimize the waste generation, the option of changing the packaging material to polypropylene jumbo bags, with could accommodate 1000 kg of materials can be considered. Meanwhile, steel drums which were used to accommodate emulsifiers can be changed to tote tanks, which could accommodate a volume of 2000 liters of liquid chemicals.

Figure 4.8: Design of tote tank, compliant with United Nation (UN) and United States Department of Transportation (DOT)

Tote tanks are designed with slopped bottom for 100 % liquid discharge, thus residues left will be very minimal. Empty tote tank can be reused to refill same type of liquid chemicals without any requirement of cleaning.

Table 4.7 further analyze the carbon footprint of waste generated by packaging materials in 16 inches section and its reduction by modifying the packaging materials and its size. Although changing packaging materials of powdered chemical alone do not show a significant reduction of carbon footprint, a massive reduction of 0.9 MT CO_2 is observed if packaging materials of liquid chemical is changed to tote tanks.

Carbon footprint from packaging waste in 12.25 inches section is observed to be lesser than 16 inches section, although similar amount of SOBM is utilized for drilling. This is because lesser addition of emulsifiers contributes to lesser generation of empty drums. Similar trend of carbon footprint reduction can be observed from the analysis in Table 4.8. A reduction of 0.3 MT CO_2 is achievable with the same waste reduction strategies.

Table 4.7: Estimated carbon footprint from packaging material before and after waste reduction strategies (16 inches section)

Estimated carbon footprint for waste generated from packaging materials (16 inches section)				
Material	Packaging material	Weight of packaging material (kg)	Hazardous Waste generated (pcs)	Hazardous Waste generated (kg)
Calcium Chloride	Polypropylene sack	0.07	140	9.8
Lime	Paper bag	0.1	165	16.5
Viscosifier	Paper bag	0.1	45	4.5
Fluid lost control	Paper bag	0.1	90	9
Total hazardous waste generated from packaging materials (kg)				39.8
Material	Waste drum generated (pcs)	CO_2 emission factor of steel drum conditioning (kg CO_2 / drum)		Total CO_2 emission from steel drum conditioning (kg CO_2)
Emulsifier P	26	20.907		543.6
Emulsifier S	13			271.8
Total CO_2 emission from steel drum conditioning				815.4
Total CO_2 emission from packaging material (kg CO_2) [CO_2 Emission factor of hazardous waste (kg CO_2 / kg) x hazardous wastes generated (kg)] + [CO_2 emission from steel drum conditioning (kg CO_2)]				920.0
Estimated carbon footprint with waste reduction strategies				
Material	Packaging material	Weight of packaging material (kg)	Hazardous Waste generated (pcs)	Hazardous Waste generated (kg)
Calcium Chloride	Polypropylene jumbo bag	1.1	4	4.4
Lime	Polypropylene jumbo bag	1.1	4	4.4
Viscosifier	Paper bag	0.1	45	4.5
Fluid lost control	Paper bag	0.1	90	9
Total hazardous waste generated from packaging materials (kg)				22.3
Material	Waste tote tanks generated (pcs)	CO_2 emission factor of tote tank cleaning (kg CO_2 / tank)		Total CO_2 emission from tote tank cleaning (kg CO_2)
Emulsifier P	No waste generated	Tote tanks do not require any cleaning		0
Emulsifier S				0
Total CO_2 emission from tote tank cleaning				0
Total CO_2 emission from packaging material (kg CO_2) [CO_2 Emission factor of hazardous waste (kg CO_2 / kg) x hazardous wastes generated (kg)] + [CO_2 emission from tote tank cleaning (kg CO_2)]				58.6

Table 4.8: Estimated carbon footprint from packaging material before and after waste reduction strategies (12.25 inches section)

Estimated carbon footprint for waste generated from packaging materials (12.25 inches section)				
Material	Packaging material	Weight of packaging material (kg)	Hazardous Waste generated (pcs)	Hazardous Waste generated (kg)
Calcium Chloride	Polypropylene sack	0.07	200	14
Lime	Paper bag	0.1	75	7.5
Viscosifier	Paper bag	0.1	45	4.5
Fluid lost control	Paper bag	0.1	90	9
Total hazardous waste generated from packaging materials (kg)				35
Material	Waste drum generated (pcs)	CO_2 emission factor of steel drum conditioning (kg CO_2 / drum)		Total CO_2 emission from steel drum conditioning (kg CO_2)
Emulsifier P	6	20.907		125.4
Emulsifier S	8			167.3
Total CO_2 emission from steel drum conditioning				292.7
Total CO_2 emission from packaging material (kg CO_2) [CO_2 Emission factor of hazardous waste (kg CO_2 / kg) x hazardous wastes generated (kg)] + [CO_2 emission from steel drum conditioning (kg CO_2)]				384.7
Estimated carbon footprint with waste reduction strategies				
Material	Packaging material	Weight of packaging material (kg)	Hazardous Waste generated (pcs)	Hazardous Waste generated (kg)
Calcium Chloride	Polypropylene jumbo bag	1.1	5	5.5
Lime	Polypropylene jumbo bag	1.1	2	2.2
Viscosifier	Paper bag	0.1	45	4.5
Fluid lost control	Paper bag	0.1	90	9
Total hazardous waste generated from packaging materials (kg)				21.2
Material	Waste tote tanks generated (pcs)	CO_2 emission factor of tote tank cleaning (kg CO_2 / tank)		Total CO_2 emission from tote tank cleaning (kg CO_2)
Emulsifier P	No waste generated	Tote tanks do not require any cleaning		0
Emulsifier S				0
Total CO_2 emission from tote tank cleaning				0
Total CO_2 emission from packaging material (kg CO_2) [CO_2 Emission factor of hazardous waste (kg CO_2 / kg) x hazardous wastes generated (kg)] + [CO_2 emission from tote tank cleaning (kg CO_2)]				55.8

4.4.3 Dead volume reduction in mud tank

Dead volumes are usually observed as fluid volume in the mud tanks which are unable to be pumped out or occurrence of lost suction by pump. Most of these volumes are solids which settles down at the bottom of mud tank, forming a thick layer of sludge after some time. Mud tanks are design in certain way so that it could accommodate all the limited space in offshore rig and cost effective. These designs might not prioritize dead volume built up, thus the occurrence of dead volume in mud tanks in any rig facilities are inevitable. All these dead volumes could be a huge concern upon completing the 12.25 inches section, when all the reclaimed SOBM from the well backloaded to onshore storage facility. Nevertheless, certain techniques could be applied in managing and minimizing these dead volumes.

4.4.3.1 Good operating practice

Gun-lines which is commonly used to shear fresh SOBM can be intermittently used to break the sludge beneath the mud tanks. However, gun-lines are only installed in mud pits specified for SOBM storage. Another concern raised was the plugging of gun-lines after certain period, thus this technique might not be the best solution.

Another alternative way of reducing dead volume is by transferring them to a smaller mud tank or slug pit with a very minimal dead volume. The volume salvaged will be backloaded with other SOBM to the supply vessel. Air operated pump will be utilized to transfer the dead volume in liquid form, while non-transferable dead volume will remain as sludge at bottom of the tank. The efficiency in dead volumes reduction however depending on the efficiency of air pump. More powerful pump could even transfer the flowable sludge at the bottom of the tank.

4.4.3.2 Change of design

The amount of dead volume in mud tanks is directly related to the design of the mud tank, which could be the position of agitators, flat floor surface of mud tank and height of suction line designed at the bottom of mud tank. Mud tank designs in this rig are open top square tanks with corrugated wall structure and flat floor surface. The suction lines are placed 1 inch from the bottom of the mud tank. Smaller mud tanks, with volume capacity less than 400 bbls are designed with one agitator, while bigger mud tanks, with volume capacity more than 550 bbls are designed with 2 agitators.

The design of agitators needs to be reviewed periodically. The position of agitator blades has to be right on the bottom tanks to minimize the solid settlement. Instead of having one layer of blades, 2 layer of blades on the same rod could be more effective. High powered motor on the agitators can be also considered to produce high rpm of agitation. Combining all these designs, solid settlement at the bottom of the mud tanks could be minimized.

Figure 4.9: Mud tank view from the top with agitators and discharge lines

Another change of design which can considered to reduce dead volume is involving the mud tank itself. Square mud tanks are designed with internal piping and sharp corners, encouraging the solid settlings in those areas. A round mud tank with hemispherical bottom, with suction lines right on the bottom, combined with properly engineered agitators will enhance better stirring and mixing of drilling-fluids, as well as minimizing solid settlings (Helmerich & Payne IDC et al., 2001). This type of design would be suitable for land rigs due to vast operating perimeter and if permits, can also be also considered in offshore rig facilities.

4.4.4 Identification of CP options in lost circulation material (LCM)

Lost circulation is the scenario where drilling-fluids leak through the formation through the crack. This could commonly happen when static or dynamic pressure exerted by the total mud column exceeds formation pore pressure or fracture gradient. Sometimes, the porosity and permeability of the formation is such that it prevents the sealing effect of the filter cake, causing the fluid lost to the formation (Styles et al., 2006).

In the event of seepage losses up to 10 bbls/hr, reducing density of drilling fluid by 0.1 lb/gal to 0.2 lb/gal was considered as immediate remedial. As for more severe losses (30 bbls/hr to 100 bbls/hr) combination of various lost circulation was mixed and prepared, and eventually spotted on the loss circulation area. Contingency plans are important and must pre-designed even before the start of drilling operations. Prior to drill the 16 inches section with SOBM, 60 bbls of lost circulation pill consist of 100 lb/bbl LCM materials were prepared. If these pills could not heal the losses after several trials, more aggressive remedial action will be considered like spotting the gunk plug or establishing series of cement plugs.

Table 4.9: Component of LCM material and concentration for 60 bbls of loss circulation pill

Lost Circulation Material (LCM)	Concentration
Kwikseal (Fine)	20 lb/bbl
Kwikseal (Medium)	20 lb/bbl
Nutplug (400 micron)	30 lb/bbl
Calcium Carbonate (1000 micron)	30 lb/bbl
Total	100 lb/bbl

4.4.4.1 Alternative greener chemical

Mica is used widely in cosmetic industry because of its glittering characteristics. In oilfield industry, Kwikseal with components of mica are mixed with other lost control materials for the purpose of LCM pills. Recent studies however suggested that repeated exposure from mica could cause scarring of the lung tissue which led to fibrosis in lungs (Williams, 2021). Thus, the usage of Kwikseal should be eliminated and LCM formulation must completely rely on natural base products like Nutplug. Nutplug consist of pecan or walnut hulls and available on various particle size. They can also be used in all types and density of fluid systems. Few mud companies took extra effort in introducing their greener LCM materials like cottonseed hulls. Cottonseed is a biodegradable material which could act as an excellent bridging agent when large-particle-size LCM needed.

4.4.4.2 Change of technology

Usually, severe loss circulation is very difficult to control compared to seepage losses. Most of the time, several trials of LCM pills are required with different combination of materials. Thousands of barrels of drilling-fluid will be required during these trials to ensure the hole is always kept full. Decisions for more aggressive remedials like cement job might complicate drilling operations as well. For this type of losses, few other remedial technologies can be considered for more effective lost zone sealing.

Usage of resin base product that could react with bottom hole temperature could be one of the options. This particle free resin appears in liquid form and can be formulated with other chemicals to react with temperature, and subsequently solidify as a resin plug in lost zone. This type of strategy was widely employed in onshore and offshore operations with wells prone with lost circulation issues in Saudi Arabia.

The main challenge of this type of remedial is the determination of bottom hole temperature. A wrong temperature assumption could either cause the resin to solidify inside the drill pipe or the entire resin loss to the formation. This remedial however could be successful with good interpretation of bottom hole temperature or real time temperature logging. Resin and its additives could be more costly than the conventional LCMs, but due to its effectiveness, consumption of conventional materials and fluids can be conserved leading to lower operational costs.

Table 4.10: Case studies with lost control remedial strategies with resin slurry in Saudi Arabia

	Case Study 1	**Case Study 2**
Well name	Well-22	Well-96
Hole size	12 inches section	8.375 inches section
Challenges	To cure a severe loss circulation at 11,874 ft with 120 - 150 bbl/hr loss rate. Few remedial attempts with 280 lb/bbl LCM were pumped with no success to stop the losses.	To secure loss circulation zone at 9685 ft and establish full circulation to continue drilling operation.

Table 4.10: Case studies with lost control remedial strategies with resin slurry in Saudi Arabia

	Case Study 1	Case Study 2
Solution	Drill string was pulled out to the depth of 11,317 ft (557 ft above bottom). Pumped 50 bbls of 16.0 lb/gal resin slurry, displaced with 168 bbls of 16.4 lb/gal mud at 4.0 bbl/hr. 15 bbls before the resin slurry reach the bit, the annulus was closed. A further 15 bbls of mud was then pumped. 50 bbls of resin slurry followed by 14.2 bbls of mud were squeezed into the loss zone at 3.0 bbl/min at 550 psi while maintaining 50 psi back pressure on choke. Pulled out 3 stands and circulate 1 string volume to ensure the drill string clear from the resin slurry.	Prepared 26 bbls of 10.0 lb/gal resin slurry with the setting time of 9 minutes at 70°C (estimated circulation temperature). Drill string was pulled back to 9155ft, 530ft above the loss zone. Pumped 26 bbls of 10.0 lb/gal resin slurry at 4 – 5 bbl/min. Displaced with 127 bbls of 10.0 lb/gal mud with 4 – 5 bbl/min. Just before the resin slurry reach the bit, the annulus was closed. 26 bbls of resin slurry followed by 10 bbls of mud were squeezed into the loss zone at 1 – 2 bbl/min. Observed low pressure (45-50psi) while pumping and displacing the slurry, indicated the hole still taking fluid during the operation.
Result	No resistance was observed while tripping in from 11,023 to 11,874 ft. After 4.5 hours, there were no sign of static or dynamic losses. This indicated the slurry migrated into the thief zone and eventually isolate it from the open hole.	After waiting on slurry to cure for an hour, drill string was slowly tripped in to tag the top of the solidified plug. Managed to tag the top of plug at 9322 ft with 7.0 klbs. Established circulation to check for the loss rate. Full returns of fluid were observed with no sign of losses.

4.4.5 Reducing the frequency of mud tank cleaning

Tank cleaning is required after completing the intervals with SOBM system or when all SOBM is transferred to the supply boat for onshore storage. Cleaning will take at least 3 rig crews; two to perform the cleaning from inside the mud tanks and one to monitor the activity from the top of tanks. Depending on the amount solid settlement at the bottom of the tank, cleaning will take one to two days. Each tank cleaning will require 200 liters of detergent for flushing. This will be followed by removing the solid sedimentation with high pressure gun. Tedious paper works like permits and isolations were required prior to cleaning and a lot of physical exertion are involved in this activity. Tank cleaning could not be completely avoided with single well drilling, but the frequency of cleaning can be reduced with option of batch drilling by intervals. Batch drilling however do have a slight disadvantage on the solid settlement on the mud tanks. If the SOBM being contained in a long period of time, solid settlement in that particular tank could be higher as well.

4.4.6 Good operating practice in drilling waste management (DWM)

As discussed before, cuttings generated from the drilling SOBM intervals will go through series of separations and treatments before discharged directly to sea. Meanwhile, to maintain the solid intrusion in fluids circulation system, centrifuges are continuously run in the active mud tanks during the drilling operations. Average oil retention on the cuttings is carefully monitored and must not exceed compliance limit set by the client companies. Good operating practice while operating solid control equipment (SCE) could be essential in succeeding the CP strategies here. Despite performing periodic maintenance in the rig site, SCE must go through series of test runs and preventative maintenance prior to mobilization to offshore facility. Well trained and experienced DWM supervisors must be assigned to run these equipment with the assistance of their co-workers. Certain client companies assign "Mud Cop" from DWM companies if drilling requires SOBM system. Mud Cop reports and updates average well ROC from their SCE and any findings which could lead to harming environment and aquatic life at ocean. Mud cop also advices DWM supervisors if the efficiency of their solid control equipment depreciates. The effort of having a Mud Cop who polices all these drilling waste operations could also lead to good operating practice.

4.4.7 Minimizing small volume discharge

During the well fluid displacement from WBM to SOBM, SOBM from active tanks will be lined up to the well, and the return WBM from the well will be directly discharged from dump valve at shale shakers. Fluid engineer will monitor the appearance of SOBM returns at shale shaker area and upon his justification, dump valve will be closed and SOBM will be circulated back to active mud tanks. Usually, about 10 to 15 bbls of contaminated SOBM are dumped each time during the well fluid displacement. For this type of small volume discharges, a default value of 25 % base fluid retained on the cuttings shall be used for calculating ROC (U.S. Environmental Protection Agency, 2011). This will significantly impact the overall average ROC of the well.

Contamination of SOBM can be minimized by pumping a layer high viscosity SOBM, spiked with synthetic fiber materials prior to pumping the fluids from the active tank. The first trace of fibrous material appearing on the surface is the indication that the well is fully displaced, thus minimizing the grey area of fluid engineer's justifications. Eventually all the fiber materials added are screened out from shale shakers during the circulation.

However, SOBM displacement should be executed in low pumping rate to avoid fluid turbulence which could elevate SOBM contamination. Another way of reducing small volume discharge is by setting a limit of 5 bbls of contaminated discharge for each well fluid displacement operation. Few argues that this could lead to deterioration of SOBM performance, but this could be easily treated with base oil and other additives. While displacing WBM to SOBM in first interval, 14 bbls of contaminated SOBM were directly discharges to the sea. By applying the strategy of 5 bbls limitation, carbon footprint caused by SOBM could be reduced by 1.3 MT in this operation.

4.4.8 Re-use drilling cuttings

In Malaysia, dried drilling cuttings from cutting dryer are directly discharged to sea with the compliance by the client company. For this particular well, 1749.0 bbls of drilling waste were discharged on the first interval and 1212.2 bbls in second interval. Hence, drilling waste discharged can be summarized as 0.5 bbls / footage drilled in first interval and 0.4 bbls / footage drilled in second interval.

Table 4.11: Drilling waste generated in first and second interval

Interval	Footage drilled (ft)	Drilling cuttings generated (bbls)	Small volume discharges (bbls)	SOBM disharged with drilling cuttings (bbls)	Baseoil discharge with drilling cuttings (bbls)	Total drilling waste discharged to the sea (bbls)
First Interval (16" Section)	3237	805.0	14	944	594.7	1749.0
Second Interval (12.25" Section)	3013	439.2	93	773	463.8	1212.2

In certain part of the world, drilling cuttings are mobilized and treated onshore with methods like thermal desorption, bioremediation and landfarming (Mkpaoro et al., 2015). Sometimes, drilling cuttings are collected, blended as slurry and utilized for cutting re-injections. Recently, the possibility of using stabilized drilling cuttings for the purpose of concrete application are being studied. The study indicates that drilling cuttings can be used as substitute material, replacing fine aggregate in concrete mixture designed for compressive strength greater than 300 psi (Foroutan et al., 2018). Utilizing stabilized drilling cuttings for agriculture might not be recommended but can be explored for other industrial purposes. Considering transportations, mobilizations and treatments of drilling cuttings, this CP strategy might not contribute to reduction in carbon emission, but definitely reduces the impact on marine environment.

4.4.9 Training for personnel handling SOBM

In a way, trainings could be another way of promoting CP strategies in drilling-fluids management. DWM supervisors and technicians need to first understand the concept of CP, and how this could be integrated in drilling fluids and waste management on the rig site. Usually, a fluid engineer will undergo Mud School (drilling-fluids training) for 6 weeks before they are being sent to offshore rigs as trainee. The same type of training should be introduced to DWM supervisors and the technicians. Fresh technicians must be given hands-on training solid control equipment and their jobs need to be supervised thoroughly by the seniors. Meanwhile, trainee fluids engineer must be trained under a supervision of a senior fluids engineer. A good judgment and management from fluids engineer is always essential in reducing the fluids contaminations and other fluids related wastes.

Rig hands who are assisting the management SOBM should be also trained accordingly. They might not require a rigorous training program, however basic understandings in accidental fluids discharge, waste segregations and dead volume reduction would encourage their initiatives towards CP approaches.

4.5 Identification of CP options in fourth interval

The fourth section of 8.5 inches was drilled from 8564 ft to 11,388 ft. After conditioning the tight spots in the well, well fluid was displaced from water base NDF to inhibited calcium chloride brine. Subsequently, 7 inches liners with 7.625 inches completion assembly were ran in and set at the depth of 11,368 ft. A total of 6 days was taken from the making up 8.5 inches bottom hole assembly to completion of this section. Total volume NDF mixed for this interval was 4353 bbls. From this volume, 918 bbls were identified as losses from solid control equipment and the balance 3435 bbls were dumped or discharged directly to the sea, prior to completion operations. Therefore, total mud usage of this interval can be summarized as 1.54 bbls per footage drilled or 725.5 bbls per day.

Table 4.12: Estimated carbon footprint of NDF utilized in fourth interval

Chemicals	Total chemical usage (kg)	CO_2 emission factor (kg CO2/kg)	Total CO_2 emission (kg)
Viscosifier	3300	1.2733	4202
Magnesium Oxide	1325	1.11	1471
Starch	7500	0.996	7470
Calcium Carbonate	40,000	1.73	69,200
Sodium Bicarbonate	250	1.31	328
Sodium Chloride	75,000	0.238	17,850
Water	593,500	0.00024	142
Biocide	208.2	5.0938	1061
Total CO_2 emission, (kg CO_2)			101,723
CO_2 emission, (kg CO_2 / bbl)			23.4

As per Table 4.12, carbon emission of 1 bbl NDF is estimated at 23.4 kg CO_2. If usage of NDF is analyzed from the aspect of carbon emission, 36.0 kg of CO_2 is emitted per footage drilled or 17.0 MT of CO_2 is emitted per day. Overall process flow for reservoir section drilling of 8.5 inches and the management of drilling-fluid and drill cuttings are shown in Figure 4.10.

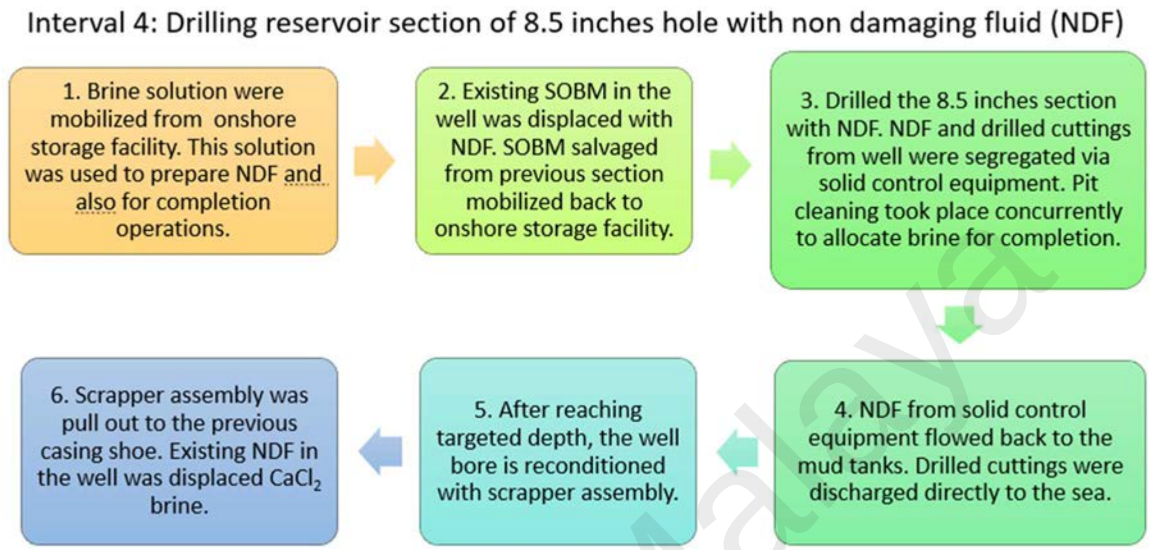


Figure 4.10: Interval 4 – Drilling reservoir section of 8.5 inches hole with water base NDF

4.5.1 Optimization of NDF volume and material usage

With 30 % volume excess, minimum volume NDF required to drill the entire reservoir section is about 3072.9 bbls. Instead, an extra 1280.1 bbls were prepared totaling up to 4353 bbls for this interval. Such a vast volume was necessary to encounter uncertainty of severe losses scenarios in limestone formation. As the fluid depletes through the loss zone, the pressure exerted by mud column will reduce, causing “kick” from the formation pore pressure. Thus, huge contingency volume was required so that the well is continuously filled with fluid and kept full.

4.5.1.1 Preparing just the right volume of NDF

Preparing "just the right volume" of NDF for this interval could be very subjective. Loss circulation scenarios could lead to well blowouts in worse case, thus limiting the volume of NDF must also consider the contingency volume as safety margin. With the approval from clients, contingency volume with 84.2 % in excess should be reduced to 30 %. If this volume is not capable of containing loss circulations in a long run, immediate changes in drilling technics and procedures are required. This will ensure drilling operations not completely depend on the NDF volume as a sole solution. By reducing contingency volume to 30 % in excess, about 29.9 MT of CO_2 emission are reduced concurrently.

4.5.1.2 Volume and material optimization with batch drilling

As discussed in first interval, similar strategy of batch drilling can be applied in fourth interval for the purpose of volume and material optimization. Since huge amount of chemicals needed for fluids mixing in the rig site, the approach of batch drilling will definitely ease the process of material logistics. At the same time, drilling experience and technics from the first well can be studied and applied for succeeding wells. As an example, if the first well do not encounter any severe losses, this could indicate fluids engineer to prepare just the right volume of NDF for next wells in the same interval. Table 4.13 will further elaborate the carbon footprint reduction with batch drilling strategy by assuming same well design for 3 wells with contingency volume of 30 % in excess.

Table 4.13: Estimated carbon footprint of NDF in batch drilling

Drilling of 8.5 inches section (Fourth interval)				
Drilling Type	**Batch drilling**			**Single well drilling**
Well name	**Well-KLM**	**Well-ABC**	**Well-XYZ**	**Well-KLM**
Volume mixed (bbls)	4353.0	0	952.3	4353.0
Volume salvaged from previous well (bbls)	0	3236.8	2120.6	0
Volume inside casing (bbls)	646.6	646.6	646.6	646.6
Volume inside open hole (bbls)	198.2	198.2	198.2	198.2
Volume of active mud tank + sand trap + line (bbls)	601.0	601.0	601.0	601.0
Circulation volume (bbls)	1445.8	1445.8	1445.8	1445.8
Volume loss (bbls)	918.0	918.0	918.0	918.0
Volume left in open hole (bbls)	198.2	198.2	198.2	198.2
Min. volume required to complete drilling (bbls)	2363.8	2363.8	2363.8	2363.8
Excess volume mixed for contigency (%)	84.2	36.9	30.0	84.2
Total CO_2 emission, (kg CO_2)	101723.1	0	22253.8	101723
Average CO_2 emission per well (kg CO_2)	41325.6			101723

As per Table 4.13, total CO_2 emission for all the three well in batch drilling is estimated 124.0 MT, averaging 41.3 MT of emission per well. Compared to a single well drilling, batch drilling could reduce the CO_2 emission by 59.4 % per well. However, reduction of carbon footprint with batch drilling is only practical provided that no severe losses in any of the wells in the same interval.

4.5.2 Change of technology in LCM remedials

Usually, loss circulation in upper section drilling could be managed with conventional LCM remedials, cement jobs or other non-reversible treatment. But if total loss circulation occurs while drilling fractured reservoir section, the above treatments might not be accepted. This is to preserve the reservoir section from damages or prevent the clogging from conventional LCMs (Davidson et al., 2000). The only option could be drilling "blind" while accepting losses and subsequently set casing across the loss zone or opting for Pressurized Mud Cap drilling (PMCD). Derived from Managed Pressure Drilling (MPD), PMCD could be very effective in total loss scenarios where there is no fluid return to the surface. The technique of PMCD regulates column pressure by continuous seawater injection through the annulus, concurrently assisted by surface pressure. This will ensure the wellbore pressure kept underbalanced. In PMCD mode, instead of drilling-fluid, a sacrificial fluid, usually seawater is pumped down the drill string. Seawater exiting from the drilling bit, together with the drilled cuttings are swept into the lost-circulation zone (Wilson, 2014). PMCD proved to be safer and cost-effective alternative compared to drilling blind or intermittent loss circulation remedial while drilling. According to Al-Amri et al. (2016), about 70 % cost savings could be achieved from drilling-fluid minimization. Apart from significant reduction from material usage, safety at the rig site is improved with less requirements of drilling-fluid mixing.

4.5.3 Waste reduction from packaging materials

Waste generated from packaging materials in fourth interval are mainly generated from usage of sodium chloride and calcium carbonate in NDF. Sodium chloride and calcium carbonate are packed and delivered in polypropylene jumbo bags which accommodate 1 MT of materials. Other wastes like paper bags are generated from usage of viscosifiers, magnesium oxide and starch. Paper bags are used to preserve the quality of these chemicals which are sensitive towards atmospheric humidity. Usually, this type of packing could accommodate 25 kg of materials. All the wastes from packaging materials generated for the purpose drilling fluids mixing are considered as hazardous waste. Therefore, a total of 197.3 kg hazardous waste generation is estimated in this interval as per Table 4.14. Alternatively, it can be summarized that 0.045 kg of hazardous waste being produced per 1 bbl NDF mixed.

As a CP strategy to reduce packaging wastes, concentrated NDF should be readily prepared in onshore mixing facilities and mobilized via the supply vessel. This NDF can be easily diluted to the desired density at the rig site. Since the waste from onshore facilities can be easily discarded and segregated to non-hazardous wastes, conventional treatment of solid waste could be applied, hence significantly reducing carbon footprint from packaging wastes disposal.

Table 4.14: Waste generated from packaging materials in fourth interval (8.5 inches section)

Material	Packaging material	Weight of packaging material (kg)	Hazardous Waste generated (pcs)	Hazardous Waste generated (kg)
Viscosifier	Paper bag	0.1	132	13.2
Magnesium Oxide	Paper bag	0.1	53	5.3
Starch	Paper bag	0.1	300	30
Sodium Bicarbonate	Polypropylene sack	0.07	10	0.7
Calcium cabonate	Polypropylene sack	0.07	200	14
Calcium cabonate	Polypropylene jumbo bag	1.1	35	38.5
Sodium chloride	Polypropylene jumbo bag	1.1	75	82.5
Biocide	5 gal plastic can	1.19	11	13.1
Total hazardous waste generated from packaging materials (kg)				197.3
Hazardous waste generated from packaging materials (kg) / bbl				0.045
Total CO_2 emission from packaging material (kg CO_2) [CO_2 Emission factor of hazardous waste (kg CO_2 / kg) x hazardous wastes generated (kg)]				518.9

4.5.4 Re-use drilling cuttings

Drilling through reservoir section usually produces limestone cuttings on the surface. NDF is classified as WBM or aqueous drilling-fluid, thus cuttings generated are directly discharged from shale shakers. About 1116.2 bbls of drilling waste were discharged on this interval, hence drilling waste discharged can be summarized as 0.395 bbls / footage drilled.

Table 4.15: Drilling waste generated in fourth interval

Interval	Footage drilled (ft)	Drilling cuttings generated (bbls)	NDF disharged with drilling cuttings (bbls)	Total drilling waste discharged to the sea (bbls)
Fourth Interval (8.5" Section)	2824	198.2	918	1116.2

In an industrial scale, limestone which are classified as sedimentary rock is obtained from quarry blasting. Limestone considered as valuable resource from the earth's crust due to its utilization for various purposes. In constructions, it can be used as building materials and cement production. For large scale agriculture, it is used as neutralizing agent for acidic soil to allow the plants grow more efficiently. Sometimes, limestone is also utilized to treat acidic water resources such as lake for irrigations. In heavy industries, limestone is used to remove the impurities from blast furnace in iron production (Geologyscience.com, 2021). Considering its wide contribution, recycling the limestone cuttings will initiate another CP strategy for this interval.

Drilling operations in certain part of world emphasizes zero discharge of cuttings to the sea. Thus, solids discharged from solid control equipment are transferred into a temporary bulk storage tank on the rig. Once full, this storage tanks will be placed on the boat and mobilized to onshore treatment facilities. In some cases, a dedicated boat will be stationed along-side the rig during the drilling operations. Using various technologies, the processed drill cuttings will be pumped straight into the number of holding tanks on the boat and transported onshore. If this is feasible with drilling operations in Malaysia, then same technics could be applied to recycle limestone cuttings for other industries.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The main contributor of environmental pollution in first interval can be easily distinguished with inefficiency of volume and material consumption. Contingency of kill mud is important to counteract shallow gas scenarios. Therefore, utilizing pre-mixed kill mud for spud mud without LCM additives could be a key strategy for carbon footprint reduction in single well drilling. Waste reduction from packaging materials is attainable by changing the type of packaging material and size of certain chemicals like caustic soda and Kwikseal. Further reduction in CO_2 emission could be observed if drilling in first interval in executed in close-loop circulation.

Seawater pollution in second and third interval is mainly caused by SOBM discharge or drilling cuttings with the SOBM residue. Therefore, implementing CP strategies were explored from components of SOBM itself. Reducing oil water ratio from 75:25 to 60:40 in SOBM system reduces carbon footprint by 5.7 % in second interval and 4.5 % in third interval. Packaging wastes generated in second and third interval are generally treated as hazardous waste. Thus, options of greener packaging method especially for liquid chemicals were suggested. Meanwhile, the amount discharged from pit cleaning is directly related to sedimentation of dead volume, so it could be useful to consider alternative mud tank designs. Small volume discharge which occurs from fluid displacement operation could be limited by setting the maximum allowable volume discharge. In addition, continuous training and education could enhance everyone's initiatives towards CP and the options suggested could be improvised with their ideas.

Similar to first interval, environmental impact in fourth interval is mainly caused by inefficiency volume and material consumption. Hence, CP options suggested in this interval are mainly about "preparing just the right volume of NDF", with 30 % excess as safety contingency. Beyond this safety margin, alternative drilling technics like PMCD must be instantly drafted to minimize the fluids and material wastages. Meanwhile, packaging wastes which were generated from NDF mixing could be prevented if concentrated NDF was readily prepared in onshore mixing facility and transported to the rig site. To further reduce the seawater pollution in this interval, the opportunity of recycling limestone drilling cuttings should be explored in various industries.

Compared to single well drilling, a remarkable carbon footprint reduction can be noticed with batch drilling especially in first and fourth interval. The contribution of batch drilling can be significantly observed via optimization of fluids volume and materials for both these intervals. Therefore, clients' interventions are needed so that more drilling campaign are designed with the sequence of batch drilling.

By assessing CP strategies suggested in each interval, kill mud optimization in first interval contributes the most reduction in CO_2 emission compared to other strategies. This is followed by the strategy of "preparing just the right volume" of NDF in fourth interval. Both technics, under the category of volume and material optimization reduced about 75 MT of CO_2 emission. Meanwhile, product modification emphasized in second and third interval contributes about 15.0 MT of reduction on carbon footprint. Without including batch drilling, a total reduction of 94.9 MT of CO_2 could be achieved by adhering all the CP concepts discussed in all four intervals. This is equivalent to 18.2 % of reduction from total of 520.9 MT CO_2 emitted throughout the drilling operations without considering any CP strategies.

Alternatively, all these CP options are doing the similar job of 2000 mature trees which absorb about 40 – 50 kg of CO_2 per year each.

5.2 Recommendation for future studies

The following provides recommendations with the intentions to improve future research initiatives in this area:

i. Further carbon footprint reduction can be observed with other qualitative CP proposed in this study. The method of quantifying carbon footprint from these strategies could be essential in obtaining more accurate value in CO_2 reduction before and after the CP implementation. Therefore, further studies on qualitative CP strategies proposed in this research are recommended.

ii. This study was carried out based on drilling activities performed in one well. To further analyze the CO_2 emissions with usage of drilling-fluids, material consumptions and fluids related waste generation, comparison should be done with another well with the same rig. Longer period of study is necessary as drilling operation is a slow process and its progress is depending on programs and ad-hoc plans during any unforeseen scenarios during the operations.

iii. Carbon emission factor for drilling-fluids discussed in this study is not golden value which can be referred for other drilling operations using same type of fluid system. For instance, SOBM with the density of 1.2 SG has different carbon emission factor than SOBM with 1.5 SG due to various composition of chemicals and additives. Hence, new set of carbon emission factor must be calculated to examine the efficiency of suggested CP strategies.

iv. Finally, all the CP strategies suggested must prioritize the safety of the workers in the rig site. Other human factor and ergonomic issues which could be raised from the suggested CP option must also be considered. CP approaches could significantly reduce seawater pollution and other environmental impacts, but it is pointless if those strategies exposing rig hands to any sort of hazards.

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