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Treatment and Optimization of Drill Cuttings on NCS

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Abstract

As part of a Joint industry project (JIP), Norwegian Technology has developed a new treatment technology for oil contaminated drill cuttings (OCDC). The technology is intended for offshore use at the Norwegian Continental Shelf (NCS). In order to allow for offshore treatment and onsite discharge, the drill cuttings need to meet requirements set by the Norwegian Environment Agency. According to the Oslo Paris commission (OSPAR), the maximum oil content on drill cuttings should be below 1 wt% and for the Norwegian Environment Agency a maximum oil content on drill cuttings varies but is often below 0,5 wt%.

In this research, the objective was to investigate and optimize the technology for the waste stream received by ConocoPhillips as part of the Joint industry project. Furthermore, various oil contaminated drill cuttings from the Norwegian Continental Shelf were tested, in order to evaluate the technology for drilling waste on NCS. In addition to this laboratory research, the results were combined with accessible full-scale microwave treated data, in order to predict a realistic scaleup.

The results of the optimized tests received from Eurofins were 0,51 wt% oil on cuttings (OOC) for ConocoPhillips 17-inch, 0,53 wt% OOC for ConocoPhillips 16X-inch, 0,44 wt% OOC for ConocoPhillips 16Y-inch and 0,07 wt% OOC for Equinor.

These result was optimized with respect to energy consumption in relation to oil separation. The energy consumption for ConocoPhillips 17-inch was reduced by 23 % while achieving 0,51 wt% OOC. ConocoPhillips 16X-inch was reduced by 20 % in energy consumption while achieving 0,53 wt% OOC. ConocoPhillips 16Y-inch was reduced by 12 % in energy consumption while achieving 0,44 wt% OOC. Equinor was reduced by 16 % in energy consumption while achieving 0,07 wt% OOC.

According to existing work found in the literature, a 35-50 % energy decrease for the cuttings is expected when treating the drill cuttings in full-scale. This relates to increased power density and a decrease in microwave frequency. By applying this to the laboratory results it leads to a technology that can reduce oil content to market leading levels, while simultaneously maintaining energy efficiency.

Testing of ConocoPhillips 17-inch drill cuttings was done with a fellow student, Bernt-Helge Vedeld Nygård.

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Abbreviations

BAT	Best Available Technology
COP	ConocoPhillips
EMR	Electronic Magnetic Radiation
MEG	Monoethylene Glycol
NCS	Norwegian Continental Shelf
OBF	Oil-Based Fluids
OCDC	Oil Contaminated Drill Cuttings
OSPAR	Oslo Paris Commission
OOC	Oil on Cuttings
PAH	Polycyclic Aromatic Hydrocarbons
ppm	Parts per million
SBF	Synthetic-Based Fluids
TCC	Thermomechanical Cuttings Cleaner
TEG	Triethylene Glycol
TWT	Travelling Wave Tube
WBF	Water-Based Fluids
Wt%	Weight percent

1 Introduction

1.1 Background

Drill cuttings and drilling mud are by products due to drilling when extracting oil and gas. A lot of different methods are used to deal with these products including discharge into sea and treatment onshore. Due to Oslo Paris Commission (OSPAR) regulations, discharge of drill cuttings in the North Sea can have a maximum oil content of 1% (OSPAR, 2000).

Due to the extra cost and emissions of transport related to onshore treatment the goal is to create the Best Available Technology (BAT) for offshore treatment of drill cuttings. Using a microwave with a susceptor to treat drill cuttings and remove the oil is a technology being currently implemented by Norwegian Technology AS, who have a patent for this technology. There are several benefits to this technology as follows:

- Minimal noise emission
- Fast start up
- Low cost of operation
- Robustness
- Smaller footprint
- No crushed particles

(NorwegianTechnology, 2018)

1.2 Problem description

Microwave treatment on drill cuttings without using a susceptor has shown promise to treat the OOC to an acceptable amount (Pereira, 2012) (J. Robinson et al., 2009). Promising results from the technology developed by Norwegian Technology AS has treated drill cuttings below the requirement set by OSPAR as well as the 0,5 % limited often used by Norwegian authorities.

A lot of different types of drill cuttings exists and more data is needed to map out how well the Norwegian Technology microwave treats different types of drill cuttings.

For BAT to be achievable the energy efficiency of the microwave must be high, the microwave used has a 2 kW power output. How will the energy consumption be affected when this technology is developed in full-scale?

1.3 Objectives

To see if Norwegian Technology's microwave could solve these problems different drill cuttings from Equinor and ConocoPhillips were treated in a batch microwave and three main objectives were given:

1. Find important parameters in relation to oil separation and energy consumption with the use of NT susceptor technology
2. Treat a diversity of drill cuttings from NCS and evaluate the technical robustness of the technology.
3. Use existing research to relate energy consumption and oil separation to full scale microwave treatment.

Testing of ConocoPhillips 17-inch drill cuttings was done with a fellow student, Bernt-Helge Vedeld Nygård.

1.4 Collaboration with industry

This thesis was initiated and performed with the help and support from Norwegian Technology.

With a strong environmental focus, the company is developing technologies that treat and disposes of any type of industrial water both onsite and offsite. A key focus is minimizing footprint and weight, creating technologies that can be utilized both offshore and onshore.

1.5 Novelty of research

Microwave is widely used for example in the food, textile and drying industries (Meredith & Institution of Electrical, 1998).

As a treatment for drill cuttings John Robinson at the University of Nottingham has published articles detailing mechanisms and parameters of microwave treatment and has obtained oil levels below 1 wt%.

Some treatment of oil contaminated drill cuttings has been done with a single-mode microwave combined with organic susceptor. Organic susceptors requires less energy compared to water and provide high process temperatures during treatment. Significant costs can be saved using this technology, due to high process temperature and because the oil contributes with a higher vapor pressure than water.

2 Waste problems and treatment related to drill cuttings

2.1 Application of drilling fluids for the drilling process

When oil and gas are extracted there is an impermeable rock formation above it that must be penetrated before the extraction can begin. The process of drilling through the rock formation leaves some problems. When being drilled the rock breaks into smaller bits called drill cuttings, the drill cuttings is sent up the annulus to the oil rig together with drilling fluids, then it is sent to the shale shaker as shown in Figure 1.

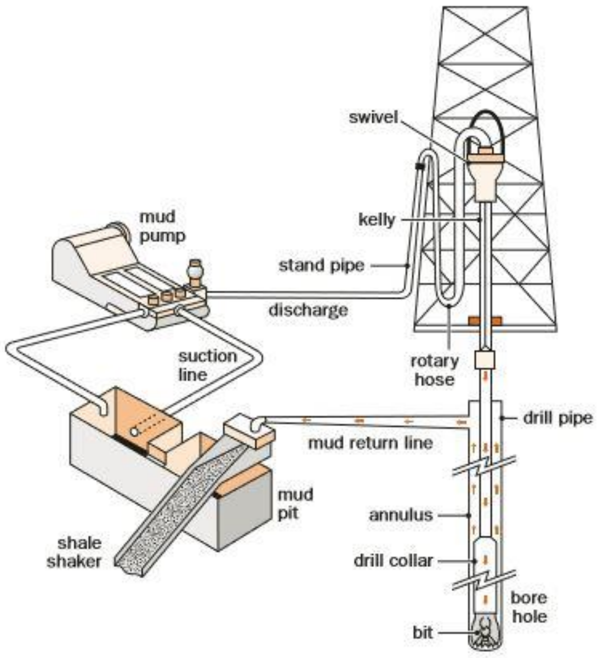

Figure 1: Overview of the drilling process (UNEP, 1997)

The purpose of the drilling fluid is to lubricate and cool down the drill bit as well as stabilizing the well bore and control subsurface pressures (Caenn, Darley, & Gray, 2017).

Since the drilling fluid has several purposes it must have high viscosity, density and lubricity to work effectively. To achieve this, several chemicals, weighing agents and clays are added to get the right properties (Pappworth & Caudle, 2008).

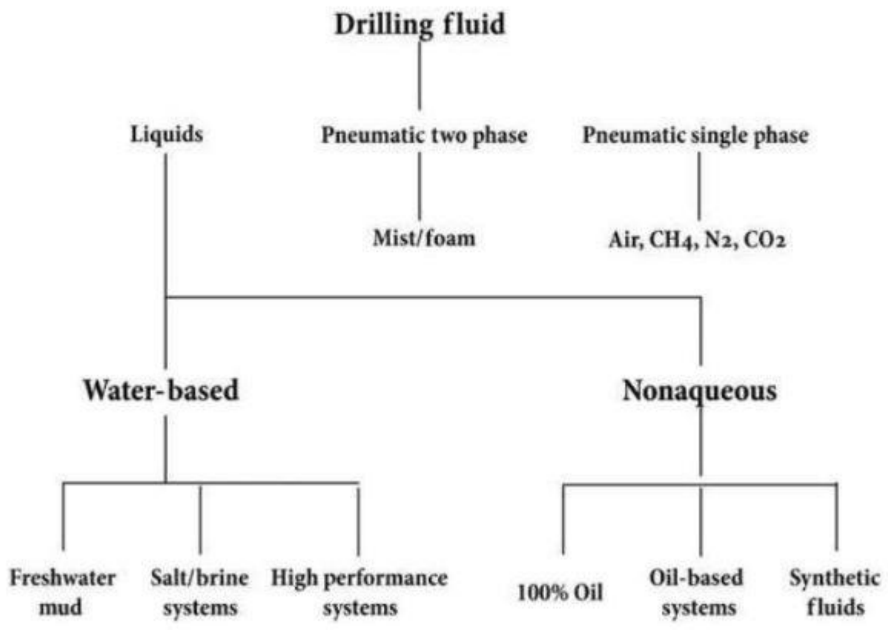

Figure 2: Overview of different drilling fluids (Caenn et al., 2017)

Figure 2 gives an overview over the different types of drilling fluids available. The most relevant drilling fluids oil-based fluids (OBF), water-based fluids (WBF) and synthetic-based fluids (SBF) are discussed below.

2.1.1 Water-Based Fluids

WBF's are fluids where water is the continuous phase, it can be either fresh or saltwater and is readily available with low cost. However, water cannot always be used as drilling fluid. Situations that water-based fluids have problems with are thermal stability in wells with a high temperature and drilling through water soluble formations such as salt (Pappworth & Caudle, 2008).

2.1.2 Oil-Based Fluids

OBF's contains oil as the continuous phase, the oil could be mineral, diesel or some other form of oil. OBF is more expensive than WBF and is used in situations WBF's do not work and are ineffective. Due to toxicity problems with OBF's SBF's were developed (Pappworth & Caudle, 2008).

2.1.3 Synthetic-Based Fluids

SBF's are composed of synthetic organic chemicals which are more environmentally friendly due to lower bioaccumulation and faster biodegradability. They are also less toxic due to there being no polycyclic aromatic hydrocarbons (PAH's). However, they are more expensive than OBF's (Pappworth & Caudle, 2008).

2.2 Toxicity and environmental impact of drill cuttings

As oil production in the North Sea started in the early 1970's the drilling waste was discharged overboard into the sea. During the 1980's a number of studies showed how oil-based fluids and drill cuttings were having a negative impact on the ecology in the area where the oil contaminated drill cuttings were discharged.

One study found that hydrocarbon levels detected closely (50 m) around an offshore installation were 1000 times higher than levels detected 250 m from the platform. The high concentration of hydrocarbons detected were due to OBF's and drill cuttings (Davies et al., 1984).

Kingston found that the main source of oil pollution came from the oil discharge attached to the drill cuttings, this being the OBF's. The discharge of oily drilling waste resulted in a decrease of species richness close to the affected platforms (Kingston, 1992).

The diatom Skeletonema costatum showed a reduction in both photosynthetic capacity and growth rate during exposure to drill cuttings, OBF's and WBF's. It should be noted that the concentration of the oil-based fluid was 100-1000 parts per million (ppm) while the water-based fluid had a concentration of 100 000 ppm with both showing a similar effect on the diatom. It was also shown that 5% of drill cuttings contaminated with oil-based fluids had been biodegraded after 180 days (Østgaard & Jensen, 1985).

Size has a huge impact on if the particle will settle in the seabed or be suspended in the water column. Small particles with a size < 20 µm will generally not settle on the seabed, while particles > 600 µm will sediment. Dumping smaller particles results in serious negative physical damages to fish and filter-feeder organisms in the surrounding ecology, including sharp particles having the potential to damage fish gills (Bytt, Vik, Stang, Henninge, & Kjønnø, 2014).

2.3 Handling of drill cutting waste

Most WBF is discharged into the sea due to its limited toxicity, OBF however is for the majority either re-injected into a disposal well or sent onshore for treatment. A small fraction of the drill cuttings in 2015 were treated to below 1 wt% oil and discharged into the sea (Norsk Olje & Gass, 2016).

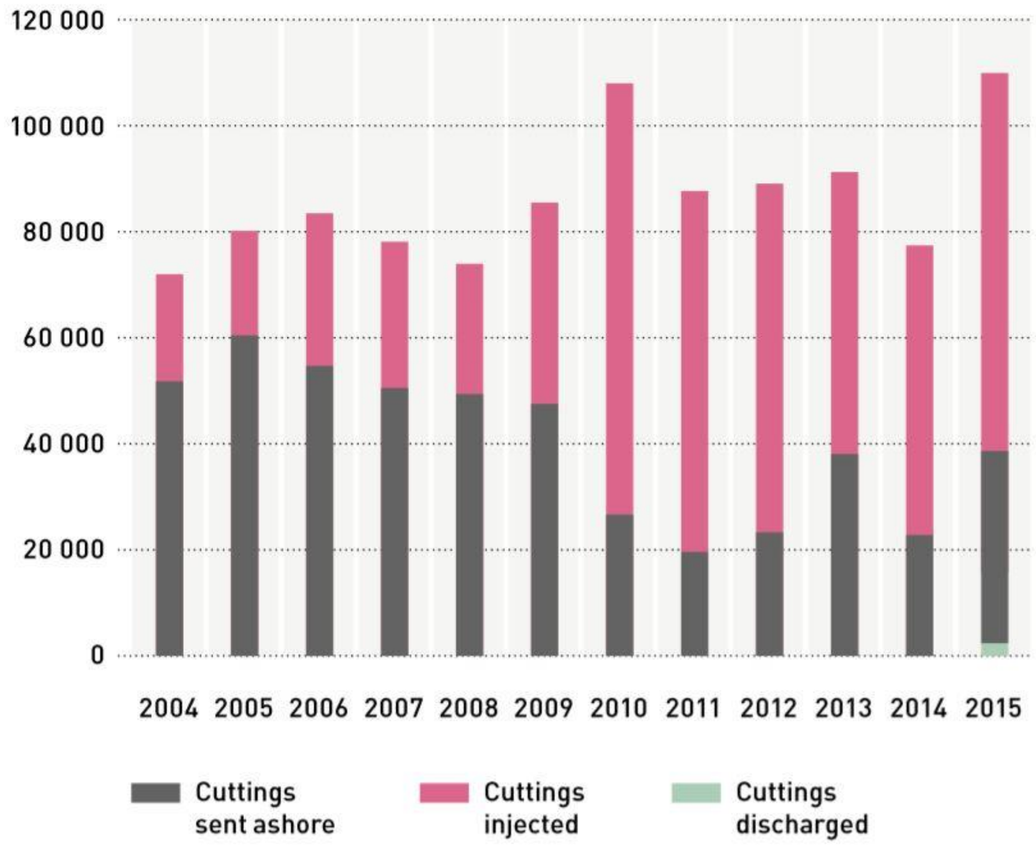

Figure 3: Amount drill cuttings treated yearly in tones (Norsk Olje & Gass, 2016)

Figure 3 illustrates the vast amount of drill cuttings being treated each year, this means a lot of energy is consumed and a lot of climate gases are released.

Reinjection is estimated to release between 16,7-18 kg CO_2 per ton drill cuttings, to drill the reinjection well approximately 3400 tons CO_2 are released. Distillation treatment onshore is estimated to release 180 kg CO_2 per ton drill cuttings while burning drill cuttings onshore is estimated to release 475 kg CO_2 per ton drill cuttings. Emissions from transporting the drill cuttings onshore are included in the estimations (Karlsen, 2012).

2.4 Treatment management and technologies for drill cuttings

There are several treatment methods available for oil contaminated drill cuttings, the treatment method can either be non-biological, biological or thermal.

2.4.1 Non-biological treatment

2.4.1.1 Reinjection

For offshore operations the drill cuttings are usually either discharged into the sea offshore or reinjected into a disposal well. Offshore drill cuttings, drill fluids and seawater are processed into a slurry and then injected into the well. An advantage with this method is that no transportation is needed; the drilling waste is dealt with onsite. Disadvantages is the risk that a fracture could lead to groundwater contamination (Wojtanowicz, 2008).

2.4.1.2 Stabilization/solidification

Stabilization/solidification is a set of processes that is used to treat the drill waste and reduce how hazardous the drill waste is. The solidification part is a process where the waste is turned into a solid by adding materials to it, which may be through chemical bonding (EPA, 1993).

The stabilization process converts the waste to a more chemically stable form, this transformation often happens through physiochemical reactions. The result is that the waste is less mobile or in a less toxic form (Leonard & Stegemann, 2010).

Advantages with this method is that the contaminants mobility or solubility is reduced therefore handling of the waste is easier since it is in solid form and the surface area is reduced, thus reducing the area of potential contamination.

2.4.2 Biological treatment

2.4.2.1 Land farming

Land farming is one of several bioremediation processes that are used to degrade the drill waste. The common denominator for all these processes is the fact that the waste products are being broken down by organisms like bacteria and plants and their enzymes. Since the organisms use the waste and converts it into stable products this process is very environmentally friendly. There are exceptions like anaerobic processes that produce methane. Land farming is done by spreading drill waste over a normal patch of soil and let the microbes break down all the different chemicals. A large area of soil is also required (Ball, Stewart, & Schliephake, 2012).

2.4.2.2 Bioreactor

Bioreactor is a different option that is based on the same principles as land farming, organisms break down the waste. The main difference between the other two processes is that here the degradation is happening in a confined space, the bioreactor. The reason for using the bioreactor is that the people operating it have full control over what is added. By continuously monitoring and controlling the reactor rates of degradation is maximized. This is due to creating the perfect environment by controlling temperature, moisture and aeration. The better conditions are in the bioreactor the quicker the process will take, 99 % of drill waste can be degraded after only 10-12 days (Ward, Singh, & Van Hamme, 2003).

Obviously, the fact that basically all the contaminants are dealt with in a very short amount of time is a huge advantage compared to land farming and land spreading. The disadvantage is that the method is expensive, both equipment as well as constant monitoring by highly skilled operators (Ball et al., 2012).

2.4.3 Thermal treatment

2.4.3.1 Thermal desorption

Thermal desorption is a process where full oxidation of the organics is minimal, and they are separated from the solid part of the drill cuttings by volatizing them. The volatized part is then sent to a special separator that separates the water and the oil. The oil is then reused either as base fluids or as fuel, the water is also reused on the treated solids (Ball et al., 2012).

2.4.3.2 Thermomechanical Cuttings Cleaner (TCC)

This is the current best available technology (BAT) in Norway for offshore treatment of drill cuttings.

Heat is delivered through a hammermill system which creates friction and in turn changes kinetic energy to thermal energy (Ormeloh, 2014).

This increase in thermal energy raises the temperature enough to volatize the organic and water parts of the drill waste. The advantages of thermal desorption are that it can be installed offshore so transportation of drill cuttings is avoided.

The kinetic energy created from the friction is due to the drill cuttings being crushed into smaller particles. A particle size distribution evaluation showed that drill cuttings treated in TCC consisted of 50-70% silt (particle size 2-63 µm), 5-15% clay (particle size < 2 µm) and 20-40% sand (particle size 63-2000 µm) (Ormeloh, 2014).

3 Theory

3.1 Microwave theory

Electromagnetic radiation (EMR) is a form of energy that is described by two different models, particle and wave. The particle model treats EMR as particles with energy called photons. The direction of the EMR can be predicted by using the wave model. The position of the magnetic and electric fields which oscillates perpendicular to each other describes the direction of propagation of the electromagnetic radiation (West, Holler, Crouch, & Skoog, 2014).

The wave model also explains the wavelength and frequency of EMR. EMR is divided into different type of waves depending on the frequency and wavelength, shown in Figure 4.

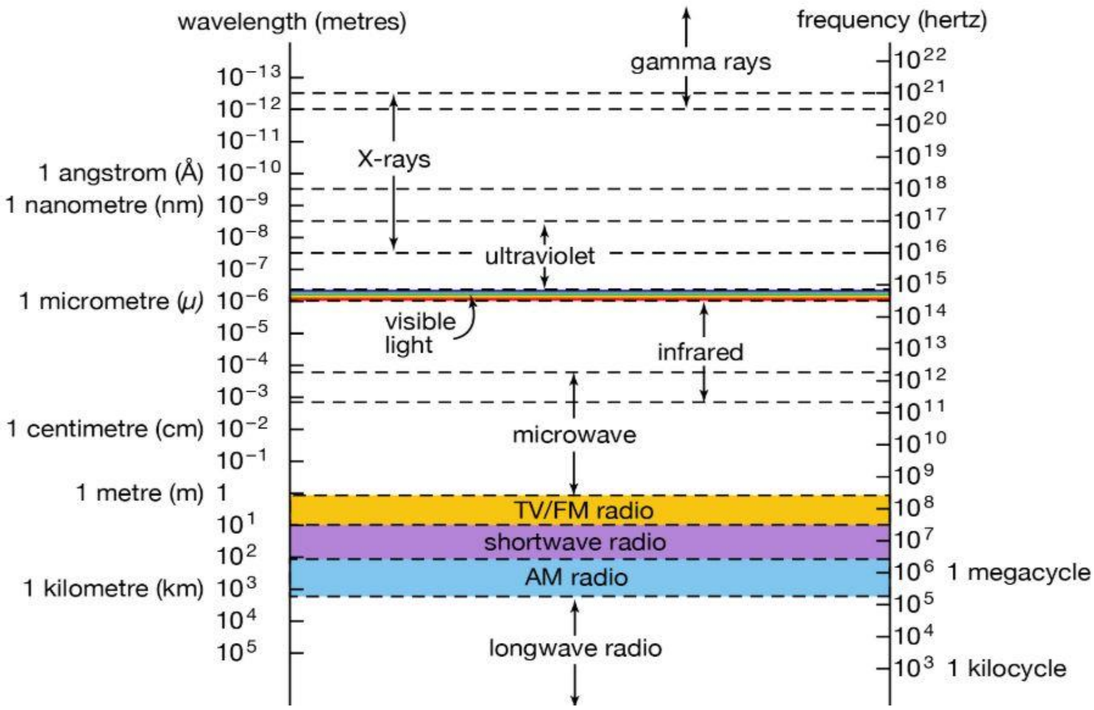

Figure 4: Electromagnetic spectrum (Encyclopædia Britannica, 2019)

Microwaves are a type of EMR with a wavelength between 1-1000 mm and a frequency between 300-300 000 MHz (Hitchcock, 2004).

The frequency of EMR is defined as the rate of vibrations made by a wave in an electromagnetic field per unit of time (Encyclopædia Britannica, 2017).

The SI unit hertz (Hz) equals the amount of cycles per second (Encyclopædia Britannica, 2013).

3.2 Application in microwave

Microwaves are unique in that energy is transferred by an electric field. In other conventional thermal processes energy is transferred through thermal conductivity resulting in every element of the material being heated. In microwave heating each element of the material interact with the microwaves and depending on their properties either get warmed or not (J. P. Robinson et al., 2010).

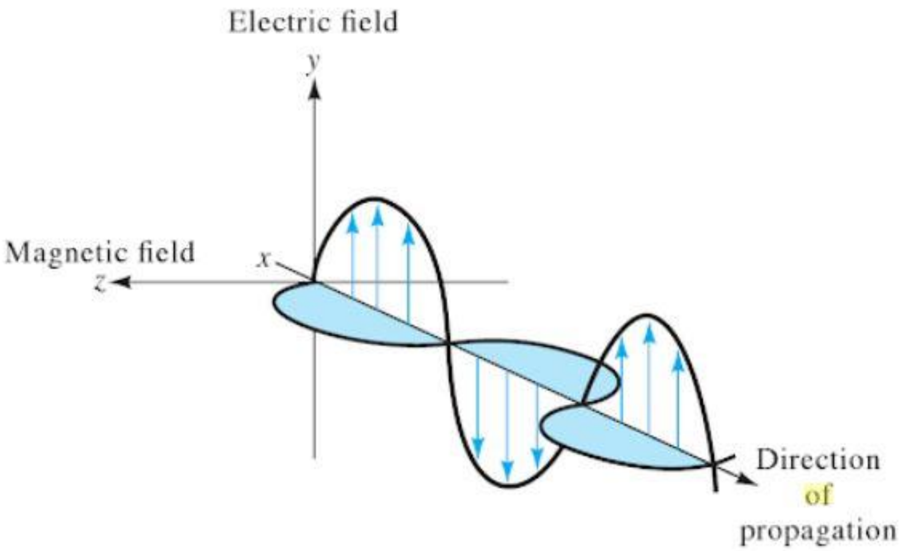

Figure 5: Wave nature of a single frequency EMR (West et al., 2014)

When a material is being hit by microwaves the electric field in Figure 5 will interact with certain molecules in the material called dielectric molecules, these molecules try to align with the electric field. The electric field changes its position at a very rapid rate, corresponding to the frequency mentioned in Chapter 3.1. Each time the electric field changes position the dielectric molecules also changes position to re-align with the microwave, resulting in frictional heat being generated (Meredith & Institution of Electrical, 1998).

Since not every molecule is dielectric microwaves selectively heat certain parts of a material, water is a dielectric molecule and will heat when being exposed to microwaves. That is why foods without water will not get warm when put in a conventional microwave oven.

3.2.1 Dielectric factors

The dielectric constant (ε') and the dielectric loss factor (ε'') are the two numbers that quantify how materials interact with microwaves (Meredith & Institution of Electrical, 1998). The dielectric constant quantifies how well a material stores energy from the microwaves. The dielectric loss factor quantifies how well a material converts electric energy to heat, this is through ion, dipolar electric mechanisms (Thostenson & Chou, 1999).

Materials are classified inn three different ways depending on how they interact with microwaves:

- Transparent – The material has low dielectric loss and only small amounts of microwaves are absorbed.
- Opaque – The microwaves do not pass through but are rather reflected.
- Absorbing – The material has high dielectric loss and a large amount of the microwaves are absorbed and converted to thermal energy.

(Shang, Snape, Kingman, & Robinson, 2005)

Two important parameters that are dependent on the dielectric properties are power density and penetration depth (Clark, Folz, & West, 2000).

3.2.2 Power density

Power density (Pd) is a parameter which is used to quantify how much power a material is absorbing per unit volume. Power density gives a clear indication how much power is being supplied. Power density is given by Equation 1,

$$Pd = 2\pi f \varepsilon_o \varepsilon''_{eff} |E|^2 \qquad (1)$$

where f is the microwave frequency, ε_o is the permittivity of free space (8,85 x 10^{-12} F/m), ε''_{eff} is the relative dielectric loss factor and E is the magnitude of the electric field (Shang et al., 2005).

There are two ways to increase power density, either by reducing the volume that the microwaves are hitting or by increasing the power of the microwave.

3.2.3 Penetration depth

As the microwave penetrates deeper into the dielectric material and is absorbed the field strength decreases. The penetration depth (Dp) is defined as the depth when the power flux has fallen to 1/e where e is the Euler’s constant (Komarov, 2012). From Equation 2,

$$Dp = \frac{\lambda o\sqrt{\varepsilon'}}{2\pi\varepsilon''} \tag{2}$$

where λo is the free-space wavelength, ε′ is the dielectric constant and ε″ is the dielectric loss factor (Meredith & Institution of Electrical, 1998).

Here the relationship between penetration depth and wavelength is established, by increasing wavelength, the penetration depth also increases. The most common frequencies used are around 900 MHz and 2450 MHz, microwaves with 2450 MHz can have a maximum power output of 30 kW/h. Therefore, full scale industrial microwaves have a frequency of 900 MHz compared to smaller units. Due to the frequency being smaller for full scale it means that the wavelength and penetration depth is bigger, the extra penetration depth means the microwaves are absorbed in a more homogenous fashion and increases the separation degree.

3.3 Microwave setup

The microwave consists of four main components:

- Microwave generator
- Microwave transmission lines
- Microwave heating applicators
- Power supply

3.3.1 Microwave generator

To generate microwaves a high power and frequency is required, to achieve this a vacuum tube is most commonly used (Thostenson & Chou, 1999).

The three main vacuum tubes used are Magnetrons, Klystrons and Travelling-Wave Tubes (TWTs) (Pereira, 2012).

The magnetron is the most used due to being mass produced and being cheap (Thostenson & Chou, 1999). Efficiency of high-power magnetrons are very high at 80-85% depending on frequency (Meredith & Institution of Electrical, 1998).

3.3.2 Microwave transmission lines

Transmission lines are used to transfer the microwaves created in the generator to the microwave applicator. For low power systems coaxial cables are used, at high output power and frequencies coaxial cables has a high-power loss and waveguides are often used instead. Waveguides are hollow tubes that propagate the electromagnetic waves, usually with a rectangular cross section (Thostenson & Chou, 1999).

3.3.3 Microwave heating applicator

An applicator is a cavity that supplies the microwaves created by the generator to the sample (Mehdizadeh, 2010).

Due to their high field strength, single-mode and multi-mode applicators are commonly used (Thostenson & Chou, 1999).

3.3.3.1 Single-mode applicator

A single-mode applicator is usually cylindrical with a radius equal to the wavelength of the microwaves (Mehdizadeh, 2010).

The reason it is called a single-mode applicator is the fact that it only supports the resonance of one mode. The single-mode cavity has one ‘’hot spot’’ where the field strength of the microwaves is strong, this is due to uneven distribution of the electromagnetic field (Pereira, 2012).

3.3.3.2 Multi-mode applicator

A multi-mode applicator is the type that is used in conventional household microwave ovens, the reason is it’s simple design, which is a rectangular cavity with dimensions of at least around twice the wavelength (Mehdizadeh, 2010).

The applicator has multiple resonating modes and by increasing the size of the cavity the amount of available modes increases as well (Thostenson & Chou, 1999).

Multi-mode applicators have a more random distribution of microwaves, this is why a turntable is used in household microwaves ovens. Multi-mode applicators can treat larger volumes, but single-mode applicators can achieve higher power densities (Shang, Snape, Kingman, & Robinson, 2006).

4 Materials and methods

For all the tests done on the drill cuttings a microwave, soxtec, retort and a lot of additional equipment was used. Table 1 contains an overview of all the equipment used.

Table 1: List of equipment used

Equipment	Model	Manufacturer
Microwave	Version 1.03en	Fricke und Mallah Microwave Technology GmbH
Voltmeter	1070 DMM	Peak Tech
Glassware	-	-
Weight	KERN440	KERN & SOHN GmbH
Susceptor	MEG	Sigma-Aldrich
Thread sealing tape	PTFE	Biltema
Pressurized N_2 gas	Nitrogen 4.0	Yara Praxair
Centrifuge	Rotomix 46	Hettich
Magnetic stirrer	Hei-Standard	Heidolph
Twist	-	Biltema
Duct tape	-	Biltema
Vacuum pump	739003	-
Soxtec system	HT1043	Foss-Tectator
Extraction cups	-	.
Boiling stones	-	-
Thimble	-	-
Cotton pads	-	First Price
Heptane	-	Sigma-Aldrich
Analytical balances	Adventurer	Ohaus
Heating plate	Hei-Standard	Heidolph
Petroleum ether	-	Sigma-Aldrich
Retort kit	165-14-3	OFITE
Measuring cylinders	-	-

4.1 The microwave unit

The microwave oven used was a single-mode custom made microwave by Fricke und Mallah (FUM) GmbH for NT. The microwave oven had a maximum power output of 2 kW, the microwaves produced had a frequency of 2450 MHz.

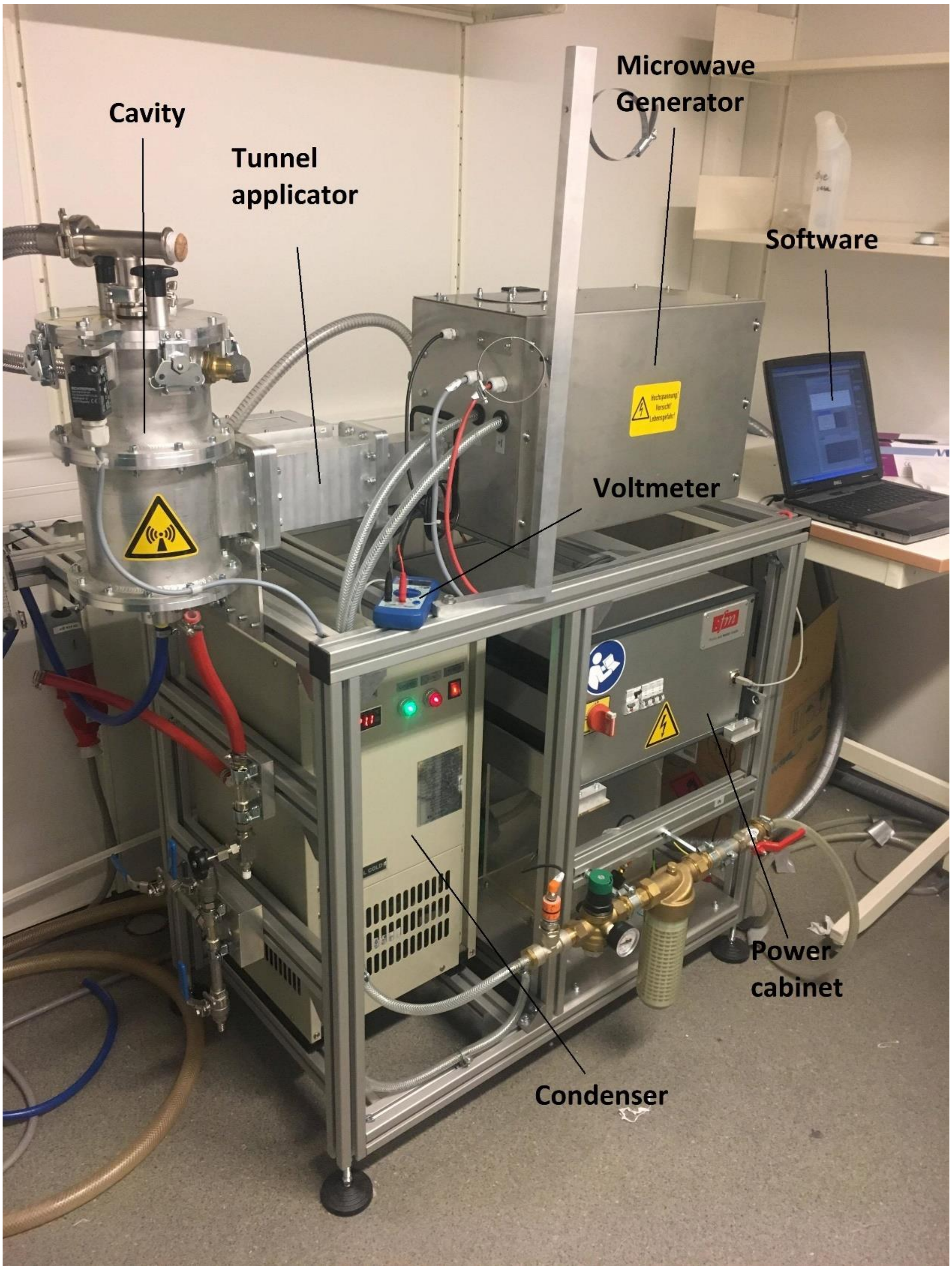

Figure 6: Microwave setup

With the software on the computer it was possible to decide how much power and for how long the microwave should treat the drill cuttings, the process was also started by the software.

The voltmeter was used to measure the amount of power reflected in millivolt. This was done by using a voice recorder and reading of the voltmeter throughout the experiment. Table 2 was used to convert millivolt to watt. The reflected power was subtracted from the total input power to find the absorbed power. All the numbers in the experiment were added together to find the total amount absorbed power used.

Table 2: Conversion between millivolt and watt

Watt (W)	Millivolt (mV)
40	7,5
50	9,1
64	10,5
80	11,5
100	15
128	20
160	22
200	29
256	35
320	41
400	50
500	60
640	70
800	85
1000	100
1280	110
1600	125
2000	150

A nitrogen tank was used to supply nitrogen to the cavity. Nitrogen was used to have an inert atmosphere and to remove the risk of explosions. A flow meter was used to control that the flow rate was around 8 l/min.

4.1.1 Preparing the sample

Custom made glass cylinders were used as sample holders for the drill cuttings. The glass cylinders had two lids, the bottom one had a small hole to allow nitrogen gas into the sample. The top lid had a long thin neck and was used to stop re-condensation, a similar configuration had been welded in the middle of the cylinder, this also to prevent re-condensation and to hold the drill cuttings in one position.

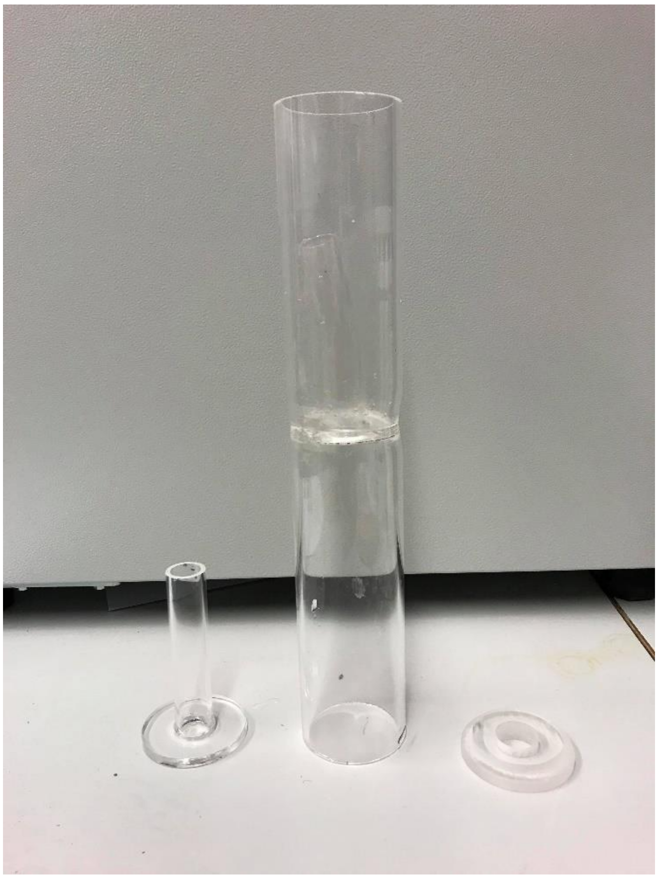

Figure 7: Glass cylinder sample holder

For all tests 150g drill cuttings were weighed and added to the bottom part of the sample holder. Twist was added both before and after the drill cuttings, this was done to position the cuttings so that the microwaves would hit when placed in the cavity. A small strip of duct tape was used to ensure the bottom lid would not fall into the cavity after treatment. Thread seal tape was used both on the top and bottom lid to ensure no leaking.

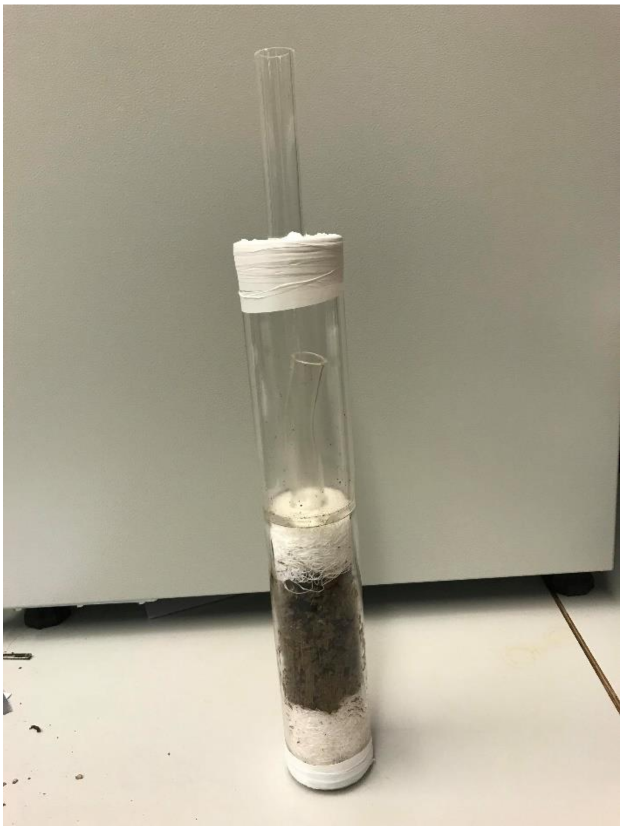

Figure 8: Sample holder with drill cuttings placed inside

When ready the sample was placed in the microwave cavity. While preparing the sample the temperature of water was also adjusted, since the microwave could only handle water with a temperature between 18-25 °C.

4.1.2 Procedure for Microwave experiments

The microwave was turned on and the software program on the computer was opened. In the program the inputs for power (%) and time (s) were chosen. The voltmeter was turned on and put on 200 millivolts, the nitrogen tank was opened, and the flow rate adjusted to 8 l/min and the pump for the condenser was turned on. The microwave was started through the software program and a 15 second countdown began. Throughout the experiment the deflected power was read into a voice recorder. When the treatment time was finished the nitrogen and pump was turned off and the cavity lid was removed, sometimes steam was coming out of the sample due to the heat, so it was removed after a few minutes.

4.1.3 Treating with glycol

When treating with glycol every step of Chapter 4.1.2 was followed but after the first treatment glycol would be added. Depending on the test the glycol would either be added straight away into the warm drill cuttings or the drill cuttings would be cooled down before being dosed with the glycol. The sample holder would be turned upside down at an angle while the glycol was added through the small hole at the bottom (Figure 9).

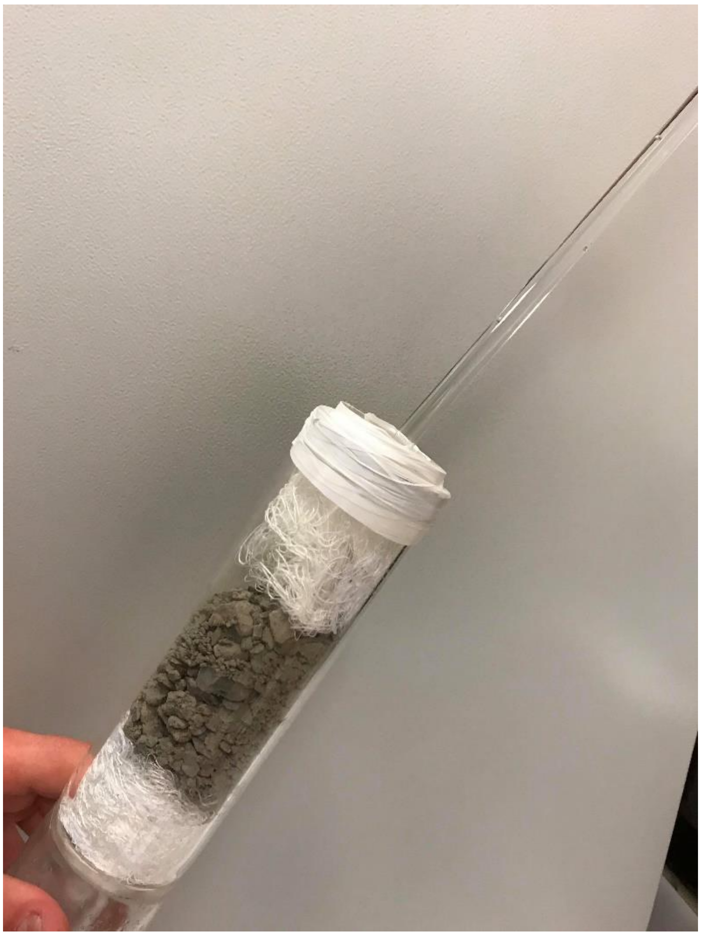

Figure 9: Dosing glycol on the drill cuttings

The test with the added glycol would then be carried out as usual, described in Chapter 4.1.2. A couple of different methods for dosing the glycol was tried. A small pipette was tried but it tended to break when putting it into the twist, due to its size it was also tedious when adding between 10-50 ml glycol. It was decided to use a 25 ml pipette (Figure 10) for dosing, due to its length it was easy to access the drill cuttings as well as being able to add a large volume at ones.

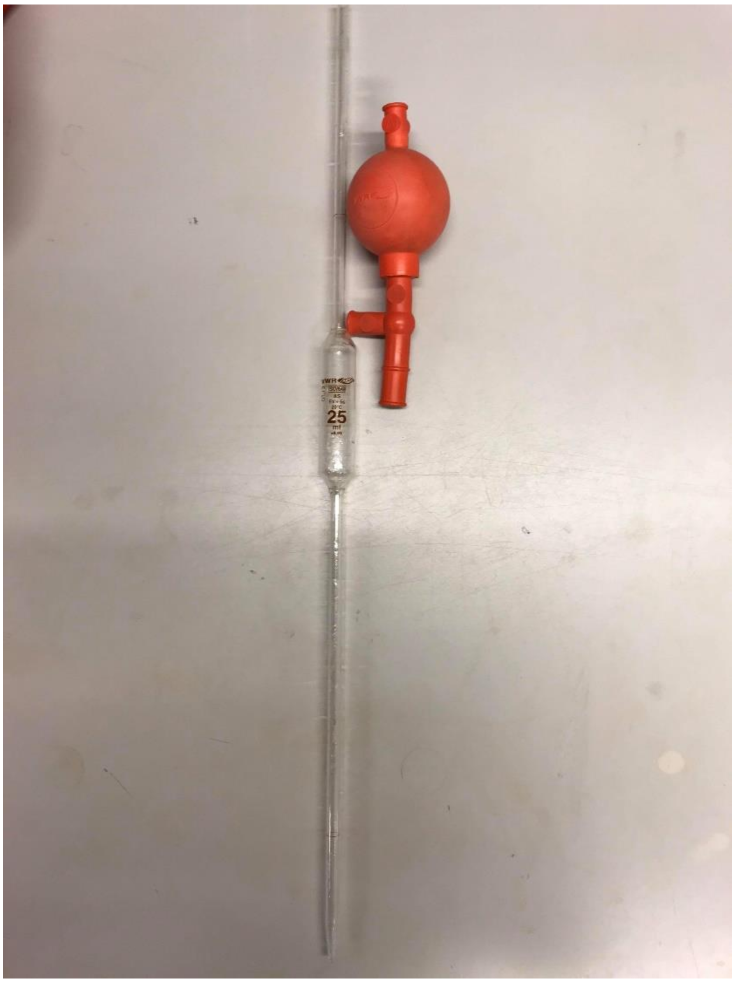

Figure 10: 25 ml pipette

When pre-heated glycol was used in tests it was warmed in an erlenmeyer flask which was placed in a silicon oil bath. A nitrogen tank was connected to the erlenmeyer flask, nitrogen was used to prevent the glycol from decomposing. A thermometer was used to check when the glycol had reached its intended temperature.

4.1.4 Adding AC into glycol

Activated carbon (AC) was added to glycol and mixed (Figure 11). A concentration of 2 wt% AC was used.

Figure 11: Mixture of glycol and AC

This mixture was heated in the same manner as the glycol described in the Chapter 4.1.3. Due to the AC clogging the hole of the pipette a glass funnel with a wider hole had to be used to dose the mixture in the drill cuttings (Figure 12).

Figure 12: AC being dosed on drill cuttings

4.1.5 Pre-heating drill cuttings

For some tests drill cuttings were placed in plastic bags and put in a water bath in a pot where they were heated up to 70 °C. A digital thermometer was placed in one of the plastic bags to control the temperature of the drill cuttings (Figure 13).

Figure 13: Setup for drill cuttings pre-heating

4.2 Soxtec

To measure the oil concentrations of the treated drill cuttings a soxtec machine was used (Figure 14).

Figure 14: Soxtec

The Soxhlet extraction is method to transfer one part of a solid phase to a liquid phase (solvent). This is done by heating the solvent until it vaporizes and travels into the sample thimble containing the solid phase where it dissolves the desired part of the solid. Over the sample there is a condenser with cold water running through which cools the rising solvent resulting in condensation dripping back into the solvent flask (de Castro & Priego-Capote, 2010).

The Soxtec extraction methods is similar with some modifications. A mechanism to lower and raise the thimble is used in a three-step process. First the thimble is lowered into the solvent and is boiled. The thimble is then raised over the solvent to rinse. The solvent is then evaporated from the extraction cup so that all that is left is the dissolved substance. The first step of boiling the sample in the solvent is what accelerates the process and makes it a faster method then the classical Soxhlet method (Anderson, 2004).

The six extraction cups were washed with a solvent before being weighed. It is crucial that the extraction cups were dry, and that no solvent was left when being weighed, since only a few grams off drill cuttings is being used some extra weight from the solvent will give very wrong numbers. The six cellulose thimbles were then weighed, approximately 4 g of drill cuttings was added to each thimble, a cotton pad was placed on top of the thimble. Approximately 50 ml of petroleum ether was placed in each extraction cup along with 7 boiling stones. The cups were then placed in the Soxtec unit which was then turned on along with the condensation water. The thimbles were then submerged into the extraction cups and boiled for 50 minutes. The thimbles were then loaded and rinsed for 40 minutes. After this the Soxtec unit was turned off and the extraction cups were placed on a heating plate at approximately 50°C. The solvent in the extraction cups was evaporated until only a small amount was left. The last part was evaporated by swirling the extraction cups at room temperature. The reason for removing the cups from the heating plate was that the oil can easily evaporate with the solvent at higher temperature due to there being such a small amount of oil. Since only around 4 g drill cuttings is used the results will be wrong if only a small fraction of the oil evaporates with the solvent.

Oil concentration was calculated by using Equation 3,

$$Oil\ concentration\ (\%) = \frac{W_2 - W_1}{T} * 100\ \% \tag{3}$$

where W_1 is weight of empty extraction cup, W_2 is weight of extraction cup + oil and T is weight of drill cuttings.

4.3 Retort

Since the soxtec machine only measures oil concentration a retort was used to measure the water concentration of the drill cuttings. This was especially useful when looking at the pre-treatment step to see how much water had been removed compared to the untreated cuttings (Figure 15).

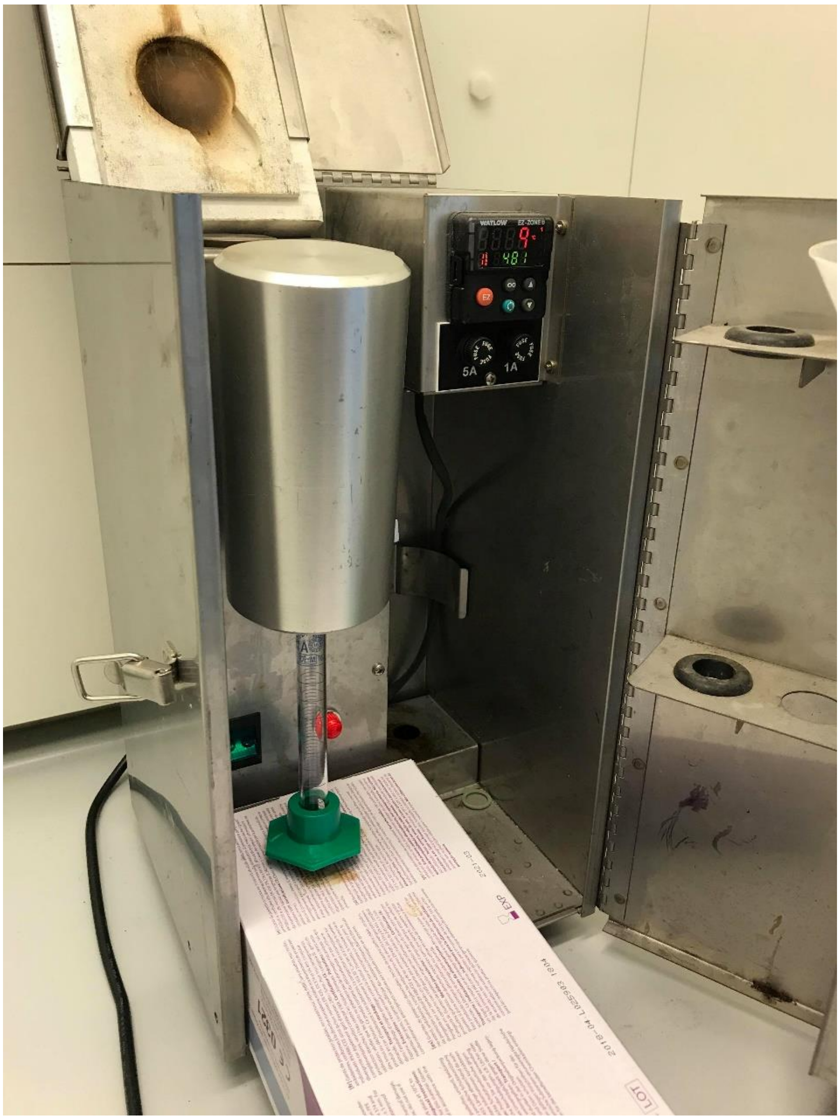

Figure 15: Retort

The retort measures the water and oil concentration by heating up the drill cuttings and vaporizing all the liquids inside. The vapours are then passed through a condenser and are collected in a graduated cylinder before being measured (Fann Instrument Company, 2013).

The retort container was weighed before and after it was filled with drill cuttings and the retort was heated to 480 °C. After 50 minutes when no liquid was coming out of the retort it was turned off and the graduated cylinder was weighed and volumetrically measured by using Equation 4,

$$Water_{dry}\,(\%) = \frac{M_{water}}{M_{wet} - (M_{oil} + M_{water})} * 100\% \qquad (4)$$

and Equation 5,

$$OOC_{dry}\,(\%) = \frac{M_{oil}}{M_{wet} - (M_{oil} + M_{water})} * 100\% \qquad (5)$$

where M_{water} is mass of water in the cuttings, M_{wet} is the mass of the wet cuttings and M_{oil} is the mass of oil in the cuttings.

The reason oil concentration was also measured with a soxtec is the fact that the accuracy of the retort is decreased when lower oil concentrations are being measured.

5 Microwave susceptor technology for drill cuttings treatment

5.1 Microwave treatment of drill cuttings

5.1.1 Microwave introduction

Microwave treatment of drill cuttings is a relatively new technology that has seen a big improvement in terms of energy efficiency since it started. This is mostly due to the use of a single-mode cavity, factors like sweep gas, power density, particle size, cuttings characteristics and moisture content also impact the oil separation (Pereira, 2012).

It has been shown that microwave heating can be more energy efficient than conventional heating and current BAT, which is the TCC.

Some advantages of microwave radiation, compared to BAT are listed below:

- Selective heating

- Homogenous heat distribution

- Proven technology

- Not crushing the particles

- No contact

- Increased capacity

- Smaller footprint and weight

- Energy efficient - Robust

- HSE (noise emission and discharge control)

- Reduced loss operation

- Less downtime

(Rødne, 2018)

5.1.2 Principle of microwave treatment of drill cuttings

The principle behind treating drill cuttings with microwaves is that not the whole cuttings is heated, only certain parts.

Table 3: Dielectric properties of water and fuel oil

Material	Dielectric constant (ε′)	Dielectric loss factor (ε″)
Water	77	13
Fuel oil	2	0,002

From Table 3 the dielectric properties of water and fuel oil are presented. Water has high dielectric values and therefore absorbs a large amount of microwaves when being exposed to them. The absorbed microwaves result in the water heating up until it vaporizes. The oil has a low dielectric loss and is not heated by the microwaves, it is however removed by the water vapor.

Three mechanisms are used to explain how water removes oil, they are steam stripping, entrainment and steam distillation. The two mechanism most believed to be the dominant mechanism is steam stripping and steam distillation (Rødne, 2018).

In steam stripping the generated steam from the drill cuttings removes the hydrocarbon. In steam distillation the water reduces the boiling point of the hydrocarbons in the drill cuttings which leads the hydrocarbons to start boiling (Rødne, 2018).

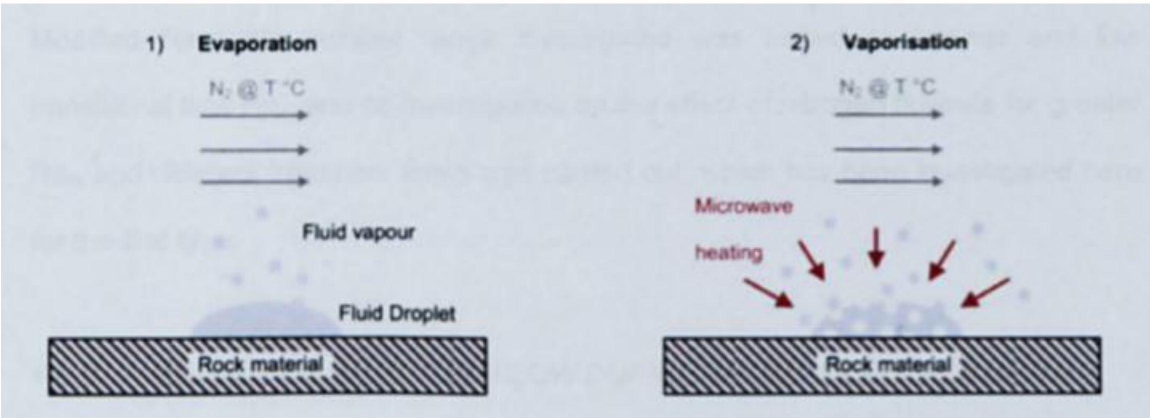

Figure 16: Physical mechanisms of steam stripping and steam distillation

Figure 16 shows the two principle of the mechanisms.

5.1.3 Research up to this point

A correlation between cavity power and oil removal was established by Shang et al (Figure 17).

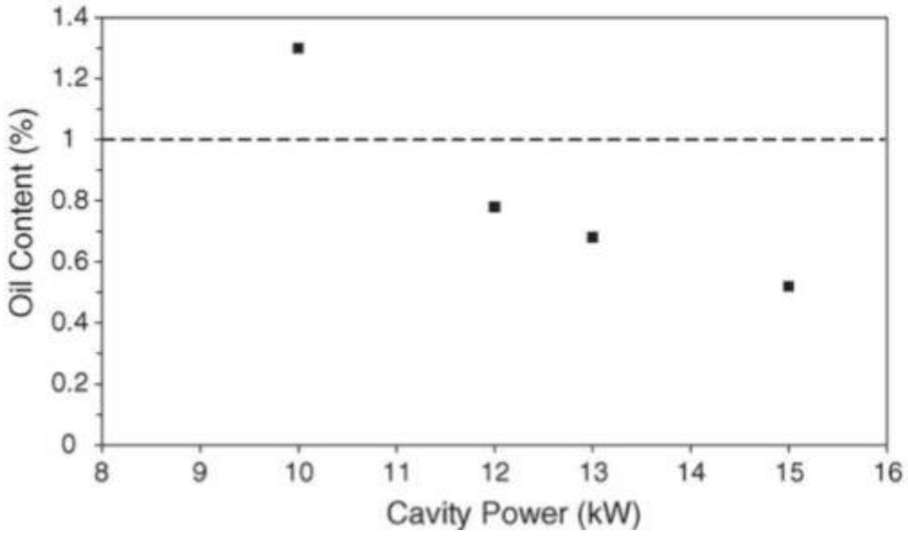

Figure 17: Relationship between cavity power and oil removal (Shang et al., 2005)

This is an important parameter to consider when creating a full-scale unit, a higher powered microwave oven may yield a higher oil removal.

Pereira et al showed that smaller agglomerates (<1mm) had a more energy efficient oil removal compared to larger (>1mm) agglomerates (Pereira, Robinson, & Kingman, 2011).

Even though energy efficiency is important, environmental risks are also a key factor to look at. From Chapter 2 it was shown that a decrease in particle size can lead to more particles being bound in the water column and damaging different species in the ecology.

It has been shown that using nitrogen as sweep gas is important. Adding nitrogen as a sweep gas is necessary because it creates an inert environment and thus reducing the possibility for an explosion to occur. The gas does not absorb microwaves and is therefore not heated. It has also been proven that by replacing nitrogen with air will reduce the chance of the susceptor degrading (Rødne, 2018).

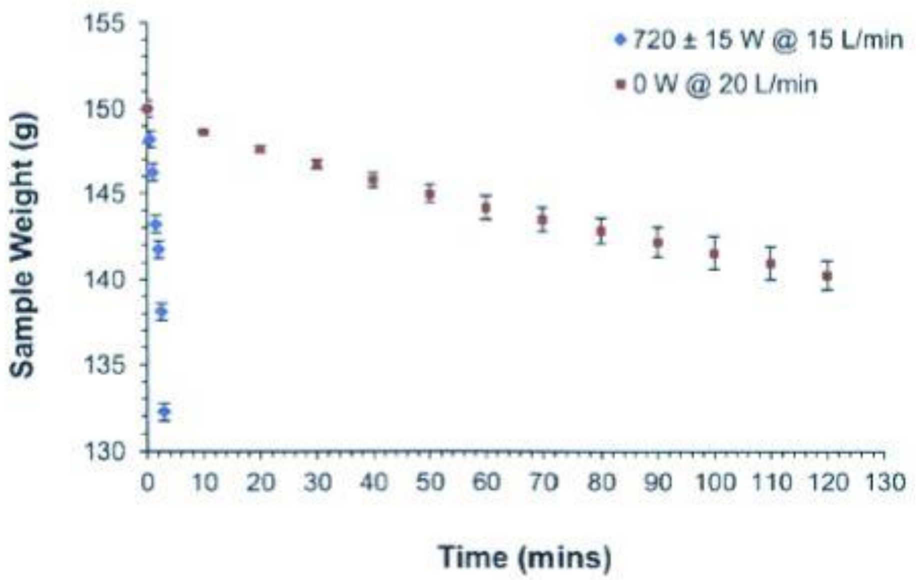

Figure 18: Effect of nitrogen sweeping with and without microwave treatment (Pereira, 2012)

Using a sweep gas has also been shown to increase the oil separation. Figure 18 shows that a sample was exposed to 15 l/min of nitrogen for 2 minutes at 700W and the weight of the sample decreased by 18 g (Pereira, 2012).

As mentioned in Chapter 3 a full-scale microwave treatment system would have to use a microwave oven with a frequency of approximately 900MHz, since microwave ovens with a frequency of 2450MHz only go up to 30 kW/h power output. Pereira showed that by using a continuous microwave system with a frequency of 896MHz and a maximum power output of 55 kW/h, energy consumption used to get drill cuttings down to 1 wt% OOC was reduced by approximately 32% (Pereira, 2012).

The increase in energy efficiency is down to two main parameters, penetration depth and power density. As mentioned in Chapter 3 penetration depth increases when the wavelength increases, this happens when a microwave with a frequency of 896 MHz is used instead of a microwave with a frequency of 2450 MHz. The microwave penetrates further into the drill cuttings and heats the water furthest away from where the microwaves are coming from.

The added power from the more powerful microwave creates a stronger field strength, this increases power density since the power is increased and the volume has not changed for the drill cuttings. By increasing power density, the velocity of the evaporating stream increases which is the main factor in mass transfer of hydrocarbons (Figure 19) (Ogunniran, Binner, Sklavounos, & Robinson, 2017).

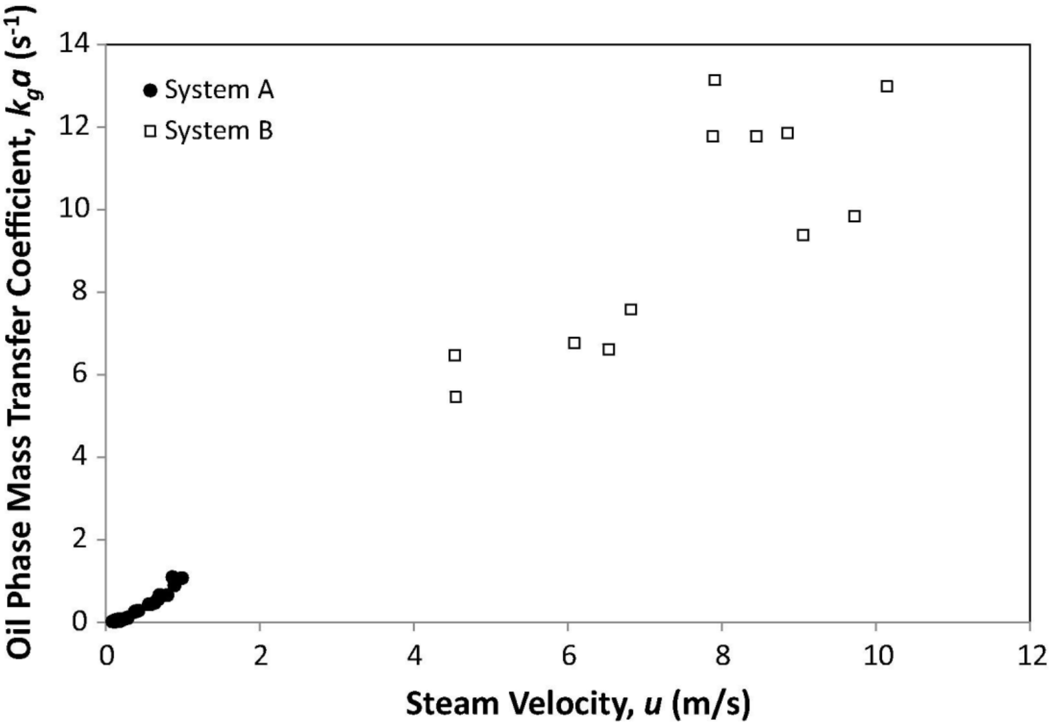

Figure 19: Correlation between oil mass transfer and steam velocity

For the 32% reduction in energy Pereira used a flowrate of 300 kg/h, this is done be adjusting the speed of the conveyor belt that the drill cuttings were placed on. Tests done with a flow rate of 800 kg/h showed a reduction of approximately 56% in energy (Pereira, 2012).

Since the flow rate increases the power has to linearly be increased to match since the drill cuttings will be hit by the microwaves for a shorter amount of time. Even though power was increased linearly the oil removal seems to increase exponentially, therefore less energy was used.

5.2 Microwave treatment of drill cuttings with susceptor technology

Norwegian Technology's microwave technology is an extension of the normal microwave technology that has also showed promising results. By using a susceptor with in a second microwave stage energy efficiency is increased due to the volatile nature and low enthalpy. Figure 20 shows the idea and setup behind a full-scale microwave susceptor treatment system.

A Joint industry project (JIP) between Norwegian Technology, Shell, ConocoPhillips and OMV started with the objective to develop a BAT for treatment of drill cuttings on NCS.

Three barrels of oil contaminated drill cuttings (OCDC) was received from ConocoPhillips. Two from 16-inch bore holes and one from a 17-inch bore hole.

The objective was to treat the different drill cuttings considering OOC concentration and energy efficiency.

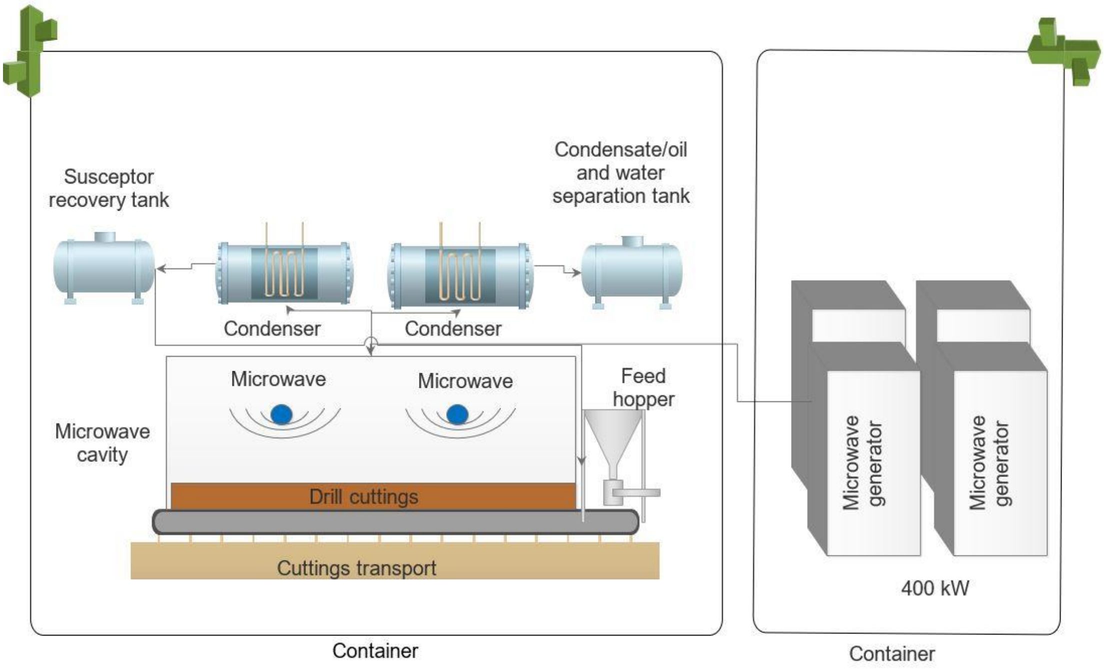

Figure 20: Full-scale setup of microwave susceptor treatment

5.2.1 Treatment principle of microwave susceptor technology

Drill cuttings with varying amounts of oil and water are sent to the first microwave which acts a dewatering system, reducing liquid content. The drill cuttings will then be dosed with a susceptor before being treated in the second microwave oven.

After the first step in the microwave a significant amount of oil and water is removed, but according to the Norwegian Environment Agency oil concentrations above typically 0,5 wt% is not allowed to discharge in the sea. Small amounts of water left in the drill cuttings a new susceptor is required to remove the remaining oil. The susceptor used in the second step is glycol, the reason glycol is used is because of its low enthalpy (Rødne, 2018).

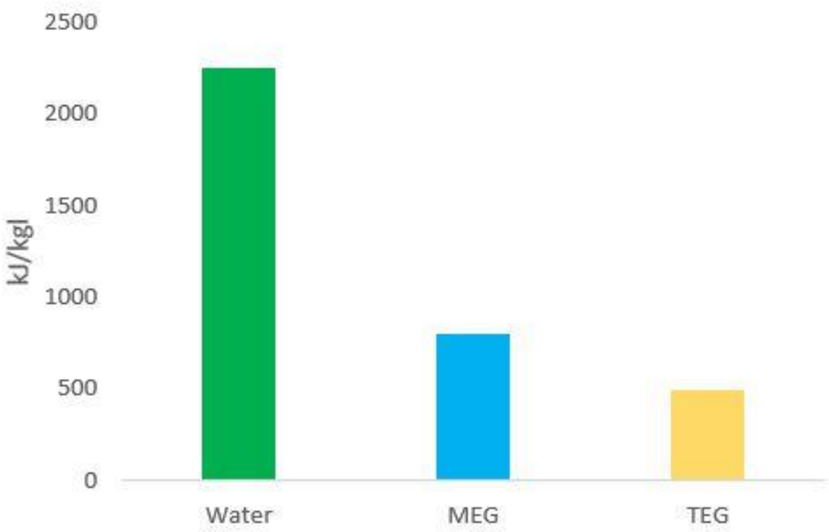

Figure 21: Enthalpy of water, MEG and TEG (Rødne, 2018)

Figure 21 indicates that if water is swapped with monoethylene glycol and triethylene glycol a guesstimate of 4 and 5 times energy could be saved, respectively.

5.2.2 Susceptor

A susceptor is a highly lossy material that is able to be rapidly heated by microwaves (Mehdizadeh, 2010).

There are solid and liquid susceptors, the main susceptor used by Norwegian Technology is MEG, also called glycol.

Susceptors exploit different physical mechanisms to decrease the energy required to separate oil from the cuttings. Decreasing boiling points and vaporization are two of the ways the susceptors does this (Rødne, 2018).

A condenser can recover all the components which makes it possible to reuse the susceptor. This makes susceptors highly attractive for use in microwave treatment of OCDC (Rødne, 2018).

By adding 5% activated carbon and 1 M NaCl oil removal was shown to be increased, leading to OOC values under 0,1 wt%. Common for solid susceptors is that energy is only distributed on the surface of the cuttings, hence thermal runoff can occur (Rødne, 2018).

6 Laboratory testing and results

To make it as easy as possible to keep control of the different parameters of each test a naming system was established. Table 4 describes the different parameters and abbreviations.

Table 4: Abbreviations of parameters for drill cutting treatment

Abbreviation	Parameter description
C	ConocoPhillips drill cuttings
E	Equinor drill cuttings
G	Glycol
A	Activated carbon (AC)
H	Hot glycol or AC
P	Pre-heated drill cuttings
K	Crushed drill cuttings

Due to testing on several cuttings with different objectives in mind, the discussion as presented below part objective. Important comments and parameters will also be discussed in this subchapter. An overall discussion and conclusion are presented in Chapter 7.

6.1 Parameters that effects oil separation and energy consumption

Norwegian technology has developed the microwave susceptor technology presented in Chapter 5. In this chapter, important parameters with regards to oil separation and energy consumption are tested for. The drill cuttings tested is from ConocoPhillips 17-inch section well, which is part of the company's Joint Industry Project.

Table 5: Overview for COP 17-inch tests

Sample	OOC_{Soxtec} (%)	OOC_{Retort} (%)	Water/Glycol $_{Dry,\ retort}$ (%)	Time (s)	Energy (kW/ton)
C17		7,86	18,64	0	0
C17.1	1,399	1,71	1,92	84	233
C17.2G	0,671	0,96	5,97	84+48	233+143
C17.3	3,298	3,62	3,42	50	161
C17.4	2,467	2,61	2,99	60	184
C17.5G	0,106	0,19	2,31	84+60	233+177
C17.6G	0,600	0,60	3,60	60+46	186+142
C17.7G	0,997	1,28	6,39	63+40	196+127
C17.8	3,670	3,98	4,48	40	140
C17.9G	1,055	1,46	3,34	40+60	140+160
C17.10G	0,698	0,87	4,80	40+48	140+150
C17.11G	0,611	0,45	3,58	40+60	140+177
C17.12G	0,523	0,43	2,56	50+60	161+166
C17.13A	0,448	0,39	3,54	50+40	161+143
C17.14GH	0,629			50+40	161+110
C17.15GH	0,311			50+60	161+154
C17.16GH	0,272	0,20	3,58	84+30	233+87
C17.17G	0,346			50+84	161+218
C17.18	0,897	0,83	2,91	120	302
C17.19GH	0,518			84+30	233+90
C17.20GH	0,346			84+30	233+86
C17.21AH	0,294			84+30	233+101
C17.22AH	0,400	0,22	2,24	84+30	233+90
C17.23GH	0,373			84+50	233+153
C17.24P	2,370			58	163
C17.25AHP	0,547			58+30	163+85

All tests were carried out with various treatment conditions and methods. In order to investigate the significant parameters that effects oil separation and energy consumption, parts of this table are extracted and presented under separate headings with separate discussions.

6.1.1 Treating cuttings from COP 17-inch section with microwave radiation

Below are results obtained from ConocoPhillips 17-inch drill cuttings (Figure 22).

Figure 22: Untreated COP17-inch drill cuttings

The drill cuttings were made up off large aggregates which contained oil on the surface. There was no excess mud mixed with the drill cuttings when collected.

Table 6: Water and oil concentration for C17 untreated

Sample	**OOC_{Retort} (%)**	**$Water_{Retort}$ (%)**
C17	7,86	18,64

The untreated drill cuttings were analyzed in a retort, which showed a water concentration of 18,64 wt% and an OOC of 7,86 wt%.

The drill cuttings were then treated in a microwave.

6.1.1.1 Pre-treatment

The drill cuttings were treated in the microwave oven, running at full input power (2kW) with various retention time. The oil and water concentration along with the energy consumption is in Table 7 below. The oil and water concentration are then plotted in the Figure 24.

Table 7: Pre-treatment for C17

Sample	OOC_{Soxtec} (%)	OOC_{Retort} (%)	$Water_{Retort}$ (%)	Time (s)	Energy (kW/ton)
C17.8	3,670	3,98	4,48	40	140
C17.3	3,298	3,62	3,42	50	161
C17.4	2,467	2,61	2,99	60	184
C17.1	1,399	1,71	1,92	84	242
C17.18	0,897	0,83	2,91	120	302

Figure 23: Treated COP 17-inch drill cuttings Left: No crushed cuttings Right: Crushed cuttings

Figure 23 shows the drill cuttings after microwave treatment, with no change to the size or formation of the cuttings and after being crushed. The DC consisted of clay and various sizes of sand grains

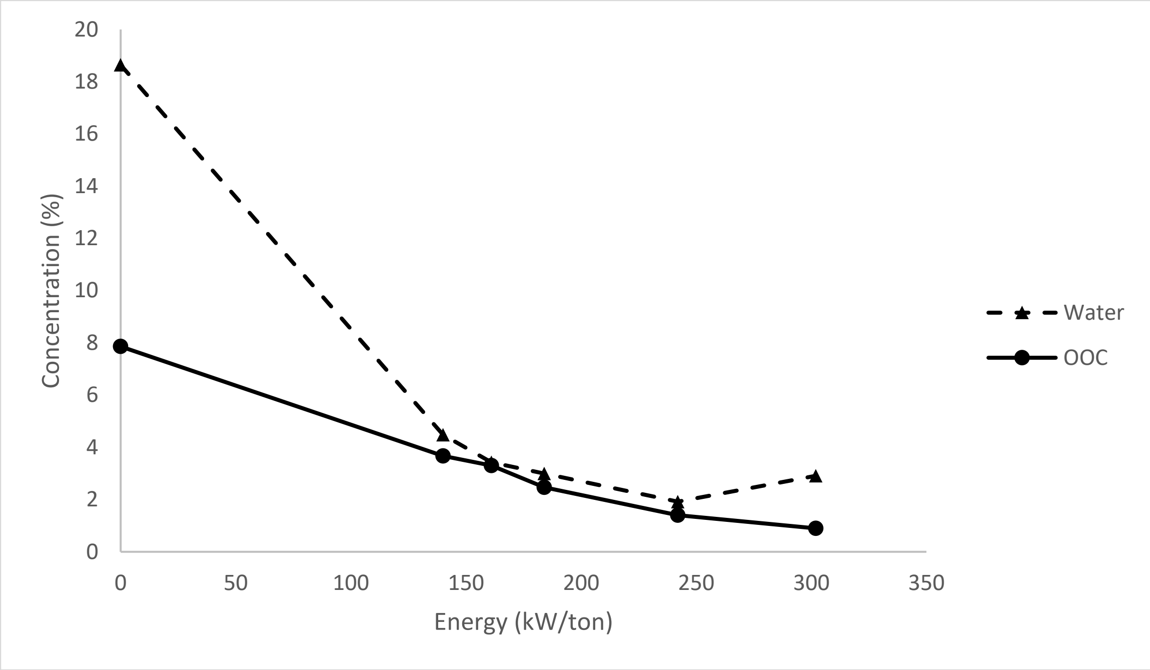

Figure 24: Pre-treatment COP 17-inch drill cuttings

Figure 24 show a relatively linear oil separation curve plotted against the water evaporation curve.

<u>Discussion</u>

The 17-inch section from ConocoPhillips seem to be relative linear with respect to oil separation. The energy consumption is relatively high when considering the amount of oil separated. This relates most likely to the high water concentration in relation to the relatively low oil concentration.

The water separation showed a u-shaped form. The curve is most likely decreasing from 140 kW/ton as a result of decreasing water concentration. This leads to higher degree of microwave reflection. The voltmeter detects microwave reflection, although some energy dissipates into the electronics. This again results in a higher measured energy consumption. Tight bound water found in capillary pores in the cuttings also have an effect on energy consumption. This remaining water can therefore be more energy demanding to extract.

The water curve is increasing in water concentration at 240 kW/ton. This can be explained by the cuttings absorbing water from the atmosphere when left hot on the table after treatment. The water concentration after 150 kW/ton is considered inaccurate. To improve the water separation results, an exicator could be used.

The importance of the water separation curve relates to the glycol separation step. Glycol should be dosed after dewatering, but seemly at when the microwave starts to consume considerable amounts of energy and starts to work ineffectively. Based on the oil separation curve, there is a tendency of decreased oil separation from 240 kW/ton to 310 kW/ton. Based on this curve, a glycol dosing point might be detected. With respect to separating water from glycol as illustrated in the process drawing: Figure 24, the glycol dosing might also take place at around 170 kW/ton. This statement is based on the motivation to separate glycol from water.

Considering microwave as a standalone technology for the ConocoPhillips 17 inch section the amount of energy required to treat the cuttings to lower than 1 wt% require a significant increase in energy consumption. Reaching oil on cuttings concentration below 0,5 wt% might not be possible for this drill cuttings. This might be caused by particle distribution in the cuttings.

6.1.2 Treating COP17-inch section with microwave susceptor technology

Based on the findings and discussion in chapter 6.1.1, the glycol dosing should be done in the power consumption range of 170-240 kW/ton.

6.1.2.1 Dosing cold glycol on cold drill cuttings

Drill cuttings were pre-treated in a microwave and cooled down before being dosed with glycol and treated a second time in a microwave (Table 8).

Table 8: Cold glycol tests for C17

Sample	OOC_{Soxtec} (%)	OOC_{Retort} (%)	Water/Glycol $_{Dry,\ retort}$ (%)	Time (s)	Energy (kW/ton)
C17.2G	0,671	0,96	5,97	84+48	233+143

The glycol dosing was added under ideal conditions, meaning mixed in relatively homogeneous into the drill cuttings.

<u>Discussion:</u>

Looking at the energy consumption table, the glycol evaporates with the use of 143 kW/ton of energy with a retention time of 48 seconds in the microwave oven. The retort analysis show that a significant amount of glycol still remains in the cuttings sample.

With respect to oil separation, 143 kW/ton was used to reduce the oil concentration from 1,4 to 0,67. Taking into consideration that the remaining oil is more challenging to extract, still a significant amount of energy is utilized in the second microwave step.

6.1.2.2 Dosing glycol on hot cuttings

In order to reduce the energy consumption for oil separation with glycol, the glycol was dosed in when the drill cuttings still remained hot from the microwave pre-treatment.

Table 9: Hot cuttings tests for C17

Sample	OOC_{Soxtec} (%)	OOC_{Retort} (%)	Water/Glycol $_{Dry, retort}$ (%)	Time (s)	Energy (kW/ton)
C17.5G	0,106	0,19	2,31	84+60	233+177
C17.10G	0,698	0,87	4,80	40+48	140+150
C17.11G	0,611	0,45	3,58	40+60	140+177
C17.17G	0,346			50+84	161+218

All tests from Table 9 were dosed with 20 ml of glycol on warm drill cuttings with. The glycol was at room temperature.

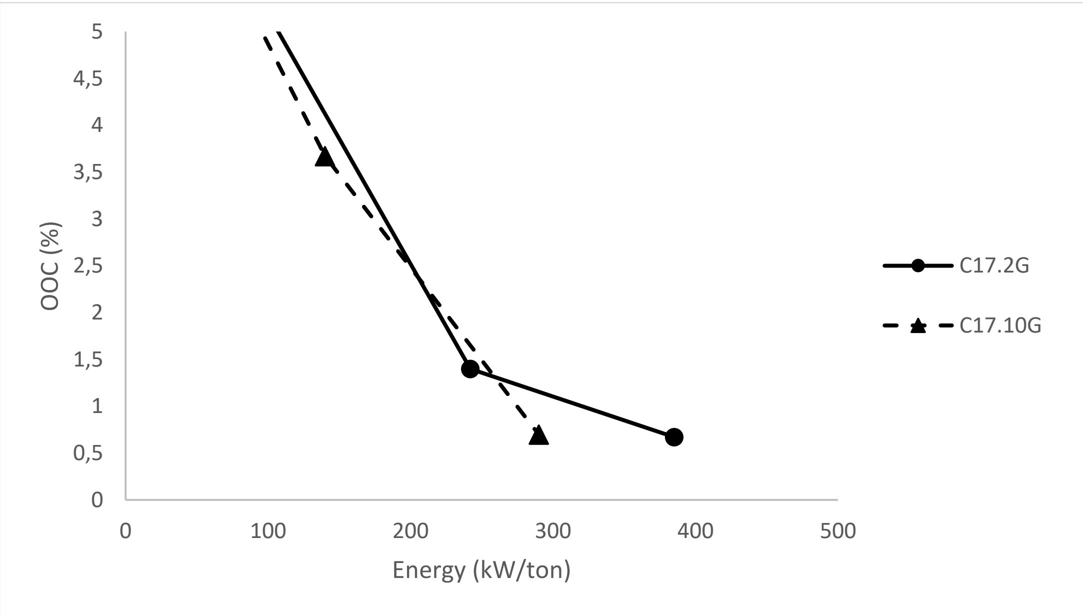

Figure 25: Cold drill cuttings versus warm drill cuttings

The glycol treatment for the C17.10G test reduced the OOC from 3,67 wt% down to 0,7 wt% by using 150 kW/ton. This test was used to compare the effect of dosing glycol on warm drill cuttings against dosing on cold drill cuttings.

Discussion:

In the C17.10G test, the energy consumption was substantially reduced by reducing the pre-treatment. The oil separation still remained the same. Due to shorter microwave treatment time less water was removed from C17.10G compared to C17.2G. The remaining liquid in the cuttings might be capillary bound water or glycol. It is therefore hard to determine the actual glycol remaining from these tests.

Due to glycol being dosed right after microwave treatment the distribution of glycol in the drill cuttings for test C17.10G was not as homogeneous as in test C17.2G, this may have an effect on oil removal and energy efficiency.

6.1.2.3 Glycol volume

To see if different glycol volumes had a positive effect on energy efficiency and oil removal tests with 10 ml, 20ml, 30 ml and 50 ml glycol were carried out. Based on findings in chapter 6.1.2.2 all tests were dosed with glycol when the drill cuttings were still warm. Glycol was at room temperature.

Table 10: Volume tests for C17

Sample	OOC_{Soxtec} (%)	Water/Glycol $_{Dry, retort}$ (%)	Time (s)	Energy (kW/ton)	Glycol (ml)
C17.6G	0,600	3,60	60+46	186+142	30
C17.7G	0,997	6,39	63+40	196+127	50
C17.9G	1,055	3,34	40+60	140+160	10
C17.11G	0,611	3,58	40+60	140+177	20

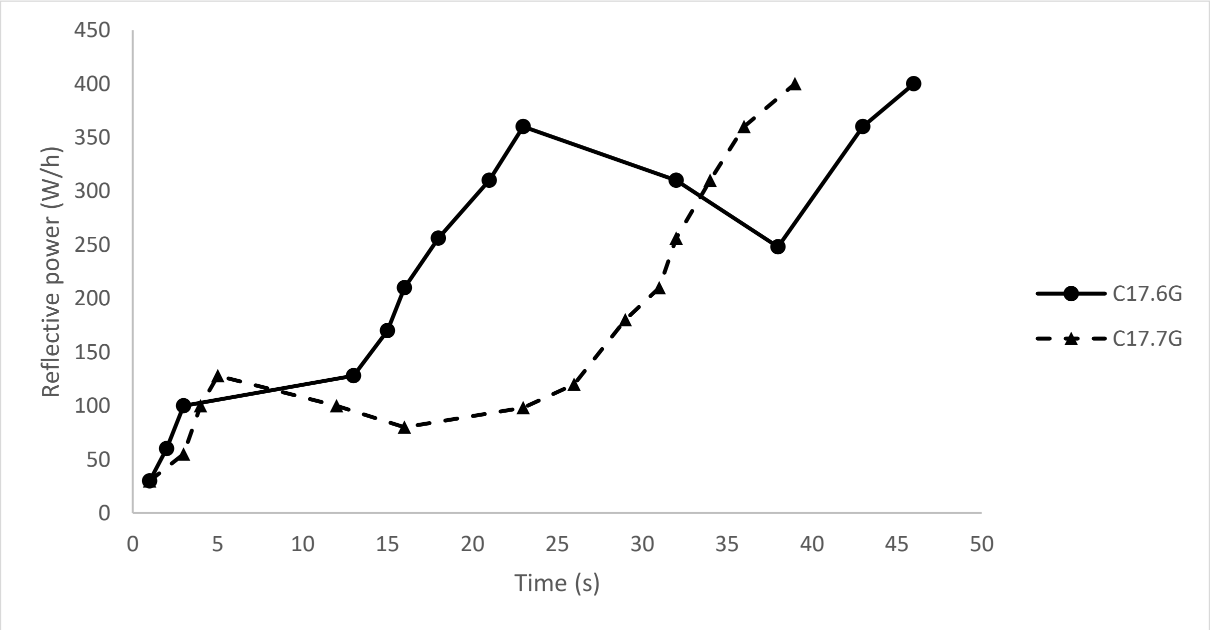

Figure 26: Reflective curves of C17.6G and C17.7G

Figure 26 shows the reflective curves of C17.6G and C17.7G. As time passes and water evaporates there is a decrease in microwave absorbing material which in an increase in reflected microwave power.

Test C17.11G achieved a significantly better OOC than test C17.9G. Both tests had the same treatment time but test C17.11G was dosed with 20 ml glycol while test C17.9G was dosed with 10 ml glycol. The glycol/water concentration was similar for both tests.

After treatment test C17.6G had an OOC of 0,6 wt% while test C17.7G had an OOC of 1 wt%. Test C17.7G had almost double the amount of glycol compared to test C17.6G after treatment. Both tests had very similar treatment times, C17.6G was dosed with 30 ml glycol while C17.7G was treated with 50 ml glycol.

Discussion:

Comparing results of C17.9G and C17.11G there seems to be a difference in OOC due to difference in glycol volume.

Comparing the OOC between C17.6G and C17.7G it seems that dosing with 30 ml is superior to dosing with 50 ml. The glycol concentrations seem to indicate that C17.7G doesn't get enough treatment time to remove enough glycol.

Figure 26 shows that the reflective curve of C17.7G is spending more time absorbing the additional glycol compared to C17.6G, this is most likely due to the additional glycol volume of C17.7G.

There seemed to be no real difference between dosing with 20 ml for test C17.11G (0,611 wt% OOC) or dosing with 30 ml for test C17.6G (0,600 wt% OOC). There was some uncertainty since the treatment times for the tests were different.

6.1.2.4 Hot glycol

In order to reduce the energy consumption for oil separation with glycol, the glycol was pre-heated before being dosed in the drill cuttings. From the previous results 20 ml glycol was used to dose the drill cuttings.

Table 11: Hot glycol tests for C17

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Glycol (ml)	Glycol temperature
C17.12G	0,523	50+60	161+166	20	-
C17.14GH	0,629	50+40	161+110	20	120
C17.15GH	0,311	50+60	161+154	20	120
C17.16GH	0,272	84+30	233+87	20	120
C17.19GH	0,518	84+30	233+90	25	160
C17.20GH	0,346	84+30	233+86	18	160
C17.23GH	0,373	84+50	233+153	25	130

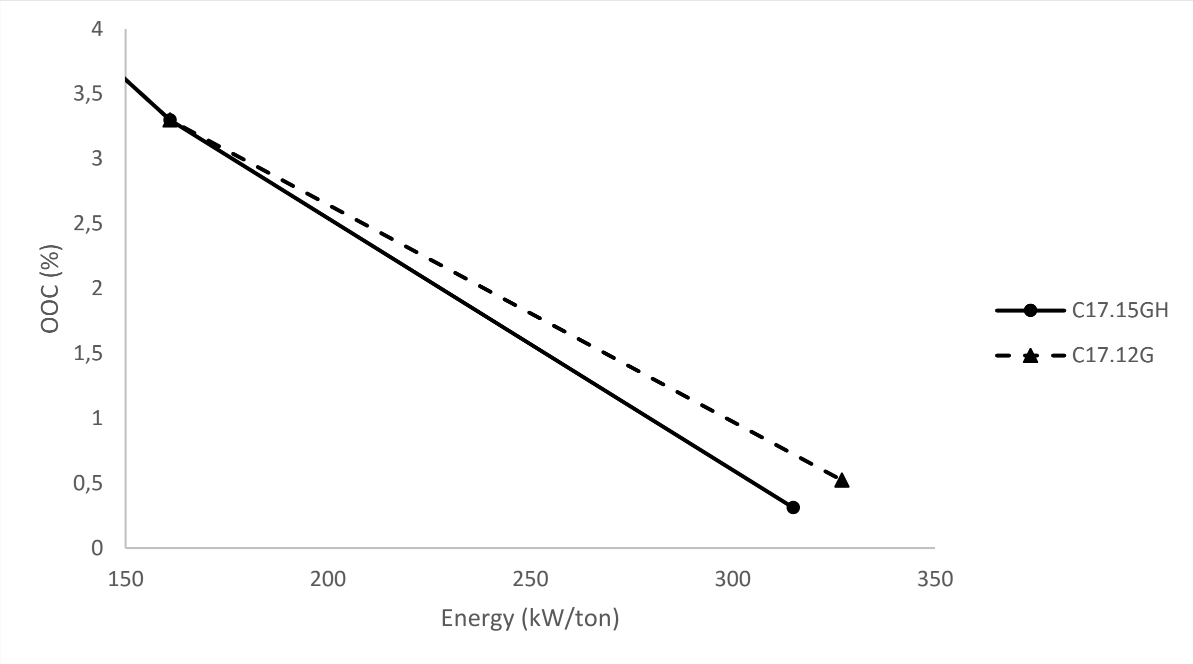

Figure 27: Cold glycol versus warm glycol

Test C17.12G and C17.15GH had the same treatment times. Test 15GH was dosed with glycol heated to approximately 120 °C while test 12G was dosed with glycol at room temperature. These two tests were compared in Figure 27.

Discussion:

Figure 27 seems to indicate that OOC is reduced by using less energy when glycol is heated before being dosed in the drill cuttings. The increase in oil removal and energy efficiency in C17.15GH may be due to the hotter glycol evaporating faster, achieving a higher steam velocity, mentioned in Chapter 5.

After some testing it was decided to dose with 25 ml instead of 20 ml. This was done due to a fraction of the glycol evaporating while being dosed hot on the drill cuttings.

6.1.2.5 Mixing in AC with glycol

Microwave treated drill cuttings were dosed with a mixture of AC and glycol before being treated a second time in the microwave.

Tabell x:

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Susceptor (ml)	Susceptor temperature	Susceptor with AC
C17.12G	0,523	50+60	161+166	20		No
C17.13A	0,448	50+40	161+143	20		Yes
C17.19GH	0,518	84+30	233+90	25	160	No
C17.20GH	0,346	84+30	233+86	18	160	No
C17.21AH	0,294	84+30	233+101	25	120	Yes
C17.22AH	0,400	84+30	233+90	20	160	Yes

C17.12G and C17.13A were compared in Figure 28 since both were dosed with a susceptor at room temperature and had similar treatment times.

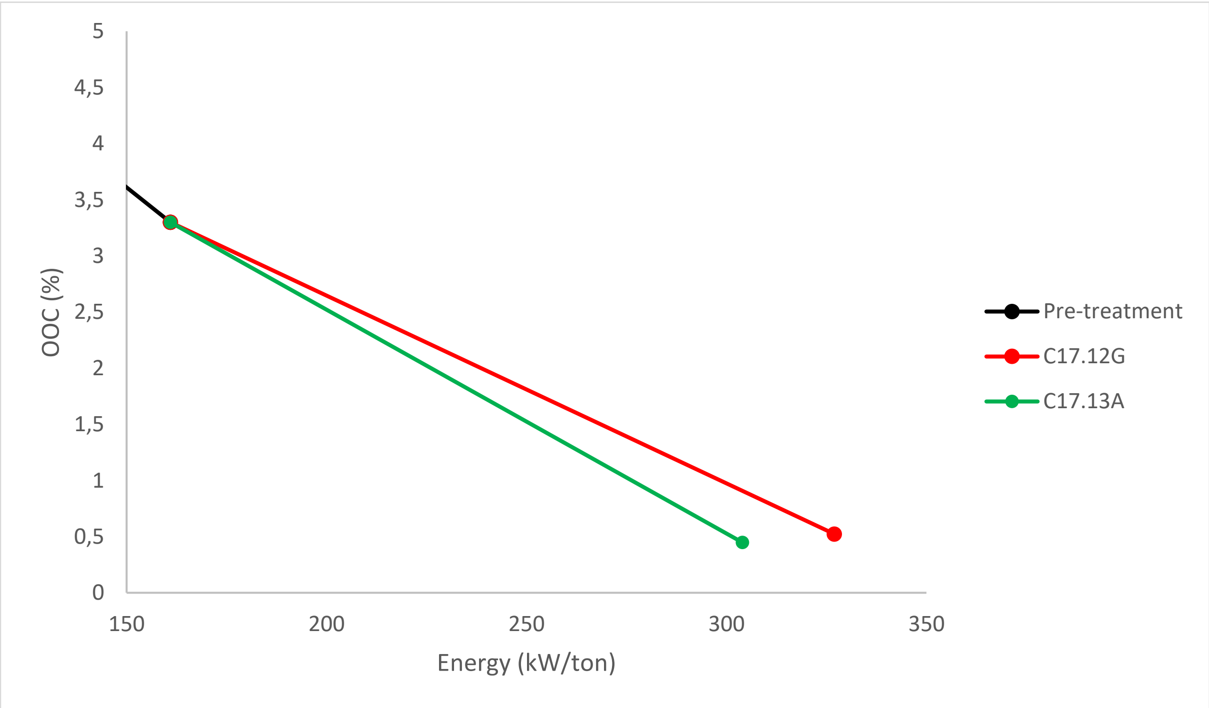

Figure 28: Cold glycol versus cold AC

Test 12G consumed 166 kW/ton to lower the OOC by 2,8 wt%, while 13A consumed 143 kW/ton to lower the OOC by 2,85 wt.

C17.19GH, C17.20GH, C17.21AH and C17.22AH had the same treatment times and were treated with hot susceptor, there was some difference in susceptor temperature being dosed. C17.19GH and C17.21AH were not treated with nitrogen stripping and was therefore compared in Figure 29, C17.20GH and C17.22AH were treated with nitrogen stripping and were compared. Nitrogen stripping will be discussed in the next heading.

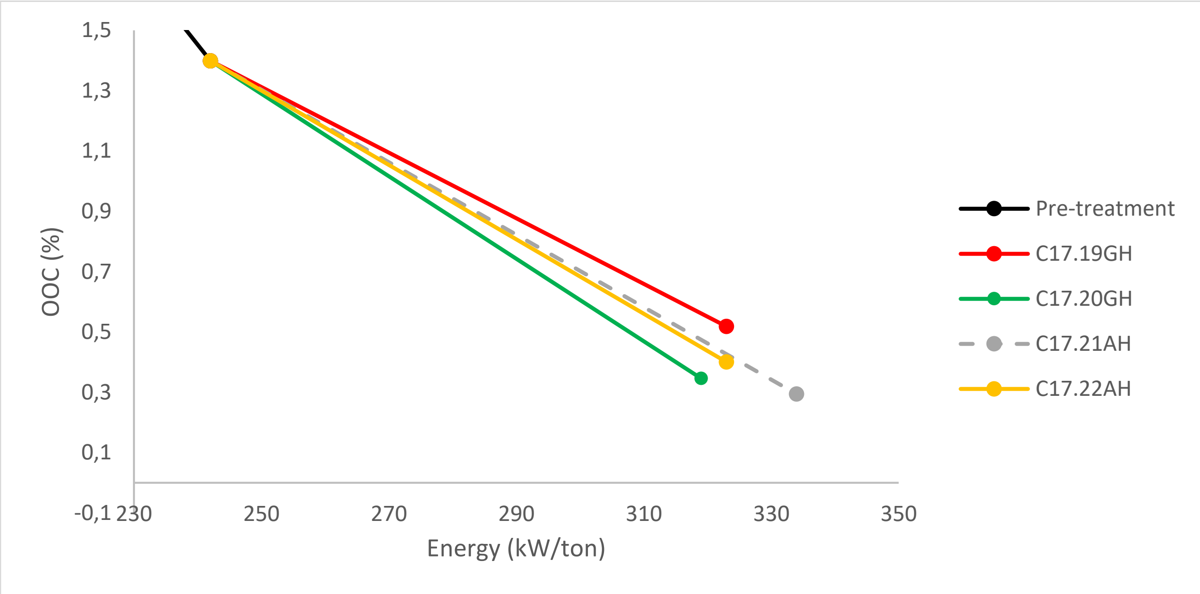

Figure 29: Warm glycol versus warm AC

Test C17.19GH achieved an OOC of 0,52 wt% compared to C17.21AH which achieved an OOC of 0,294 wt%. Both had the same treatment time. Susceptor temperature for test 19GH was 160 °C, susceptor temperature for C17.21AH was 120 °C. Test C17.21AH used slightly more energy.

Test C17.20GH achieved an OOC of 0,35 wt% compared to C17.22AH which achieved an OOC of 0,4 wt%. Both had the same treatment time.

<u>Discussion:</u>

Figure 28 seems to indicate that cold AC is more energy efficient and removes more OOC than cold glycol. This this could be because AC absorbs microwaves well and heats up rapidly as mentioned in Chapter 5.

When comparing C17.19GH and C17.21AH in Figure 29 it looks like AC has a positive effect on oil removal for test C17.21AH.

From Figure 29 when comparing C17.20GH and C17.22AH it seems like nitrogen stripping doesn’t have an effect.

It is difficult to say how much susceptor got dosed in tests C17.20GH and C17.22AH and is therefore difficult to draw to many conclusions.

6.1.2.6 Nitrogen stripping

In order to reduce OOC in drill cuttings nitrogen stripping was utilized after microwave treatment. After microwave treatment flowrate of nitrogen was adjusted to 15 l/min, this treatment lasted for 2 minutes.

Table 12: Nitrogen stripping tests for C17

Sample	**OOC_{Soxtec} (%)**	**Time (s)**	**Energy (kW/ton)**	**Susceptor (ml)**	**Susceptor temperature**	**Nitrogen stripping**
C17.19GH	0,518	84+30	233+90	25	160	No
C17.20GH	0,346	84+30	233+86	18	160	Yes
C17.21AH	0,294	84+30	233+101	25	120	No
C17.22AH	0,400	84+30	233+90	20	160	Yes

All four tests from Table 12 used the same treatment time, test C17.21AH used slightly more energy than the other tests.

Tests C17.21AH and C17.22AH used AC mixed glycol as susceptor, while the other two tests used only glycol.

Figure 30: Effect of nitrogen stripping (left cylinder)

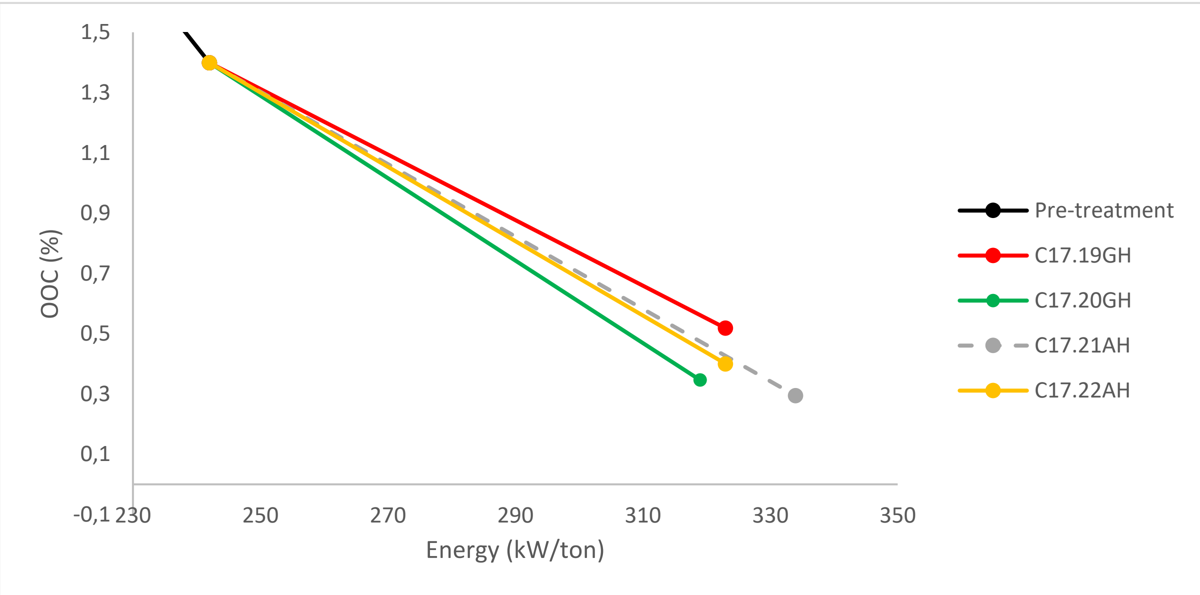

Figure 31: Effect of nitrogen stripping

Test C17.19GH achieved an OOC of 0,52 wt% without using nitrogen, test C17.20GH achieved an OOC of 0,35 by using nitrogen stripping. A fraction of the susceptor dosed in test C17.20GH did not get absorbed in the drill cuttings due to it dripping out of the sample cylinder. This may have negatively affected the OOC result.

Test C17.21AH achieved an OOC of 0,29 wt% without using nitrogen, test C17.22AH achieved an OOC of 0,40 by using nitrogen stripping. A fraction of the susceptor dosed in test C17.22AH did not get absorbed in the drill cuttings due to there not being enough left.

Discussion:

From Figure 31 it may look like nitrogen stripping has a positive effect on oil removal for test C17.20GH.

From Figure 31 when comparing C17.21AH and C17.22AH it seems like nitrogen stripping doesn't have an effect.

It is difficult to say how much susceptor got dosed in tests C17.20GH and C17.22AH and is therefore difficult to draw to many conclusions.

Figure 30 shows the effect of nitrogen stripping. It looks like the nitrogen has blown gas that usually re-condenses on the glass walls of the cylinder.

6.1.2.7 Pre-heated drill cuttings

Treating drill cuttings offshore results in receiving cuttings at the temperature of around 70 °C. This experiment was done to simulate the effect of pre-heated drill cuttings if treated offshore.

Table 13: Pre-heated drill cuttings tests for C17

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Drill cuttings temperature
C17.8	3,670	40	140	-
C17.3	3,298	50	161	-
C17.4	2,467	60	184	-
C17.1	1,399	84	242	-
C17.18	0,897	120	302	-
C17.24P	2,370	58	163	70

The pre-treatment curve was used to compare with C17.24P in Figure 32. All drill cuttings from the pre-treatment were at room temperature when treated. After microwave susceptor treatment C16Y.7P was treated with nitrogen stripping, this was not the case for the pre-treatment tests.

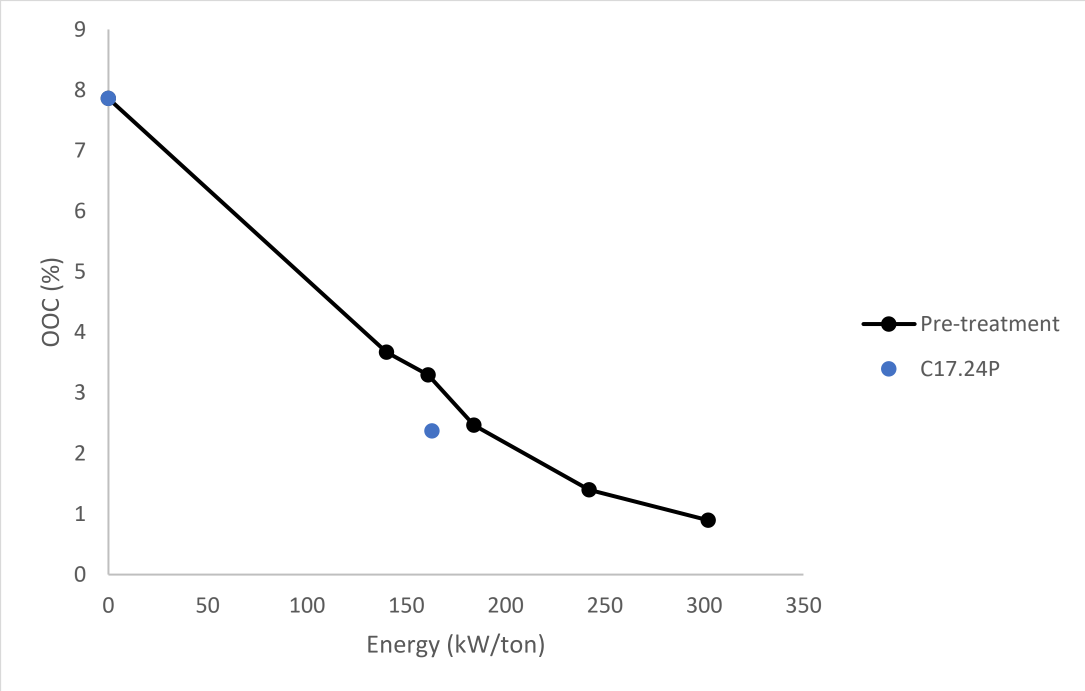

Figure 32: Pre-heated drill cuttings versus cold drill cuttings

Test C17.24P reduced the OOC of COP 17-inch drill cuttings down to 2,37 wt% by consuming 163 kW/ton with a treatment time of 58 seconds.

Figure 32 shows test C17.24P removing more oil by using less energy compared to pre-treatment from Chapter 6.1.1.1.

<u>Discussion:</u>

The pre-heating of drill cuttings seems to improve oil separation and energy efficiency. This is most likely due to the water in the drill cuttings being heated up faster, increasing the velocity of the steam which was shown in Chapter 5 to be advantageous.

The treatment time for C17.24P was decided by emulating the reflective curve of C17.1 (Appendix A) which had a pre-treatment time of 84 seconds. Test C17.1 was finished 20 seconds after the reflective curve reached 400 W/h.

6.1.2.8 Optimization of COP 17-inch drill cuttings

Considering all the results from the previous tests an optimized test was carried out for COP17-inch drill cuttings. The optimized test pre-heated the drill cuttings before pre-treatment. It was then dosed with hot AC and treated in the microwave oven before being treated with nitrogen stripping for 2 minutes.

Table 14: Optimization tests for C17

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Susceptor (ml)	Temperature	Nitrogen stripping
C17.14GH	0,629	50+40	161+110	20	120	No
C17.22AH	0,400	84+30	233+90	20	160	Yes
C17.25AHP	0,547	58+30	163+85	25	150	Yes

C17.14GH was compared with C17.25AHP since both had similar treatment times. C17.22AH was compared due to having similar treatment parameters and the most similar OOC concentration.

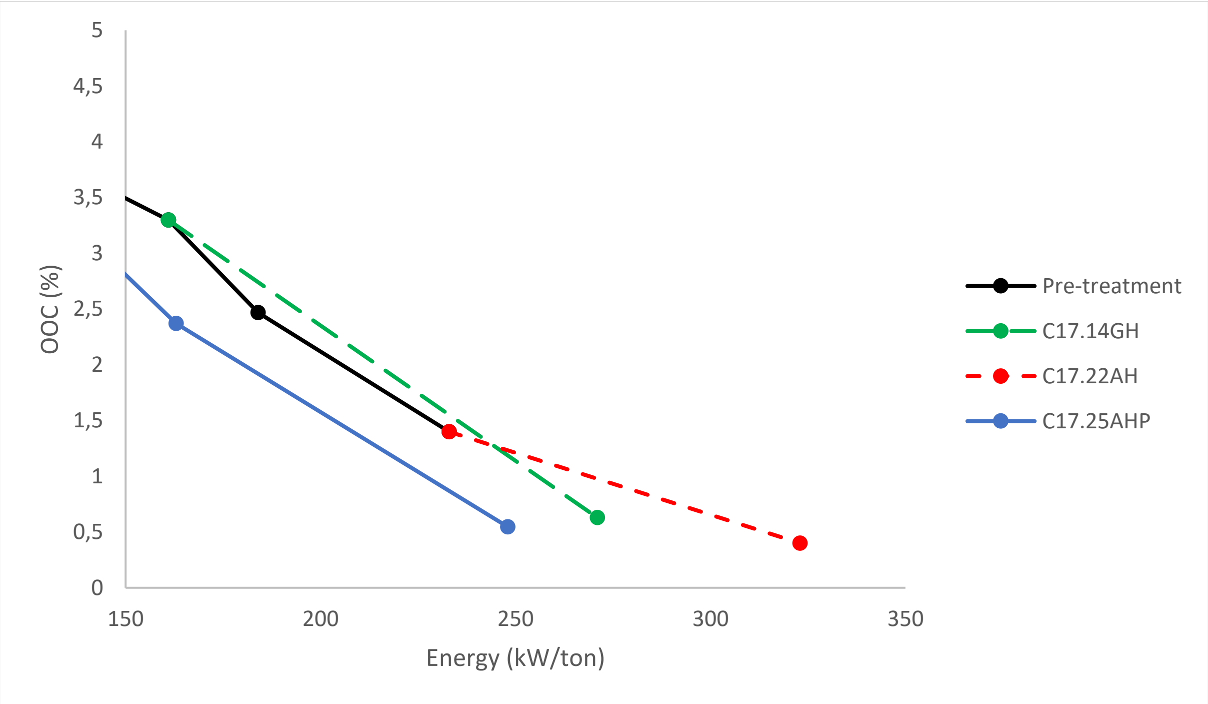

Figure 33: Optimized test comparison

Test C17.25AHP got the OOC down to 0,547 wt% while consuming 248 kW/ton. This is a considerable amount of energy, but Figure 33 showed that C17.25AHP spent less energy compared to tests that achieved similar oil removal.

<u>Discussion:</u>

From Figure 33 it seems like a large fraction of the energy saved in test C17.25AHP is due to the pre-heating of drill cuttings.

6.2 Treating various drill cuttings on NCS

By using data from ConocoPhillips 17-inch drill cuttings as a foundation, three other drill cuttings from Norwegian Continental Shelf was treated with Norwegian Technology's microwave susceptor technology. The drill cuttings tested are two ConocoPhillips drill cuttings from 16-inch section wells and an Equinor drill cuttings.

6.2.1 Treating COP16X-inch drill cuttings

Below are results obtained from ConocoPhillips 16X-inch drill cuttings.

Figure 34: Untreated COP 16X-inch drill cuttings

The drill cuttings were made up off large aggregates which contained oil on the surface. There was no excess mud mixed with the drill cuttings when collected (Figure 34).

Table 15: Water and oil concentration of untreated C16X

Sample	OOC_{Retort} (%)	$Water_{Retort}$ (%)
C16X	9,14	16,60

The untreated drill cuttings were analyzed in a retort, which showed a water concentration of 16,60 wt% and an OOC of 9,14 wt%.

The drill cuttings were then treated in a microwave.

6.2.1.1 Treating cuttings from COP 16X-inch section with microwave treatment

Based on knowledge gathered from the COP 17-inch drill cuttings, the 16X-inch drill cuttings were treated in a micro with several different treatment times, shown in Table 16.

Table 16: Pre-treatment tests for C16X

Sample	OOC_{Soxtec} (%)	OOC_{Retort} (%)	Water $_{Dry, retort}$ (%)	Time (s)	Energy (kW/ton)
C16X.1	5,234	3,67	5,31	40	131
C16X.2	2,463	3,05	2,86	60	176
C16X.3	2,075	1,96	2,44	84	236

Figure 35: Treated COP16X-inch drill cuttings, uncrushed and crushed

The left part Figure 35 shows the drill cuttings after microwave treatment, with no change to the size or formation of the cuttings. The right part of Figure 35 also shows that the drill cuttings could be crushed and consisted of clay and various sizes of sand grains.

Pre-treatment times were tested similarly to COP 17-inch cuttings. The water and oil curves were plotted in Figure 36.

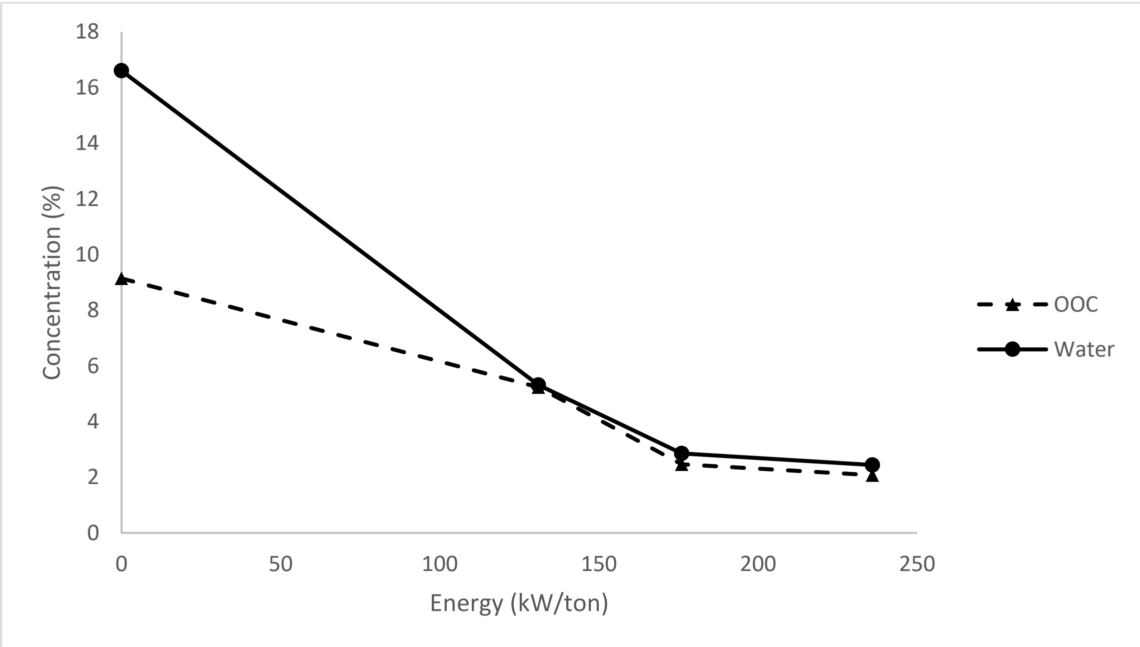

Figure 36: Pre-treatment for COP 16X-inch

Figure 36 shows two curves correlating with each other from 125 kW/ton up to 240 kW/ton.

<u>Discussion:</u>

At around 175 kW/ton the steepness of the water curves starts to decrease. A high amount of energy is spent to get the water concentration down to 2 wt%. This is most likely due to the water concentration decrease. A larger fraction of the water is bound in pores by capillary forces as the water decreases, this leads to more energy required.

As water concentration decreases there is a lack of steam to remove more oil, this may cause the decrease of the steepness for the oil curve after around 175 kW/ton.

Glycol should be dosed when a significant amount of water is removed but has to be dosed before the microwave starts to be energy inefficient in terms of dewatering.

Due to the decrease in steepness of the curve it might be ideal to add glycol at around 175 kW/ton.

Considering microwave as a standalone technology for the ConocoPhillips 16X-inch section, it is showed that the amount of energy required to treat the cuttings to lower than 1 wt% requires a significant increase in energy consumption. Reaching oil on cuttings concentration below 0,5 wt% might not be possible for this drill cuttings. This might be caused by particle distribution in the cuttings. As the steam stripping process is dependent on high steam velocity, large particles are unfavorable.

6.2.1.2 Treating cuttings from COP 16X-inch section with microwave susceptor technology

Based on knowledge acquired from treating COP 17-inch with NTMT tests from COP 16X-inch were carried out in microwave with susceptor being used.

Table 17: Microwave susceptor tests for C16X

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Glycol (ml)	Temperature
C16X.4GH	0,647	50+60	154+155	25	120
C16X.5GH	0,965	84+30	236+81	25	120
C16X.6GH	0,564	84+50	236+137	25	120

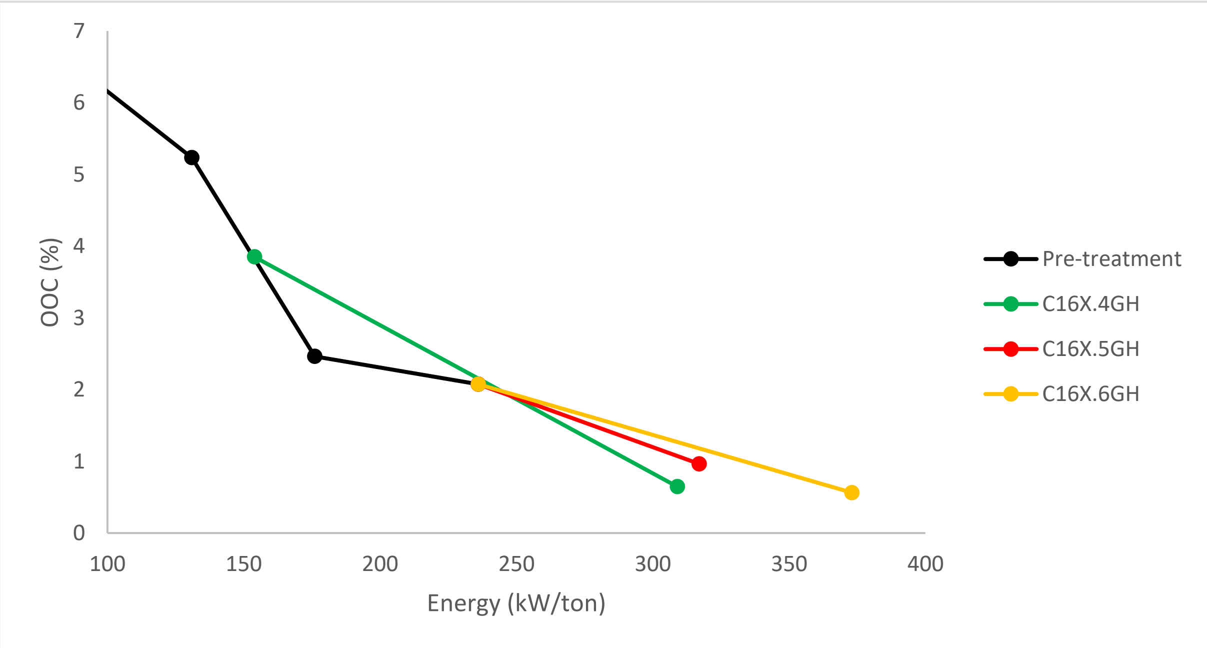

Figure 37: COP 16X-inch susceptor treatment

<u>Discussion:</u>

A significant amount of energy is required to get all three tests below 1 wt% OOC, this is probably due to the initial water concentration being large. Tests C16X.4GH and C16X.5GH both used approximately 300 kW/ton energy. Test C16X.6GH used 375 kW/ton.

Test C16X.4GH achieved an OOC of 0,645 wt% while test C16X.5GH achieved an OOC of 0,965 wt%. From Figure 37 it looks like a shorter microwave treatment of 50 s and a susceptor treatment of 60 s results in a lower OOC and less energy used compared to a microwave treatment of 84 s and a susceptor treatment of 30 s.

Hot glycol was dosed on the cuttings right after microwave treatment, when the cuttings were still warm. This is not ideal since the glycol is not dosed in a homogeneous fashion. This can have a negative effect on oil removal by the glycol.

6.2.1.3 Pre-heated drill cuttings

Treating drill cuttings offshore results in receiving cuttings at the temperature of around 70 °C. This experiment was done to simulate the effect of pre-heated drill cuttings if treated offshore.

Table 18: Pre-heated drill cuttings tests for C16X

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Drill cuttings temperature
C16X.1	5,234	40	131	-
C16X.2	2,463	60	176	-
C16X.3	2,075	84	236	-
C16X.7P	1,514	57	165	70

C16X.7P was compared to the pre-treatment curve in Figure 38. All tests from the pre-treatment were at room temperature when treated. After susceptor treatment C16Y.7P was treated with nitrogen stripping, this was not the case for the pre-treatment tests.

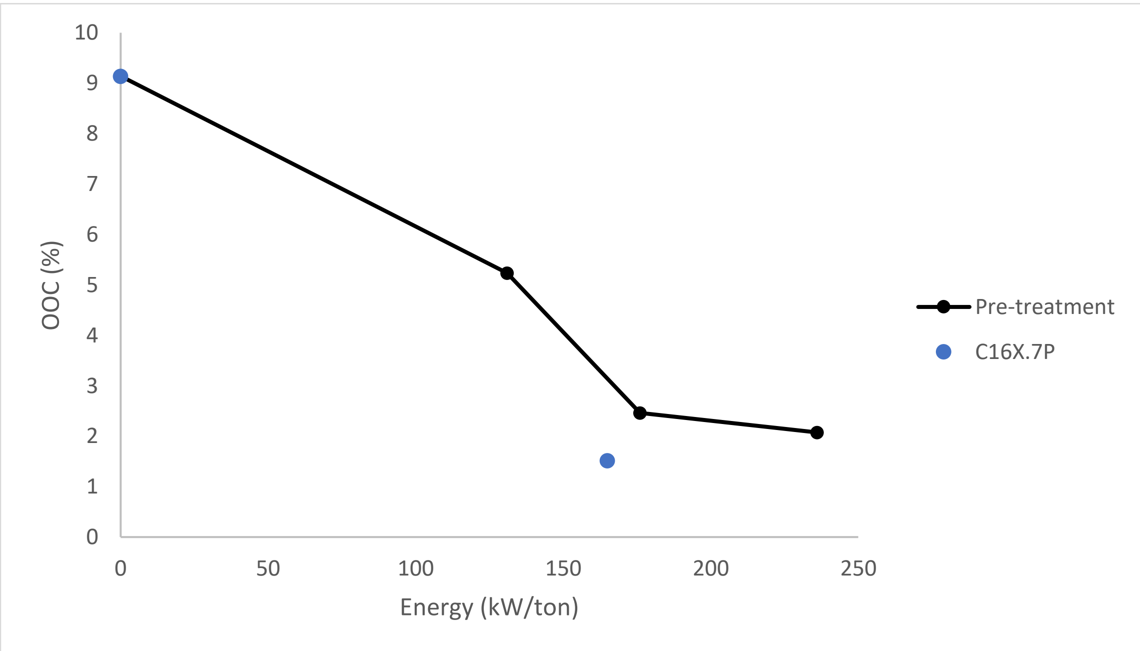

Figure 38: Pre-heated drill cuttings pre-treatment versus cold pre-treatment

Test C16X.7P reduced the OOC of COP 16X-inch cuttings down to 1,51 wt% by consuming 165 kW/ton.

Discussion:

Figure 38 shows that by consuming less energy test C16X.7P removes more oil by using less energy compared to pre-treatment from chapter 6.2.1.1. In the Pre-treatment tests the drill cuttings were not pre-heated before being treated.

The pre-heating of drill cuttings seems to improve oil separation and energy efficiency. This is most likely due to the water in the drill cuttings being heated up faster, increasing the velocity of the steam.

6.2.1.4 Optimization of COP 16X-inch drill cuttings

Considering the results from COP 17-inch drill cuttings an optimized test was carried out for COP16X-inch drill cuttings.

Table 19: Optimization tests for C16X

Sample	**OOC_{Soxtec} (%)**	**Time (s)**	**Energy (kW/ton)**	**Susceptor (ml)**	**Temperature**	**Drill cuttings temperature**
C16X.4GH	0,647	50+60	154+155	25	120	-
C16X.5GH	0,965	84+30	236+81	25	120	-
C16X.8AHP	0,749	57+30	165+82	25	140	70

Test C16X.8AHP used AC mixed with glycol as susceptor. After microwave susceptor treatment nitrogen stripping was utilized for 2 minutes using a flowrate of 15 l/min. C16X.4GH amd C16X.5GH were used in Figure 39 to compare with C16X.8AHP, these were the most similar tests in terms of treatment time.

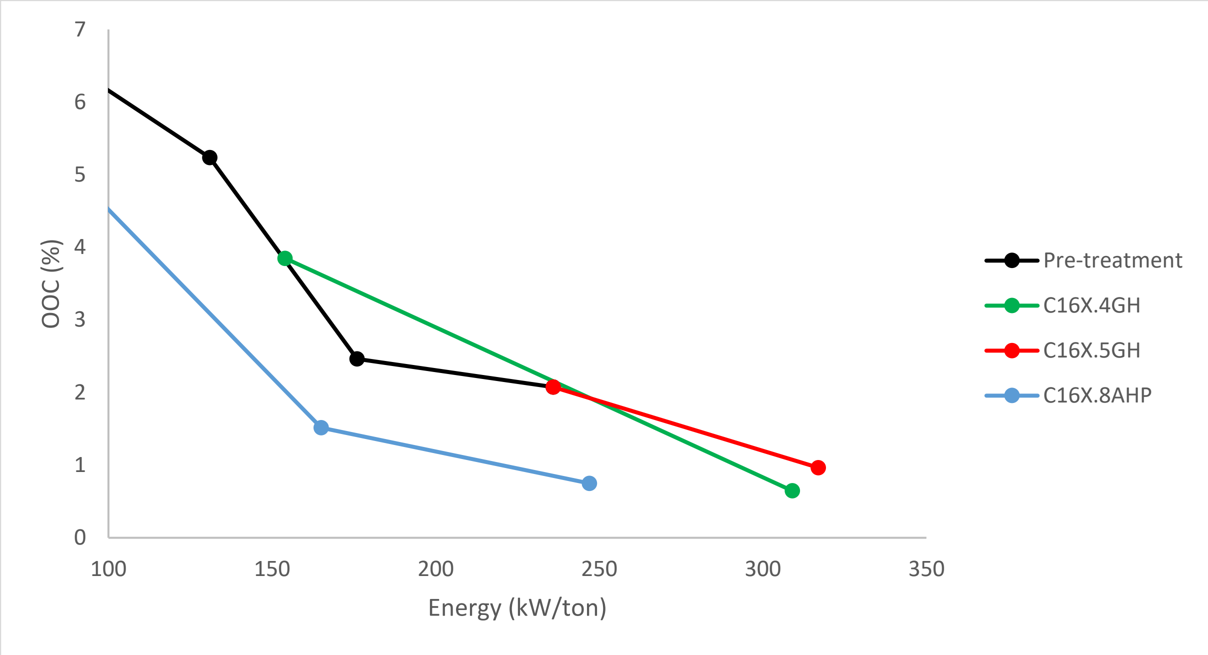

Figure 39: Optimized COP 16X-inch comparison

<u>Discussion:</u>

Test C16X.8AHP got the OOC concentration down to 0,749 wt% while consuming 247 kW/ton. This is a considerable amount of energy, but Figure 39 showed that C16X.8AHP spent less energy compared to tests that achieved similar oil removal.

The hot susceptor was dosed right after microwave treatment when the drill cuttings were still warm. Due to this glycol was not dosed in a homogeneous fashion which may impact oil separation and energy efficiency.

From Figure 39 it seems like a large fraction of the energy saved in test C16X.8AHP is due to the pre-heating of drill cuttings.

6.2.2 Treating COP 16Y-inch drill cuttings

Below are results obtained from ConocoPhillips 16Y-inch drill cuttings.

Figure 40: Untreated COP 16Y-inch drill cuttings

The drill cuttings were made up off large aggregates which contained oil on the surface. There was no excess mud mixed with the drill cuttings when collected.

Table 20: Water and oil concentration for untreated C16Y

Sample	OOC_{Retort} (%)	$Water_{Retort}$ (%)
C16Y	7,56	17,05

The untreated drill cuttings were analyzed in a retort, which showed a water concentration of 17,05 wt% and an OOC of 7,56 wt%.

The drill cuttings were then treated in a microwave.

6.2.2.1 Treating cuttings from COP 16Y-inch section with microwave treatment

Based on knowledge gathered from the COP 17-inch drill cuttings, the 16Y-inch drill cuttings were treated in a micro with several different treatment times, shown in Table 21.

Table 21: Pre-treatment for C16Y

Sample	**OOC_{Soxtec} (%)**	**OOC_{Retort} (%)**	**$Water_{Retort}$ (%)**	**Time (s)**	**Energy (kW/ton)**
C16Y.1	5,422	5,38	3,31	40	130
C16Y.2	2,322	3,85	2,70	60	182
C16Y.3	2,021	2,00	2,80	84	230

Figure 41 shows the drill cuttings after microwave treatment, on the left with no change to the size or formation of the cutting and on the right after being crushed. The crushed drill cuttings show that it consists of clay and various sizes of sand grains.

Figure 41: Treated COP16Y-inch drill cuttings uncrushed (left) and crushed (right)

The oil and water concentration from Table 21 was plotted into Figure 42.

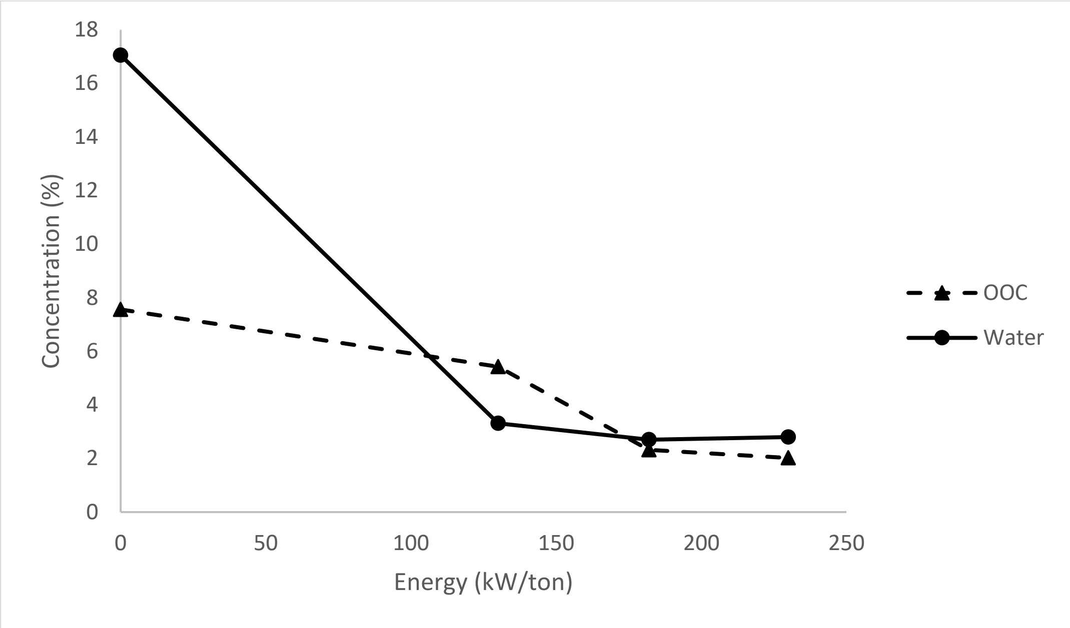

Figure 42: COP16Y-inch pre-treatment

<u>Discussion:</u>

At around 125 kW/ton the water curve is almost flat. At around 180 kW/ton the curve slightly increases. This can be explained by the cuttings absorbing water from the atmosphere when left hot and unsealed after treatment. The water concentration after 180 kW/ton is considered inaccurate. To improve the water separation results, an exicator could be used.

A high amount of energy is spent to get the water concentration down to 3 wt%. This is most likely due to the water concentration decease. A larger fraction of the water is bound in pores by capillary forces as the water decreases, this leads to more energy required.

At around 180 kW/ton the steepness of the oil curve starts to decrease, this is probably due to a decrease in water concentration which results in less steam to remove more oil.

Glycol should be dosed when a significant amount of water is removed but has to be dosed before the microwave starts to be energy inefficient in terms of dewatering.

Due to the decrease in steepness of the curve it might be ideal to add glycol at around 180 kW/ton or earlier.

Considering microwave as a standalone technology for the ConocoPhillips 16Y-inch section Table 21 showed that around 230 kW/ton was required to get the OOC down to 2 wt%. Treating the drill cuttings down to 1 wt% would require a significant increase in energy consumption. Reaching oil on cuttings concentration below 0,5 wt% might not be possible for this drill cuttings. This might be caused by particle distribution in the cuttings. As the steam stripping process is dependent on high steam velocity, large particles are unfavorable.

6.2.2.2 Treating cuttings from COP 16Y-inch section with microwave susceptor technology

Based on knowledge acquired from treating COP 17-inch with NTMT tests from COP 16Y-inch were carried out in microwave with susceptor being used.

Table 22: Microwave susceptor tests forC16Y

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Glycol (ml)	Temperature
C16Y.4GH	0,893	50+60	156+176	25	120
C16Y.5GH	1,455	84+30	230+78	25	120
C16Y.6GH	0,337	84+50	230+128	25	120

Results from Table 22 were plotted into Figure 43 and compared.

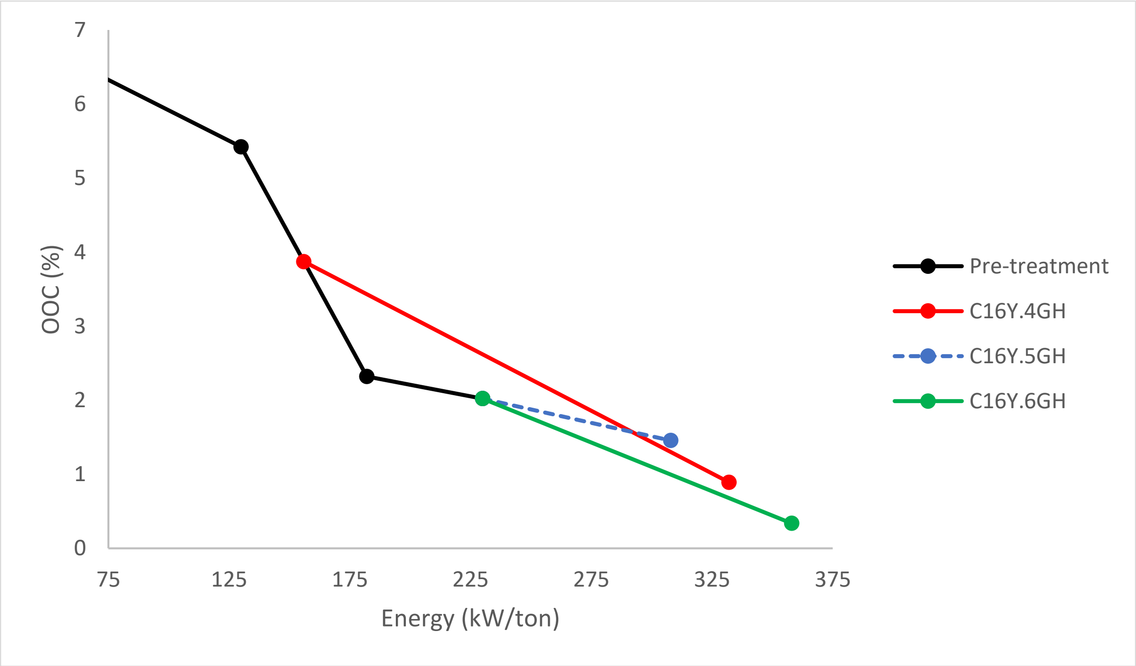

Figure 43: COP16Y-inch microwave susceptor treatment comparison

Discussion:

Around 325 kW/ton energy was consumed to reduce the OOC below 1 wt%.

Test C16Y.5GH only achieved 1,46 OOC wt% by using 310 kW/ton, test C16Y.4GH achieved an OOC of 0,89 wt% by consuming 325 kW/ton. From Figure 43 it seems like a shorter pre-treatment time and a longer susceptor treatment time results in a better oil removal and energy efficiency.

Hot glycol was dosed on the cuttings right after microwave treatment, when the cuttings were still warm. This is not ideal since the glycol is not dosed in a homogeneous fashion. This may have a negative effect on oil removal by the glycol.

6.2.2.3 Pre-heated drill cuttings

Treating drill cuttings offshore results in receiving cuttings at the temperature of around 70 °C. This experiment was done to simulate the effect of pre-heated drill cuttings if treated offshore.

Table 23: Pre-heated drill cuttings test for C16Y

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Drill cuttings temperature
C16Y.1	5,422	40	130	-
C16Y.2	2,322	60	182	-
C16Y.3	2,021	84	230	-
C16Y.7P	2,261	55	159	70

C16Y.7P was compared to the pre-treatment curve in Figure 44. All pre-treatment tests were at room temperature when treated. After susceptor treatment C16Y.7P was treated with nitrogen stripping, this was not the case for the pre-treatment tests.

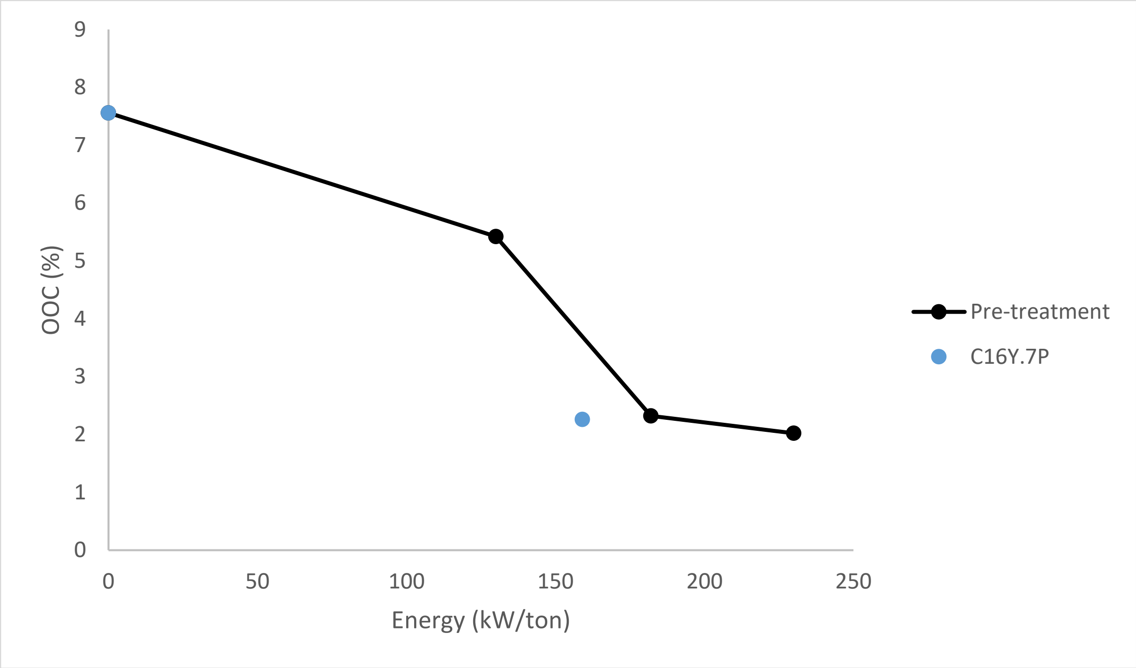

Figure 44: Pre-heated drill cuttings for pre-treatment versus cold pre-treatment

Discussion:

The drill cuttings were warmed to 70 °C before being treated in the microwave. Test C16Y.7P reduced the OOC of COP 16Y-inch cuttings down to 2,26 wt% by consuming 159 kW/ton.

Figure 44 shows that by consuming less energy test C16Y.7P removes more oil by using less energy compared to pre-treatment from chapter 6.2.2.1. In the Pre-treatment tests the drill cuttings were not pre-heated before being treated.

The pre-heating of drill cuttings seems to improve oil separation and energy efficiency. This is most likely due to the water in the drill cuttings being heated up faster, increasing the velocity of the steam.

6.2.2.4 Optimization of COP 16Y-inch drill cuttings

Considering the results from COP 17-inch drill cuttings an optimized test was carried out for COP16Y-inch drill cuttings.

Table 24: Optimization test for C16Y

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Susceptor (ml)	Temperature	Drill cuttings temperature
C16Y.4GH	0,893	50+60	156+176	25	120	-
C16Y.5GH	1,455	84+30	230+78	25	120	-
C16Y.8AHP	0,724	55+50	159+132	25	140	70

Test C16Y.8AHP used AC mixed with glycol as susceptor. After microwave susceptor treatment nitrogen stripping was utilized for 2 minutes using a flowrate of 15 l/min. C16Y.4GH amd C16Y.5GH were used in Figure 45 to compare with C16Y.8AHP, these were the most similar tests in terms of treatment time.

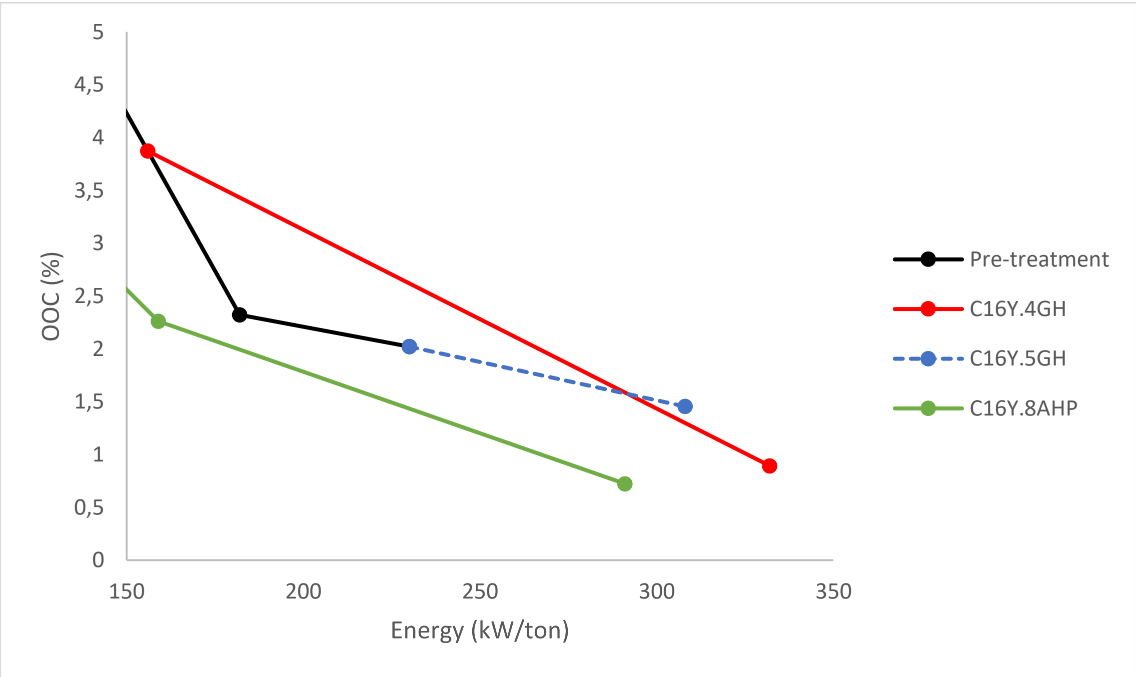

Figure 45: COP16Y-inch optimized test comparison

<u>Discussion:</u>

Test C16Y.8AHP got the OOC down to 0,724 wt% by consuming 291 kW/ton energy. This is a considerable amount of energy, but Figure 45 showed that C16Y.8AHP spent less energy compared to tests that achieved worse oil removal.

The hot susceptor was dosed right after microwave treatment when the drill cuttings were still warm. Due to this glycol was not dosed in a homogeneous fashion which may impact oil separation and energy efficiency.

From Figure 45 it seems like a large fraction of the energy saved in test C16Y.8AHP is due to the pre-heating of drill cuttings.

6.2.2.5 Effect of crushing drill cuttings

Before being treated COP 16Y-inch drill cuttings were crushed into small particles to see how this effected energy efficiency and OOC concentration.

Table 25: Effects of crushing C16Y drill cuttings before treatment

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Susceptor (ml)	Temperature	Drill cuttings temperature
C16Y.7P	2,261	55	159	0	-	70
C16Y.8AHP	0,724	55+50	159+132	25	140	70
C16Y.9PK	3,996	55	159	0	-	70
C16.10AHPK	1,105	55+50	159+122	25	140	70

All tests from Table 25 were treated with nitrogen stripping after microwave susceptor treatment.

Discussion:

Comparing C16Y.7P with C16Y.9PK and C16Y.8AHP with C16Y.10AHPK, it seems that by crushing the drill cuttings before treatment oil removal is reduced. Despite having the same treatment times the cuttings that were crushed before treatment achieved a lower OOC concentration. This was the case both for the pre-treatment and for the susceptor treatment.

The reason for the decrease in OOC concentration could be the fact that the crushed drill cuttings is very compact in the glass cylinder when treated and the steam inside the cuttings doesn’t achieve a high enough velocity to remove more oil.

6.2.3 Treating Equinor drill cuttings

Below are results obtained from Equinor drill cuttings.

Figure 46: Untreated Equinor drill cuttings

The drill cuttings were made up off medium sized particles which contained oil on the surface and on the inside. When collected the cuttings were accompanied with an excess of mud as shown in Figure 47.

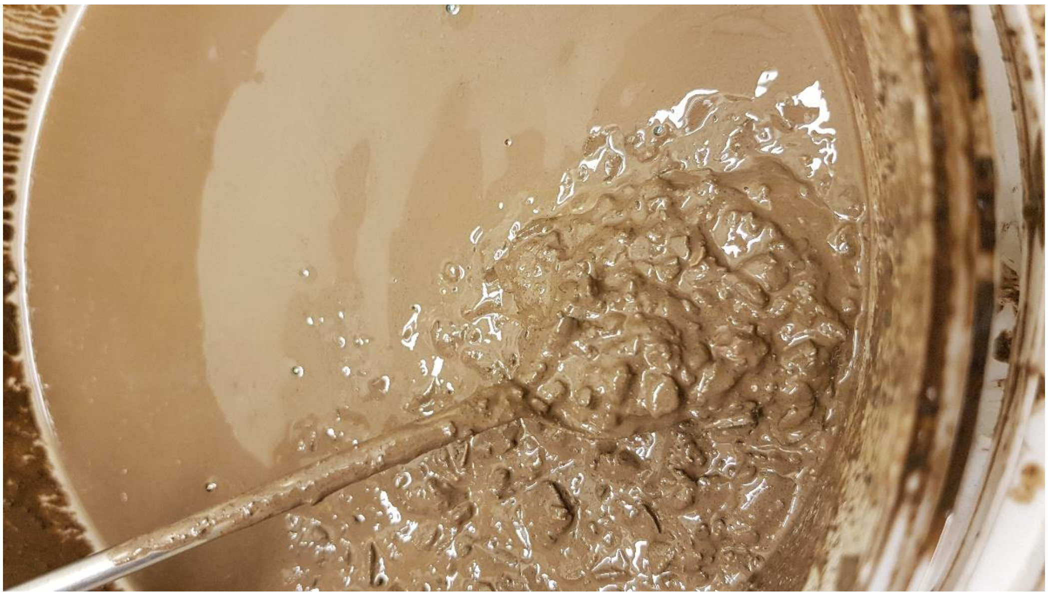

Figure 47: Equinor drill cuttings in mud

Table 26: Water and oil concentration of Equinor drill cuttings

Sample	OOC_{Retort} (%)	$Water_{Retort}$ (%)
E	14,82	15,09

The untreated drill cuttings were analyzed in a retort, which showed a water concentration of 15,09 wt% and an OOC of 14,82 wt%.

The drill cuttings were then treated in a microwave.

6.2.3.1 Treating cuttings from Equinor with microwave treatment

Based on knowledge gathered from the COP 17-inch drill cuttings, the Equinor drill cuttings were treated in a micro with two different treatment times, shown in Table 27.

Table 27: Pre-treatment for Equinor

Sample	OOC_{Soxtec} (%)	OOC_{Retort} (%)	$Water_{Retort}$ (%)	Time (s)	Energy (kW/ton)
E.1	0,940	0,97	2,08	84	202
E.4	2,341	2,17	3,54	60	186

Figure 48 shows the drill cuttings after microwave treatment, with no change to the size or formation of the cuttings. Figure 48 also shows that the drill cuttings could be crushed and consisted of clay, various sizes of sand grains and white particles, which is lime.

Figure 48: Treated Equinor drill cuttings uncrushed (left) and crushed (right)

Due to limited drill cuttings only two pre-treatment tests were carried out. More tests would give a more accurate curve.

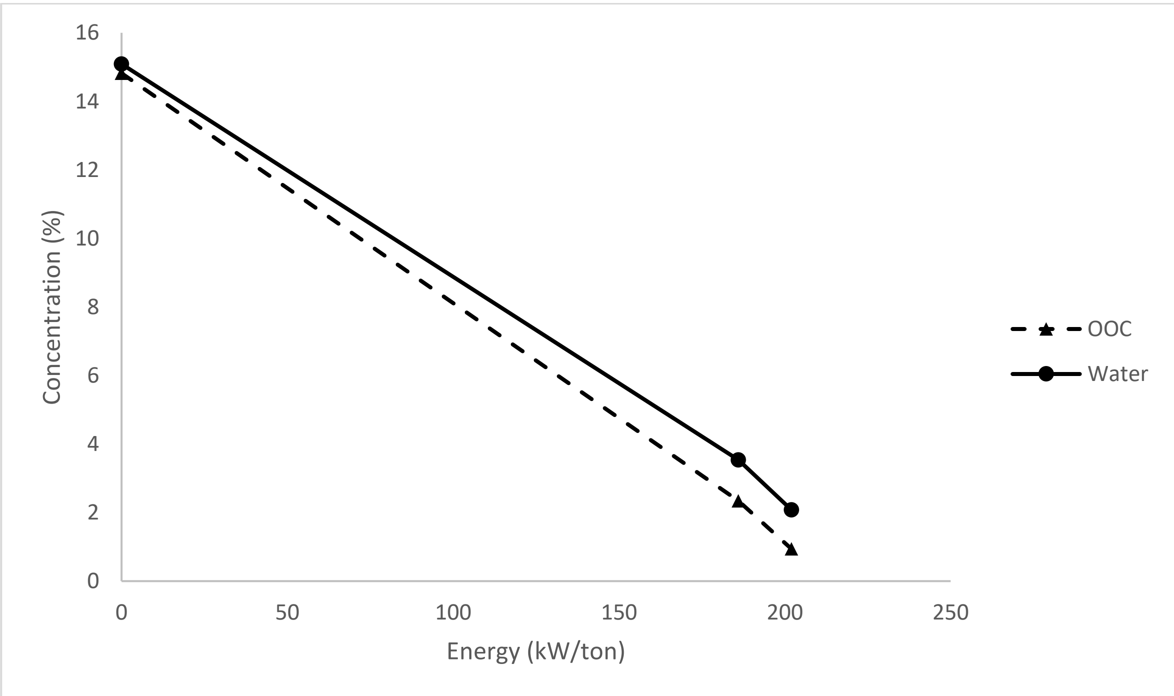

Figure 49: Equinor drill cuttings pre-treatment

Discussion:

The drill cuttings for test E.4 was misplaced in the sample cylinder leading to the tests not being effectively treated in the microwave. If done properly a lower OOC and water concentration would probably be expected. Due to limited drill cuttings the test was not re-done.

By consuming 200 kW/t the microwave reduces the water concentration down to 2 wt%.

Glycol should be dosed when a significant amount of water is removed but has to be dosed before the microwave starts to be energy inefficient in terms of dewatering. Due to few tests it is difficult to be to sure, but 84 s seems like a good middle ground in terms of energy efficiency and oil removal.

Considering microwave as a standalone technology for the Equinor drill cuttings Table 27 showed that around 200 kW/ton was required to get the OOC down below 1 wt%. Reaching OOC concentration below 0,5 wt% is probably possible. Energy efficiency would probably be lower since most of the water is removed. A large fraction of remaining water is bound by capillary forces in the pores of the drill cuttings.

6.2.3.2 Treating cuttings from Equinor with microwave susceptor technology

Based on knowledge acquired from treating COP 17-inch with NTMT tests from Equinor were carried out in microwave with susceptor being used.

Table 28: Microwave susceptor treatment tests for Equinor drill cuttings

Sample	OOC_{Soxtec} (%)	OOC_{Retort} (%)	Water/Glycol $_{Dry}$ (%)	Time (s)	Energy (kW/ton)	Glycol (ml)
E.2G	0,052			84+84	202+210	20
E.3G	0,366	0,39	3,09	55+40	157+119	20
E.5G	0,279	0,40	3,56	60+48	186+152	20

The three tests in Table 28 were plotted and compared in Figure 50. Dosed glycol was at room temperature.

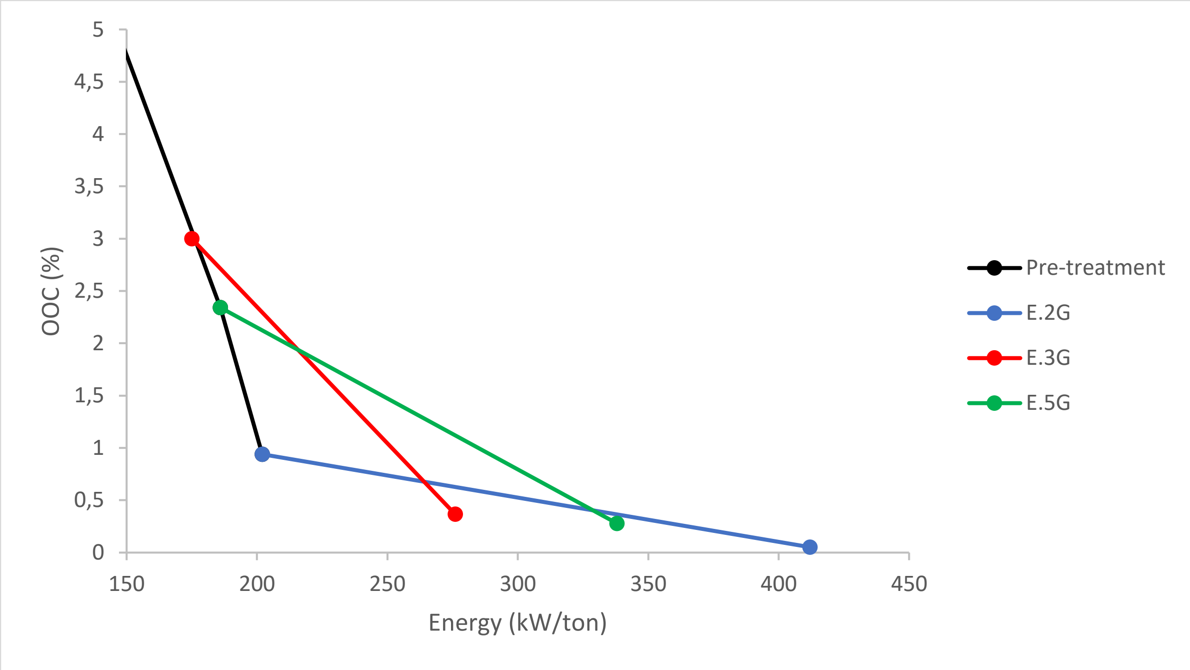

Figure 50: Equinor drill cuttings microwave susceptor test comparison

<u>Discussion:</u>

Test E.2G achieved 0,05 OOC wt% by using 412 kW/ton, test E.3G achieved an OOC of 0,37 wt% by consuming 276 kW/ton. Test E3G has a steep curve, the steepness may be reduced if more energy had been supplied.

From Figure 50 it seems like a shorter pre-treatment time and a longer susceptor treatment time may result in better oil removal and energy efficiency.

Hot glycol was dosed on the cuttings right after microwave treatment, when the cuttings were still warm. This is not ideal since the glycol is not dosed in a homogeneous fashion. This may have a negative effect on oil removal by the glycol.

Drill cuttings in test E.5G were misplaced in the sample cylinder reducing the area being treated with microwaves. If done properly a lower OOC and water concentration would probably be expected. Due to limited drill cuttings the test was not re-done.

6.2.3.3 Optimization of Equinor drill cuttings

Considering the results from COP 17-inch drill cuttings two optimized tests were carried out for the Equinor drill cuttings.

Table 29: Optimization test for Equinor drill cuttings

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Susceptor (ml)	Temperature	Drill cuttings temperature
E.2G	0,052	84+84	202+210	20	-	-
E.3G	0,366	55+40	157+119	20	-	-
E.5G	0,279	60+48	186+152	20	-	-
E.6GHP	0,342	80+40	190+113	25	140	70
E.7AHP	0,188	60+40	172+112	25	140	70

Tests E.2G, E.3G and E.5G were dosed with glycol at room temperature, E.6GHP was dosed with hot glycol and E.7AHP was dosed with a hot AC and glycol mixture. After microwave susceptor treatment E.6GHP and E.7AHP were treated with nitrogen stripping for 2 minutes with a flow rate of 15 l/min.

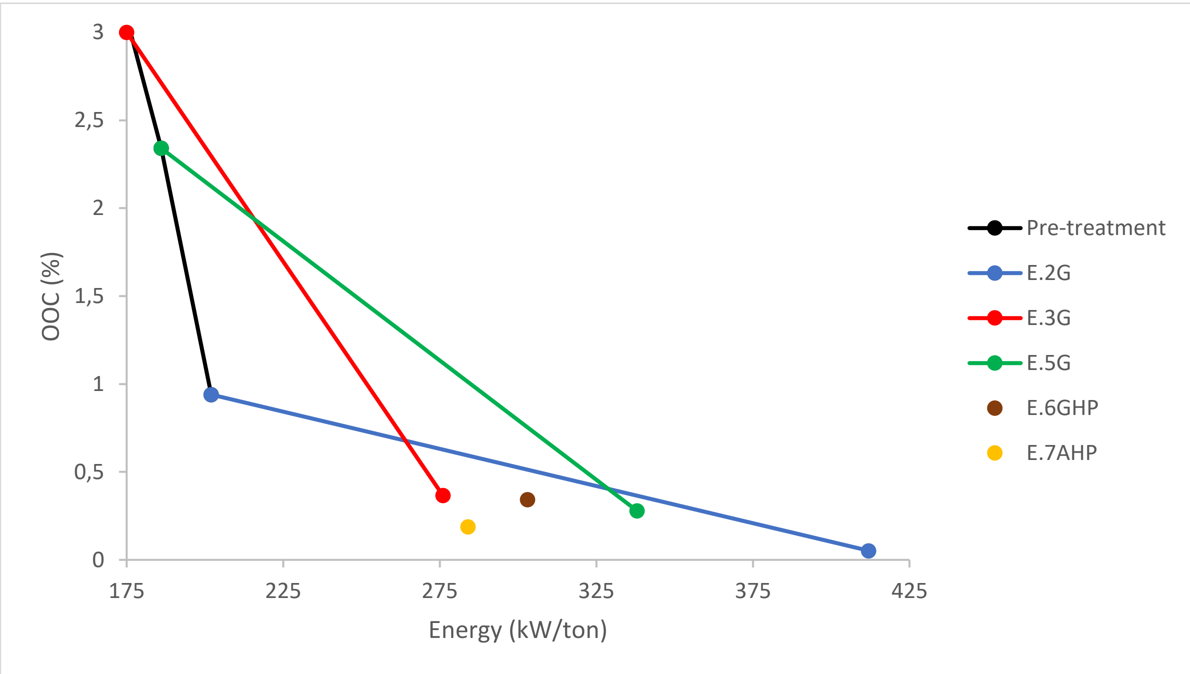

Figure 51: Equinor optimized test comparison

<u>Discussion:</u>

While being pre-heated the bag containing drill cuttings for test E.6GHP was pierced, resulting in water being mixed with the drill cuttings. Due to limited amounts of drill cuttings the test was carried out with a longer pre-treatment than originally planned.

OOC concentration of drill cuttings pre-heated and treated in a microwave was not measured due to limited drill cuttings. No comparison can be made between pre-treatment with cold drill cuttings and drill cuttings at 70 °C.

E.7AHP achieved the lowest OOC concentration from Figure 51, when not considering test E.2G which used a significant amount of energy.

6.3 Treatment results scaleup

To relate the optimized results obtained for the different drill cuttings to a full-scale situation an estimation of energy consumptions was calculated and summarized in Table 30.

Table 30: Energy efficiency for scaleup

Sample	OOC_{Soxtec} (%)	Time (s)	Energy (kW/ton)	Energy with 32% reduction (kW/ton)	Energy with 56% reduction (kW/ton)
C16X.8AHP	0,749	57+30	244	166	107
C16Y.8AHP	0,724	55+50	291	198	128
C17.25AHP	0,547	58+30	248	169	109
E.7AHP	0,188	60+40	284	193	125

Discussion:

These numbers are only estimations, many factors are involved in determining the energy consumed. However, they should be of value since the energy reductions calculated were taken from results where only the input power had been increased.

Table 30 shows substantially lower energy consumptions are possible for all drill cuttings tested. With lower energy at full scale the treatment times of the ConocoPhillips cuttings can be most likely be increased to achieve an OOC concentration below 0,5 wt%.

6.4 Measurement methods of OOC concentration

Tests that achieved the best OOC and energy results were sent to the external lab Eurofins for gas chromatography testing. Table 31 shows the difference in OOC between soxtec and GC.

Table 31: Measurement methods comparison

Sample	OOC_{Soxtec} (%)	GC (%)
C17.1	1,399	0,93
C17.5G	0,106	0,001722
C17.18	0,897	0,1747
C17.21AH	0,294	0,1613
C16Y.3	2,021	1,1156
C16Y.6GH	0,337	0,001817
C16Y.8AHP	0,724	0,4356
C16X.6GH	0,564	0,3863
C16X.8AHP	0,749	0,5313
E.6GHP	0,342	0,1237
E.7AHP	0,188	0,072476

Discussion:

Comparing the two measuring methods a large difference is found for each test, with many OOC concentrations decreasing by over 50 % for the GC measurements.

The reason for the low oil concentration measured by the Eurofins is that the standard method used (GC FID) measures only C10 to C40, in a soxtec every organic molecule is extracted and is part of the measurement of the extraction cups when weighing.

In terms off energy optimization there are probably many tests that can reduce treatment times and still be under the 0,5 wt% NCS oil concentration.

7 General discussion and conclusion

Several treatment parameters were adjusted on COP 17-inch section to further reduce the energy consumption and increase oil separation.

The adjustment of dosing glycol on hot drill cuttings after the pre-treatment seems to be advantageous. This will also be the only way to proceed in full scale, as this will be the actual treatment unit orientation in accordance with Figure 20. This statement is also in line with general thermodynamics, as reheating the cuttings will require energy.

Dosing approximately 25 ml susceptor on the drill cuttings after pre-treatment seemed to be optimal in terms of oil removal and energy efficiency. It seemed like a larger volume susceptor would require too much energy to evaporate, but it would probably remove more oil if the treatment time was increased accordingly. If energy consumption is a lot lower in a full scale set-up and considering warm susceptor, a larger volume susceptor might be beneficial.

Pre-heating the susceptor seemed to be beneficial both in terms of energy efficiency and oil removal. The increased energy efficiency statement is in line with general thermodynamics since heating the cuttings requires energy. The statement about increased oil removal is in accordance with the findings of established microwave theory that shows an increase in mass transfer with an increase in steam velocity resulting from quicker heating.

Mixing AC with glycol seemed to improve the oil removal and energy efficiency when compared with glycol when the susceptor was at room temperature. When warm mixture of AC and glycol was compared to warm glycol the results were inconclusive. Bad dosing of the susceptor in some of the tests may also have an impact on the conflicting results. AC absorbs a high degree of microwaves and heats up rapidly, AC might have more of an effect when used as a cold susceptor, since it may increase the time glycol is evaporated. When the glycol is pre-heated the additional heating effect from the AC may have a miniscule effect.

Nitrogen stripping also had conflicting results, poor dosing again makes it hard to draw any strong conclusions. From a visual point of view nitrogen stripping seemed to remove a significant amount of condensation from the glass walls of the sample cylinder.

By pre-heating the drill cuttings to approximately 70 °C there seemed to be a reduction in both oil removal and energy efficiency, an 11 % improvement in energy efficiency was achieved in COP17-inch drill cuttings. Like with pre-heating glycol these statements are in line with general thermodynamics and the relationship between increased steam velocity and increased mass transfer of hydrocarbons.

The technology seemed to meet both the OSPAR and NCS requirements of typically 0,5 wt% for all drill cuttings. The tradeoff of some cuttings types is energy consumption. This seems especially to be the case for C.16X.8AHP and C16Y.8AHP which were achieved 0,75 and 0,72 wt% OOC respectively. This were tests with optimal conditions found from the 17” section. Adding in more energy will most likely reduce the oil concentration to below 0,5.

However, when considering the GC FID analysis from Eurofins, all tests were below 0,15 wt% oil, which is significantly under the legislations. This shows that the optimization could be significantly improved as the oil concentration was significantly lower with respect to BAT in relation to oil separation, the technology stands out to be superior.

Pictures of all the drill cuttings before and after microwave susceptor treatment showed no change in particle size or formation. This is an environmental advantage that the Norwegian Technology microwave technology has over the TCC which is the current BAT. A particle size distribution evaluation showed the different particle sizes of treated drill cuttings in TCC, a big fraction will struggle to settle on the ocean floor and will stay in the water column.

Research using a full-scale microwave was used and related to the optimized results from the four drill cuttings. Some very promising energy consumption results were obtained for all four drill cuttings.

Combining this with the OOC concentration results received from Eurofins, a full-scale microwave susceptor system seems to have a lot of potential.

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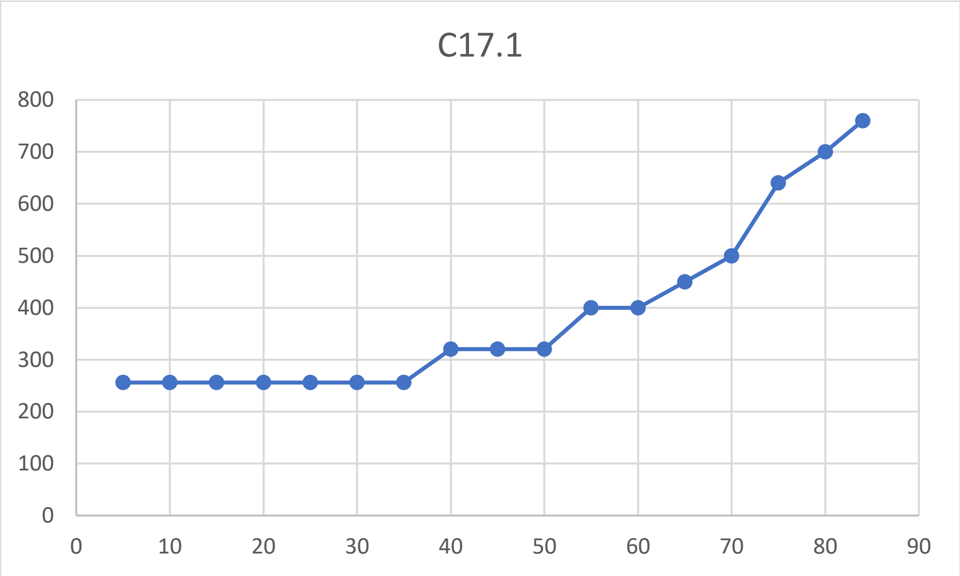
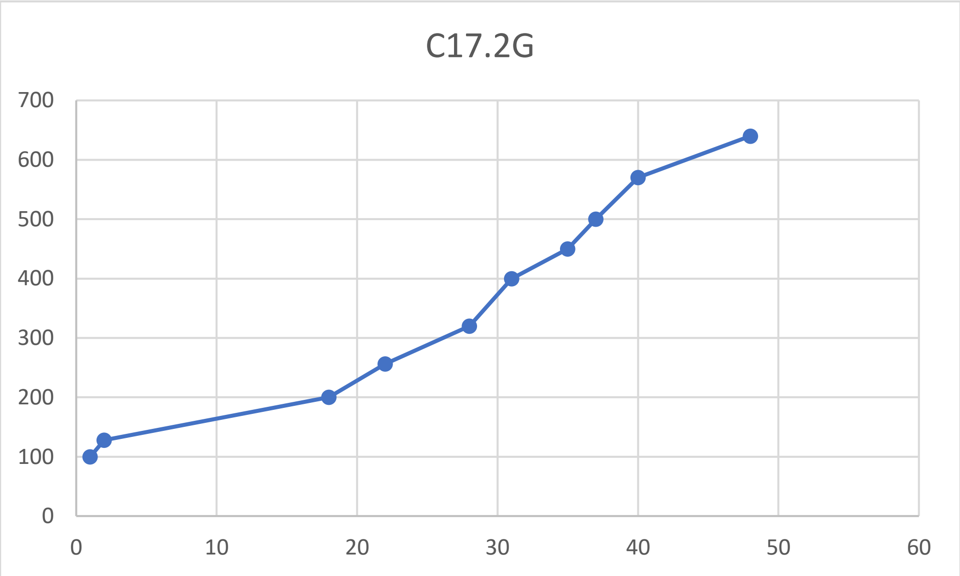
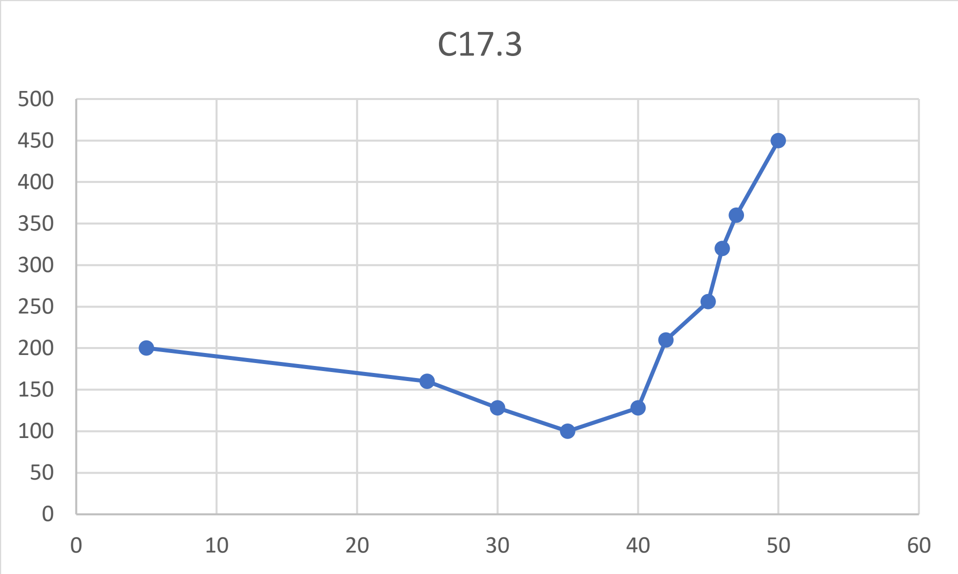
Appendix A

The reflective curves of all the tests performed are placed in Appendix A, the x-axis of the graphs represents time, with seconds as the unit. The y-axis of the graphs represents the amount of power reflected with the unit W/h.



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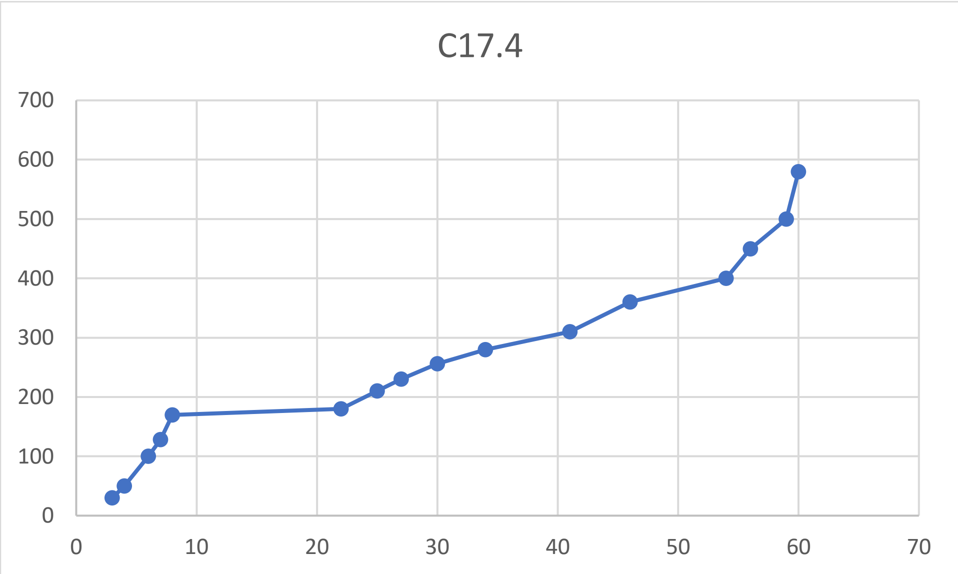
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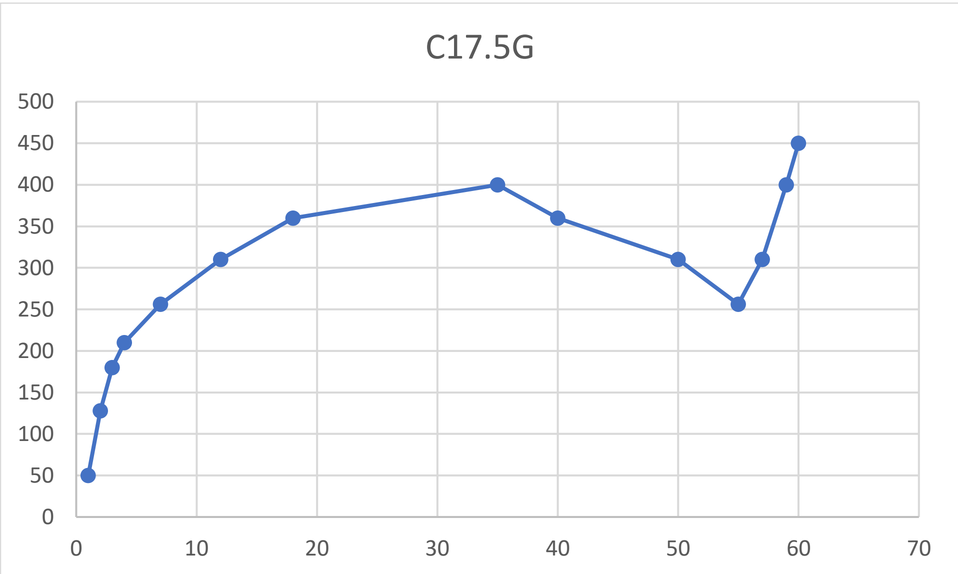
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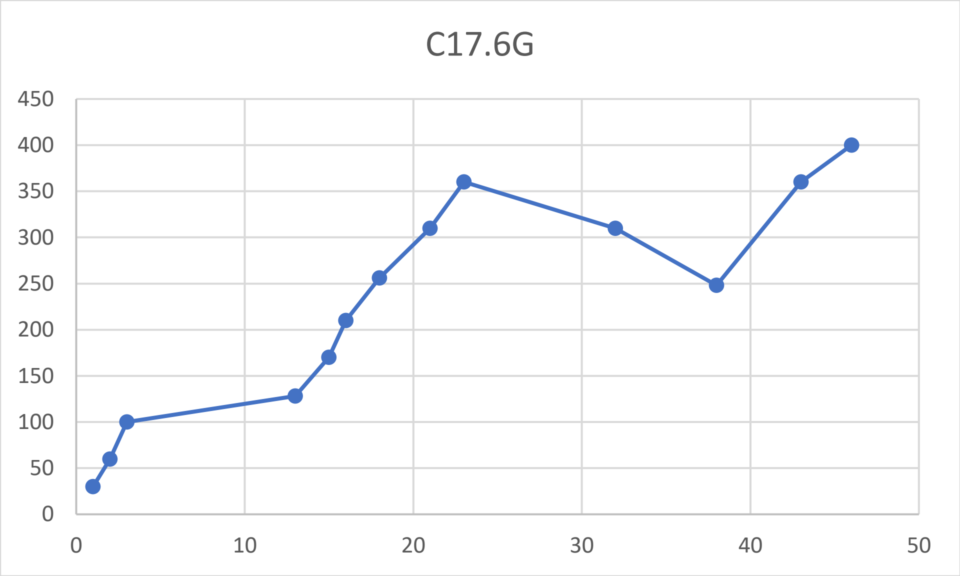
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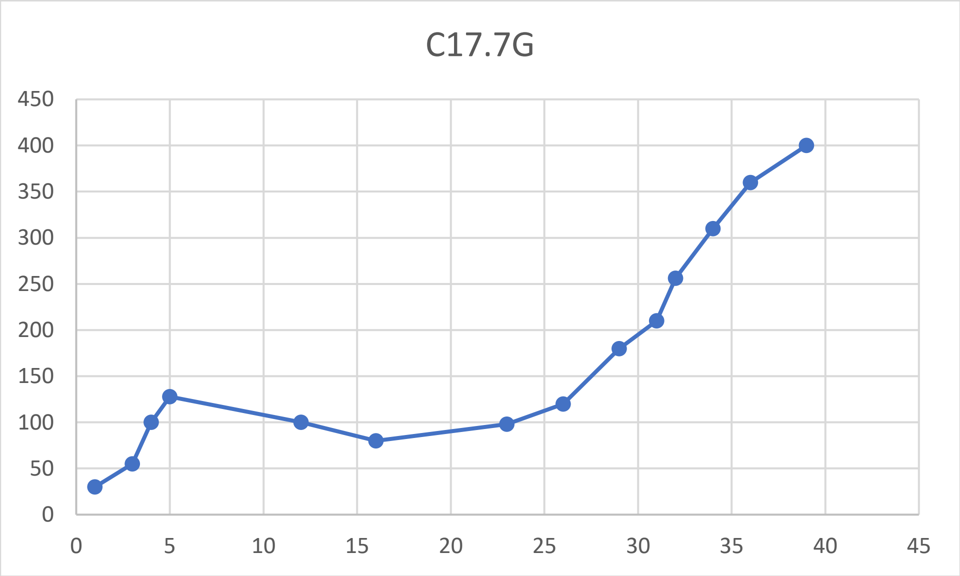
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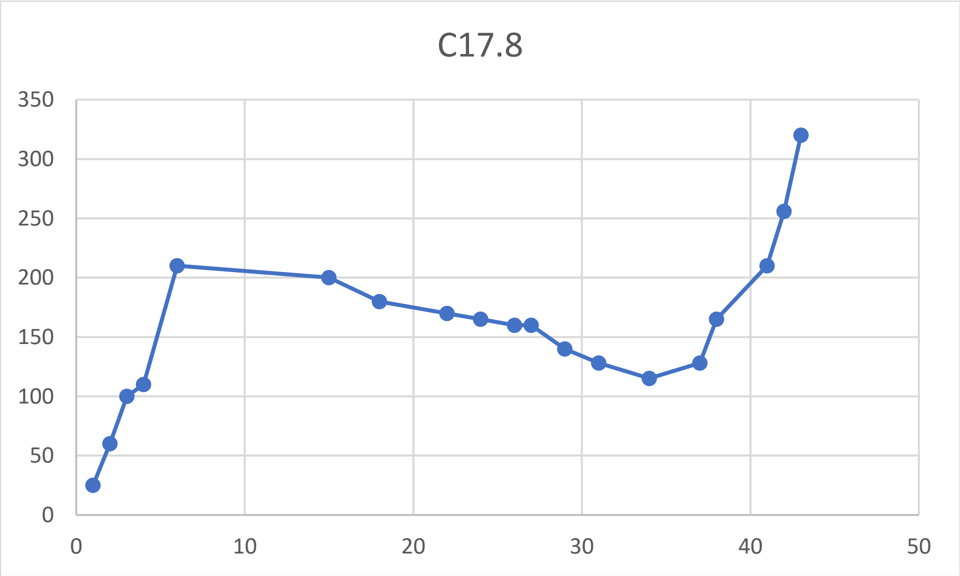
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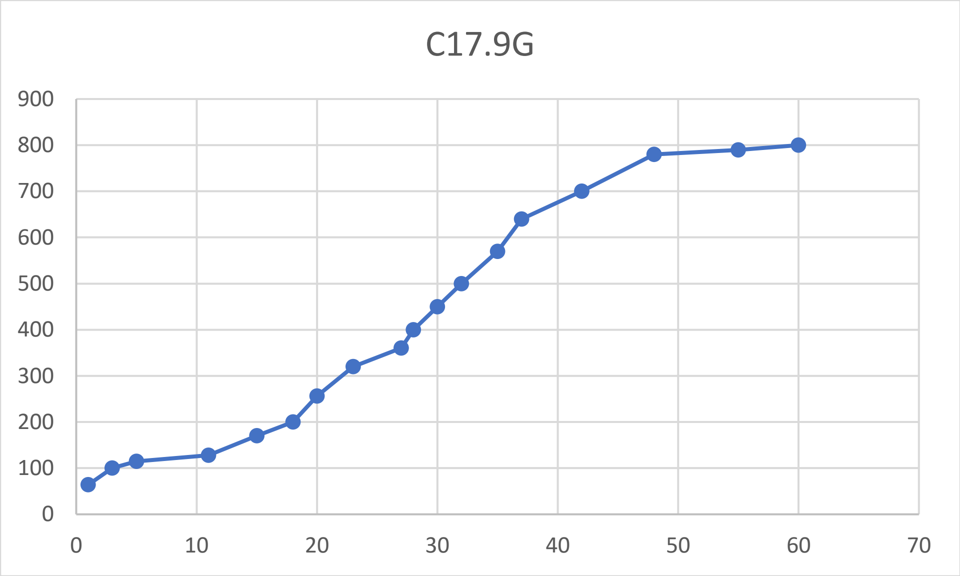
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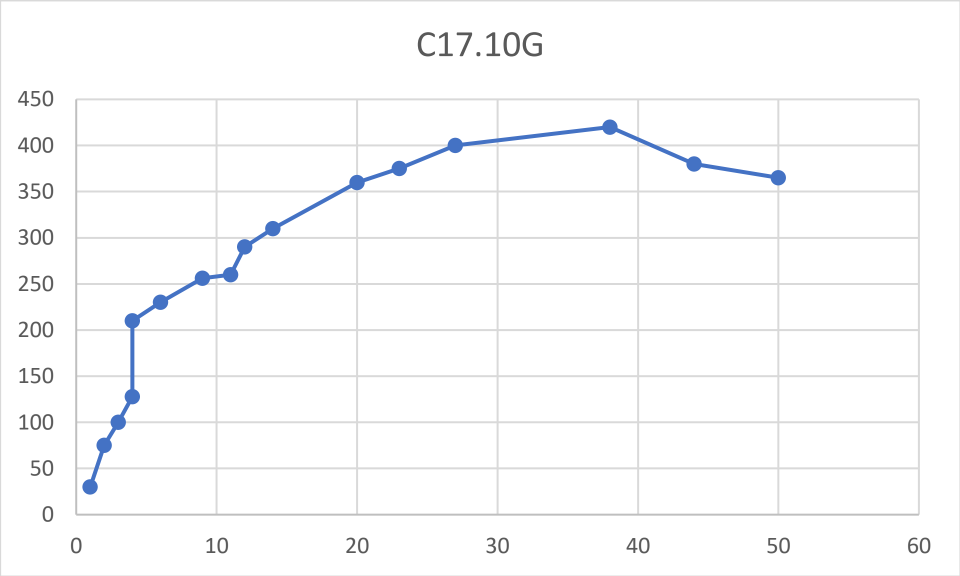
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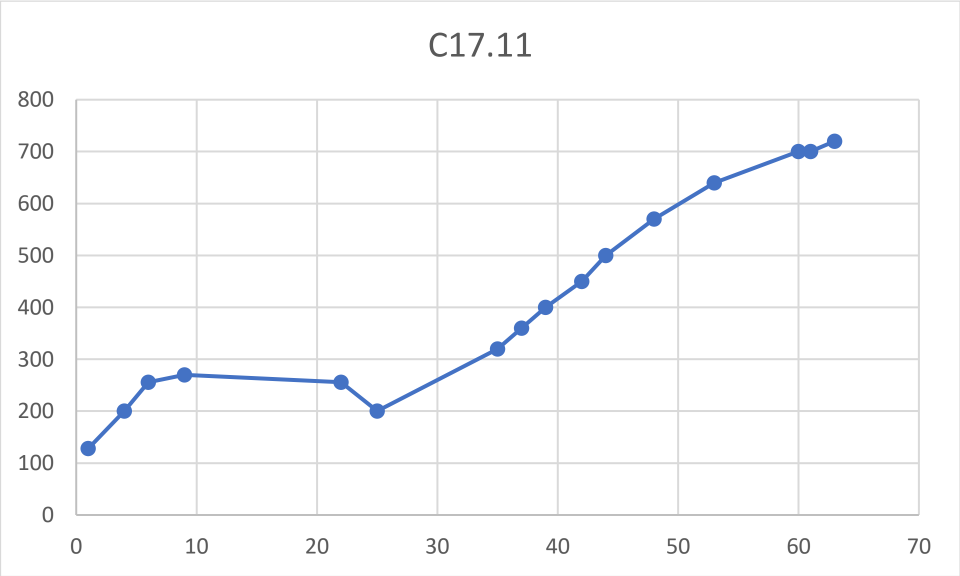
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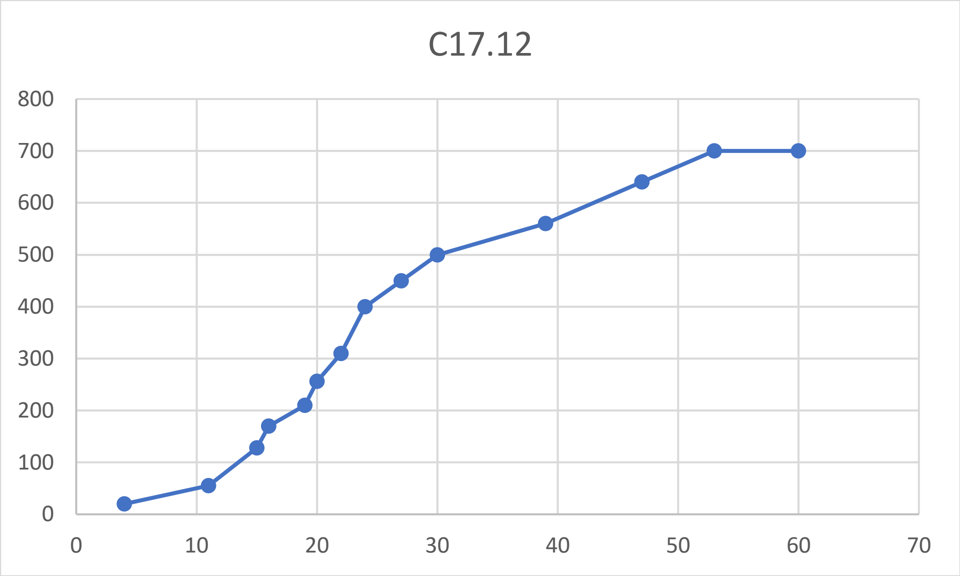
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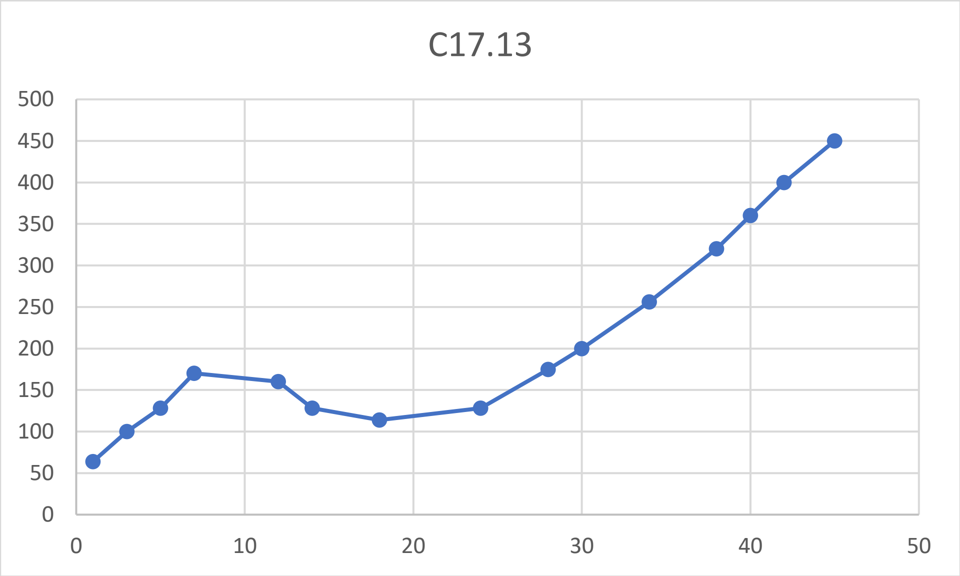
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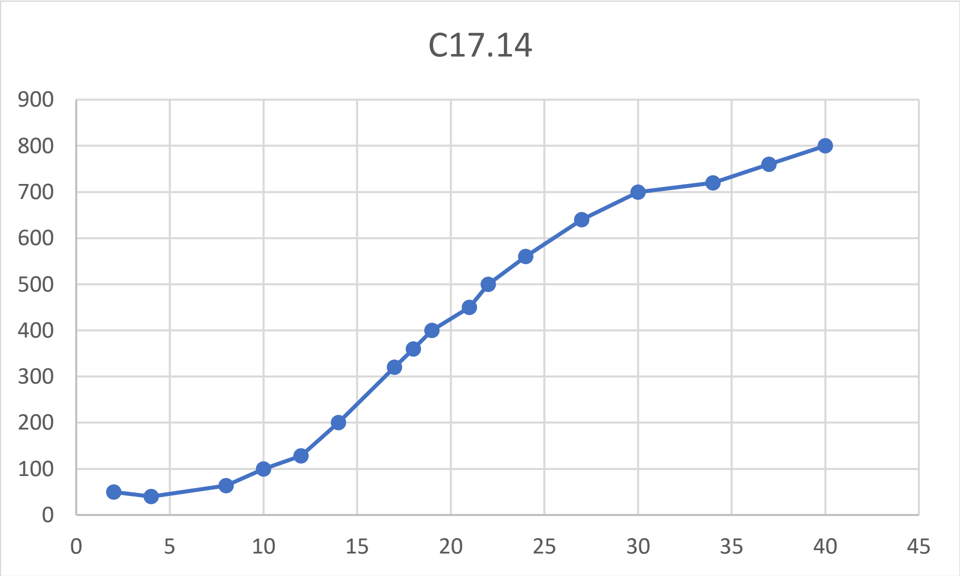
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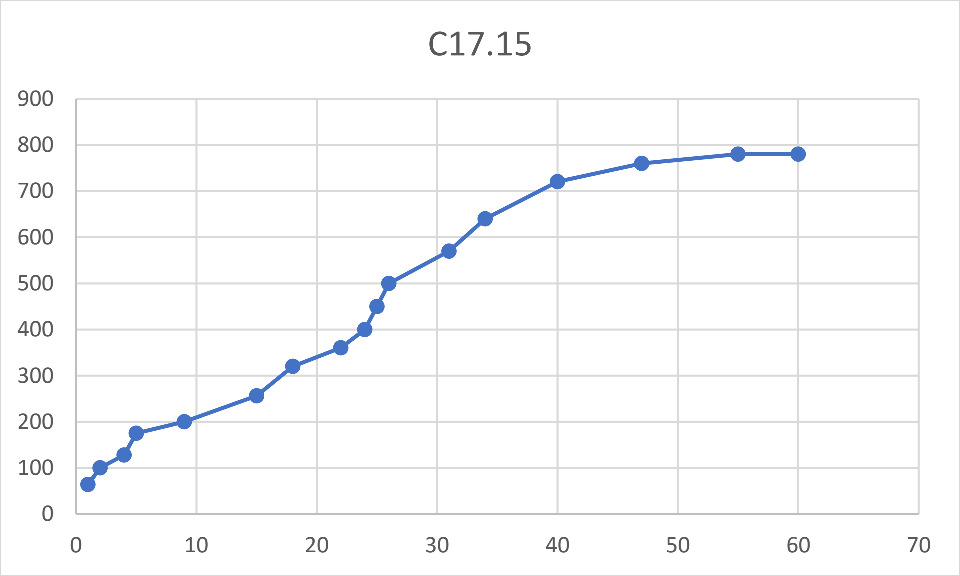
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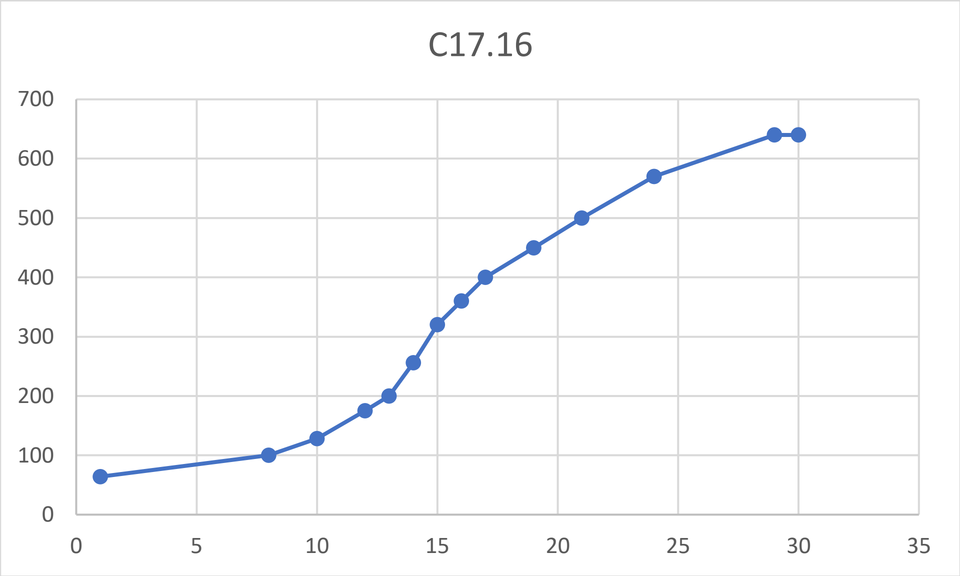
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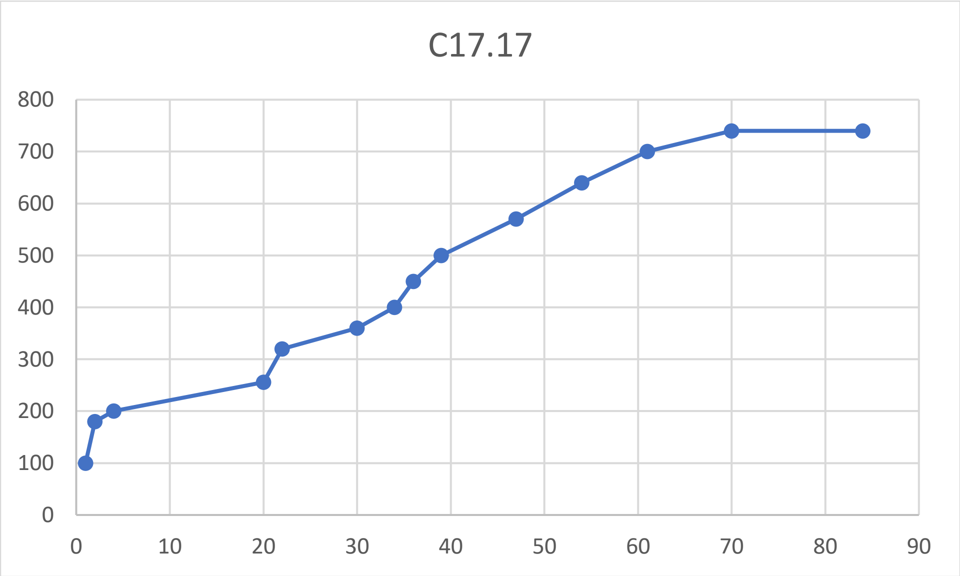
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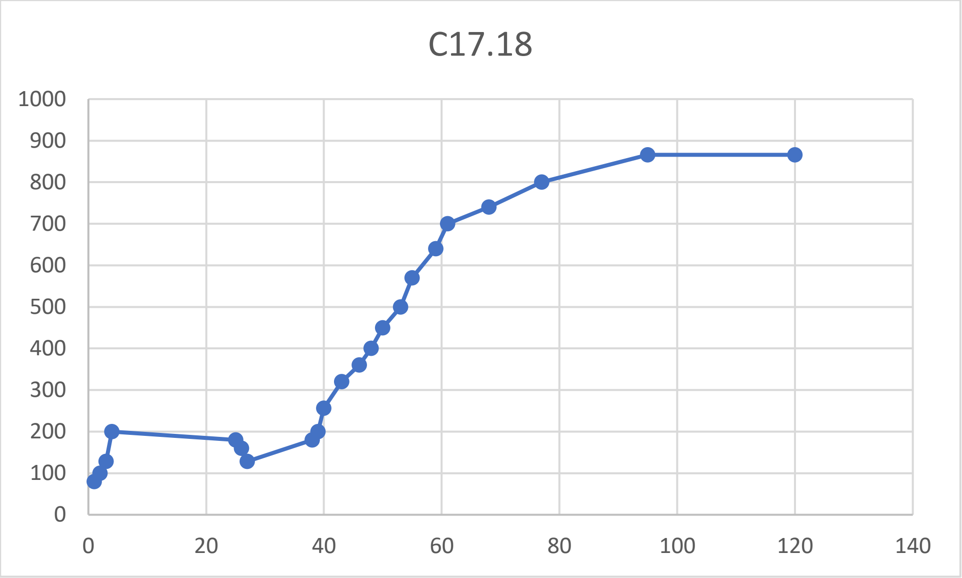
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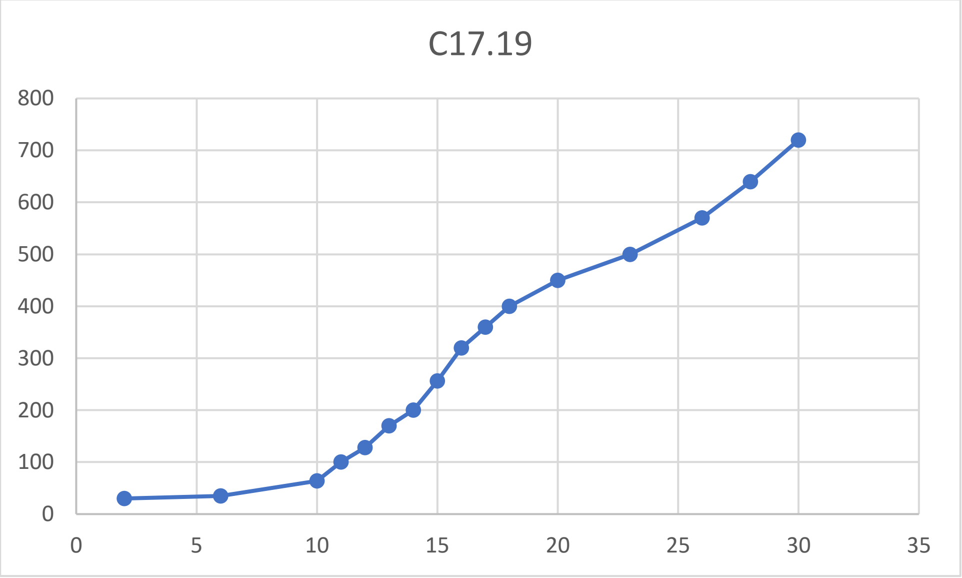
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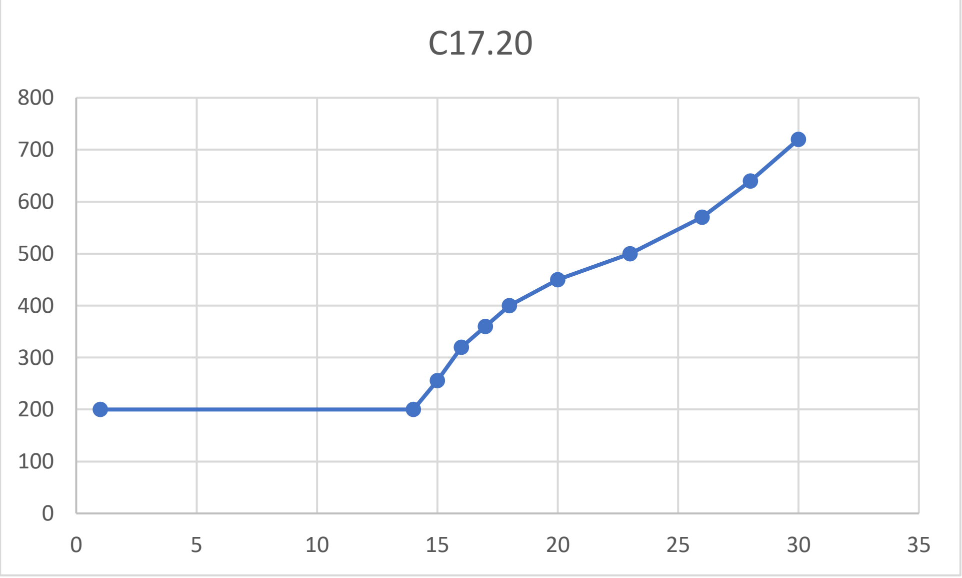
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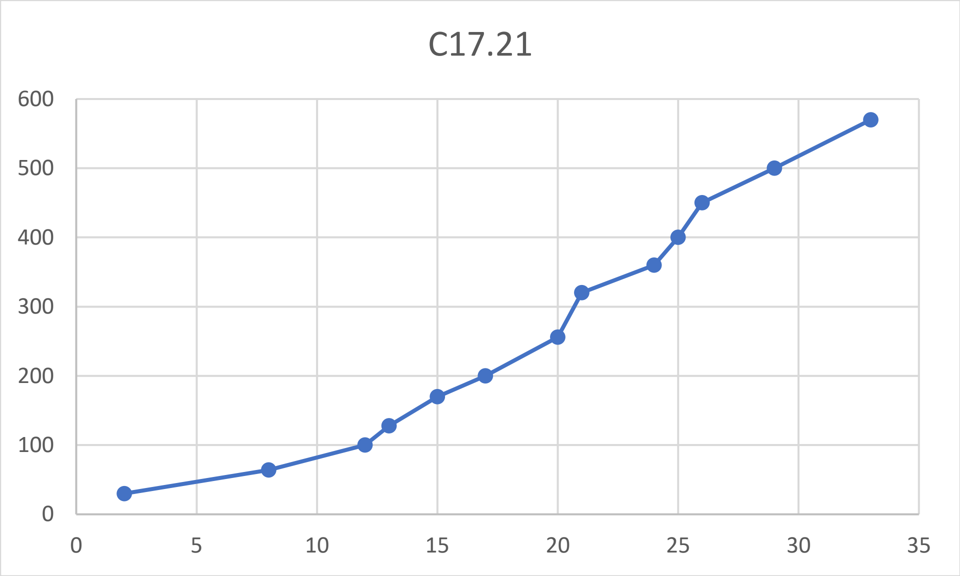
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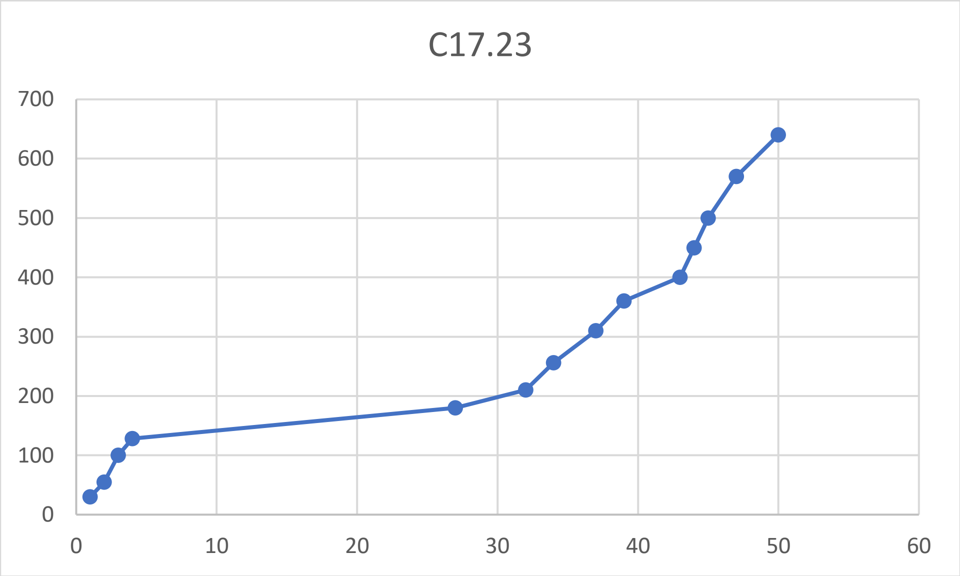
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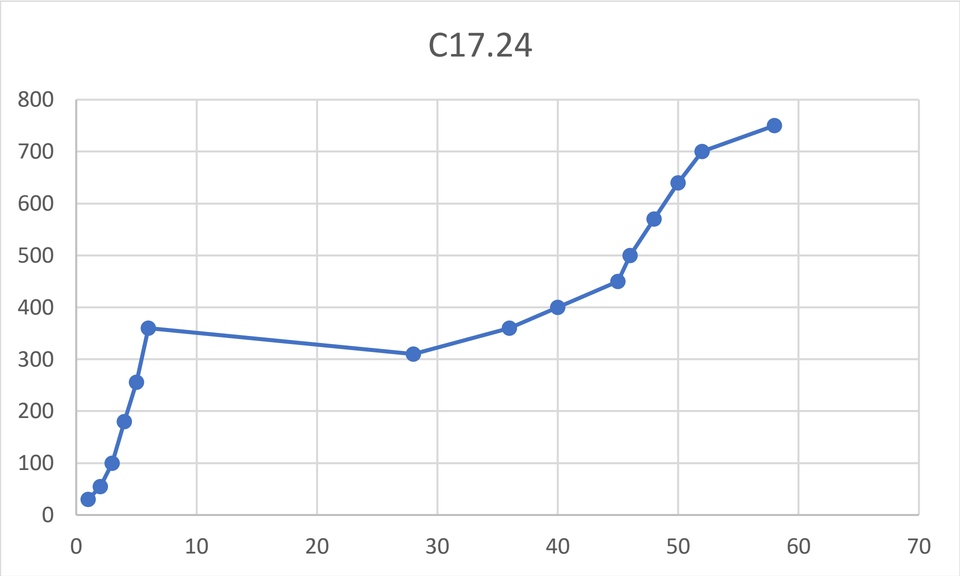
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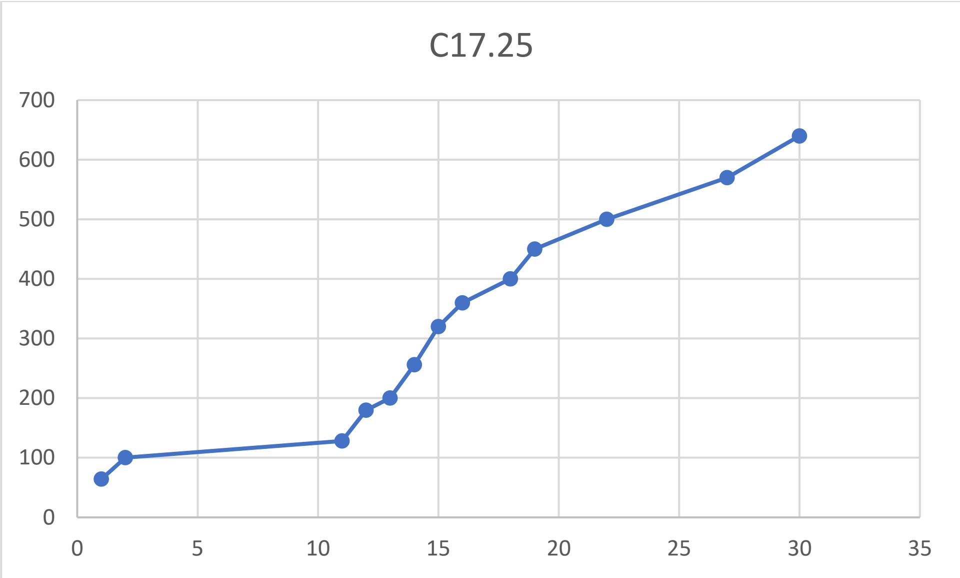
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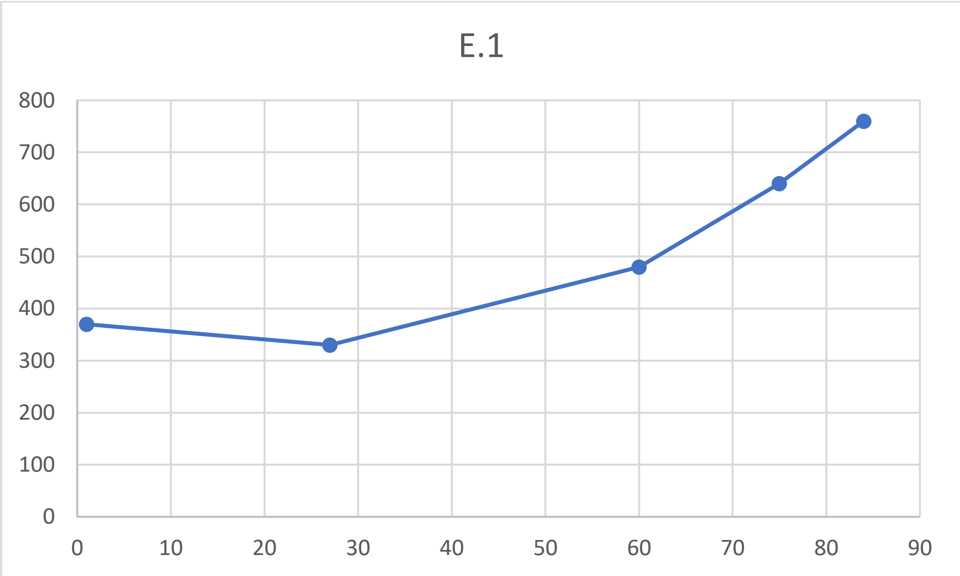
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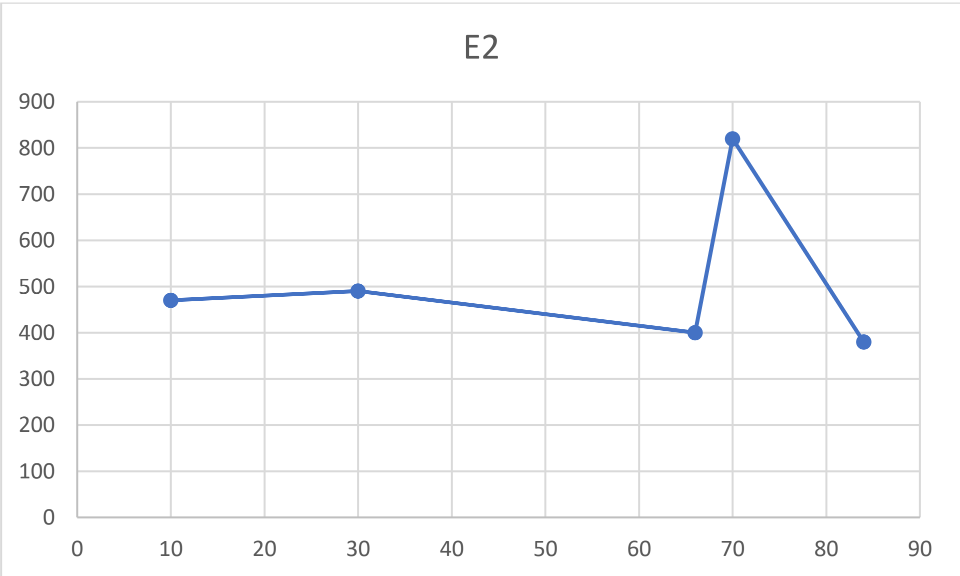
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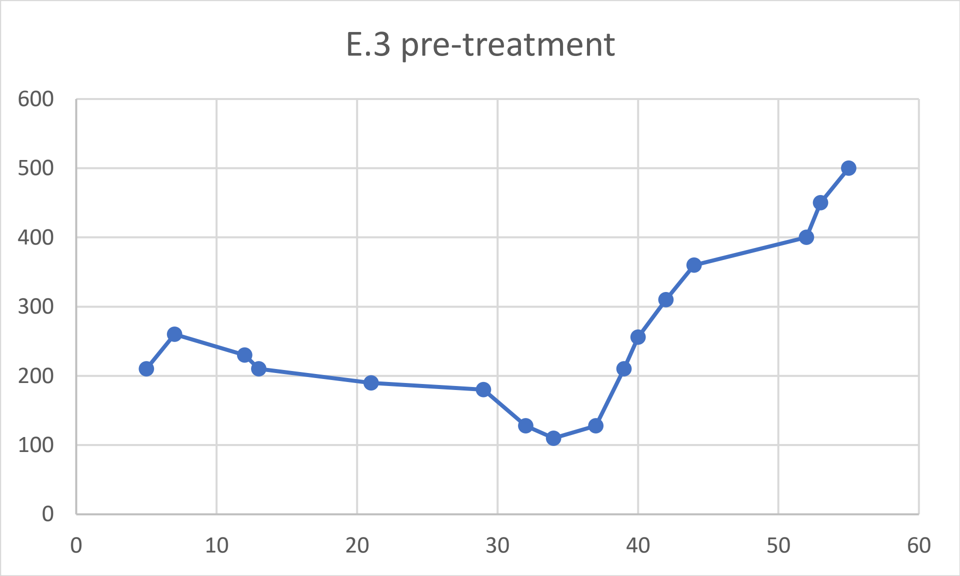
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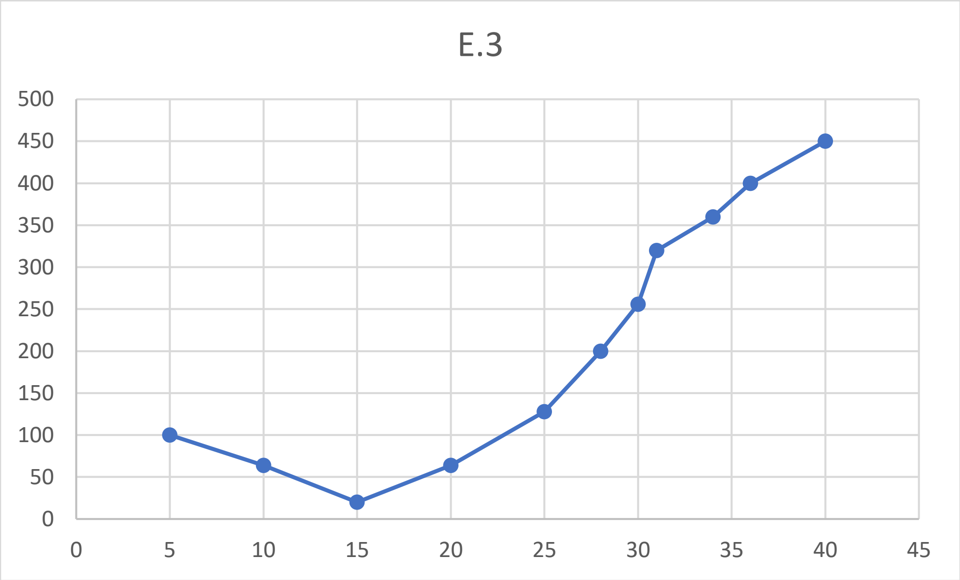
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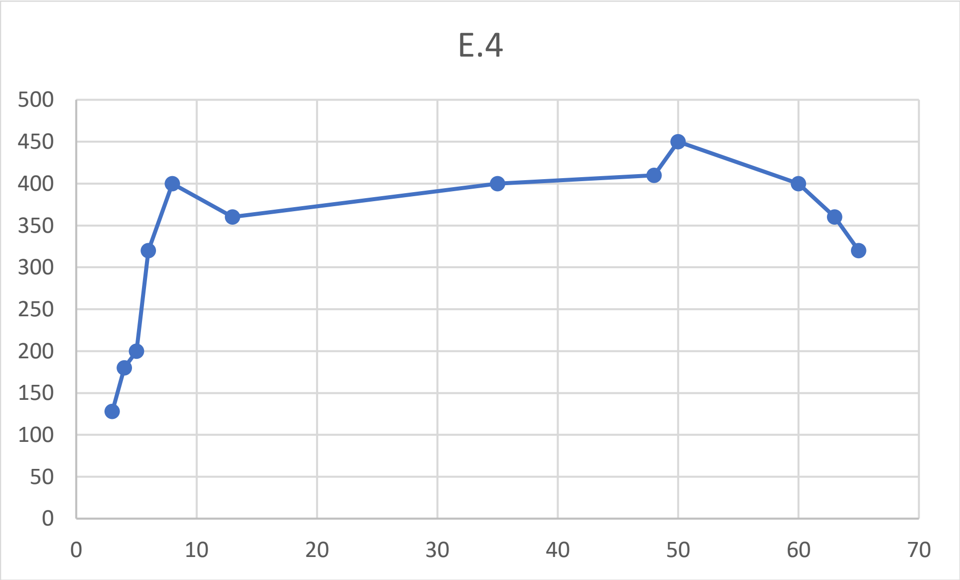
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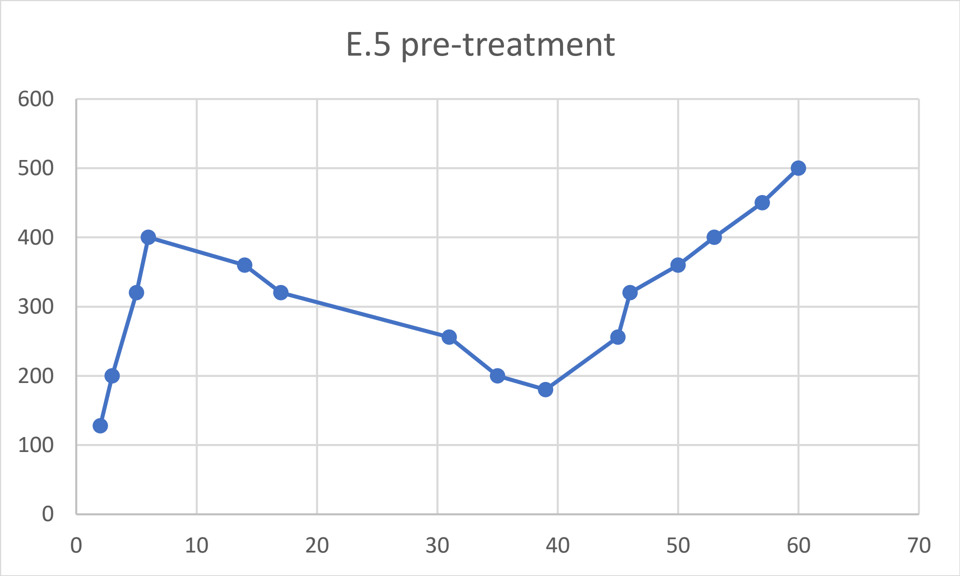
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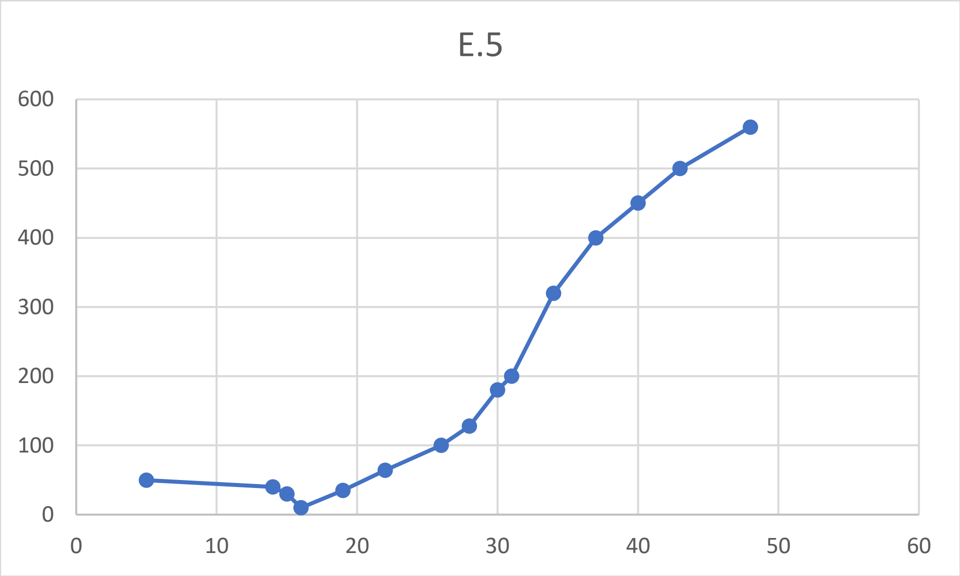
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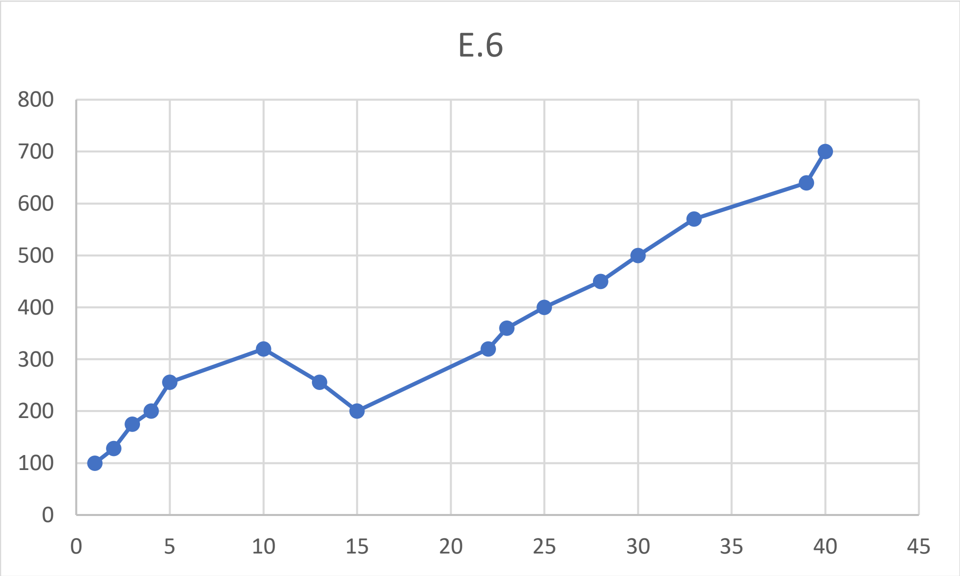
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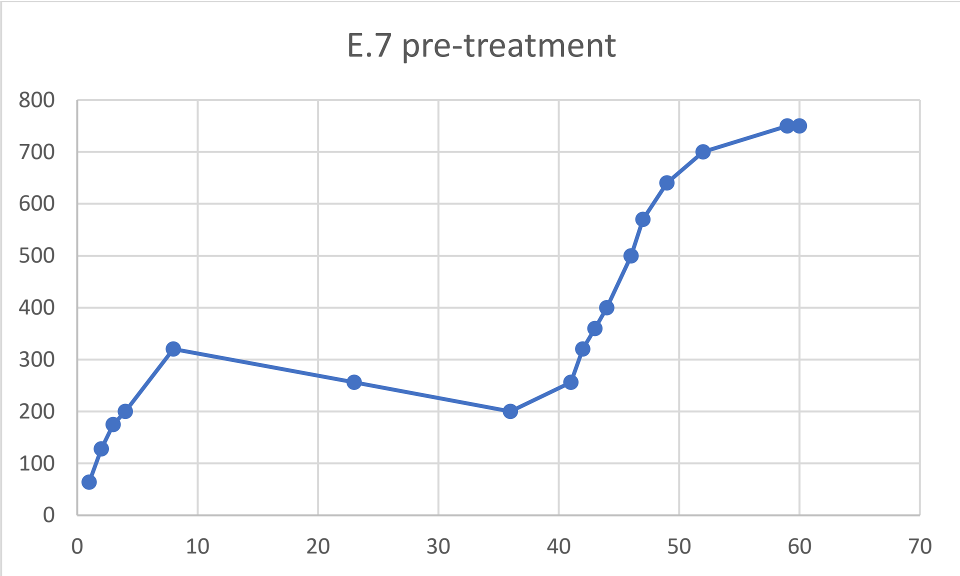
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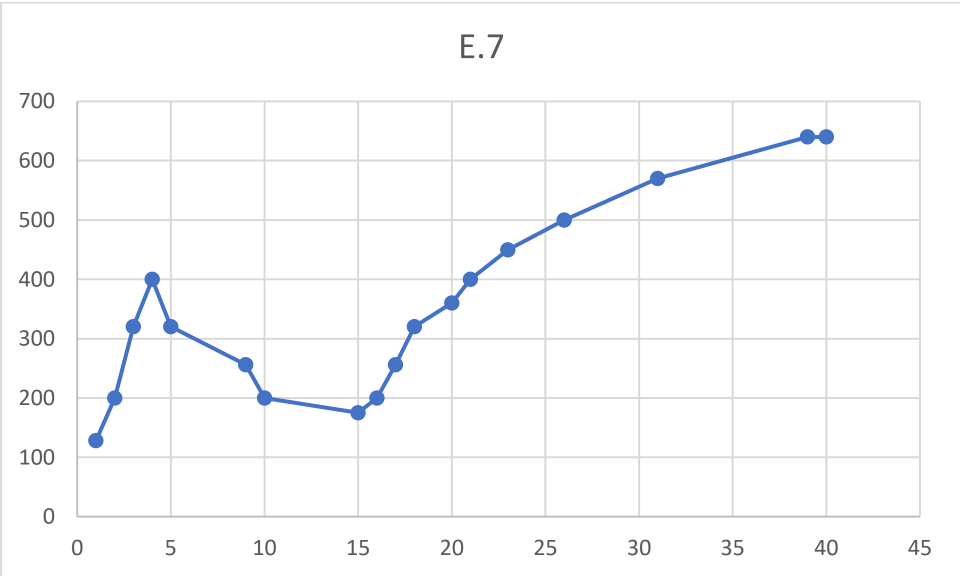
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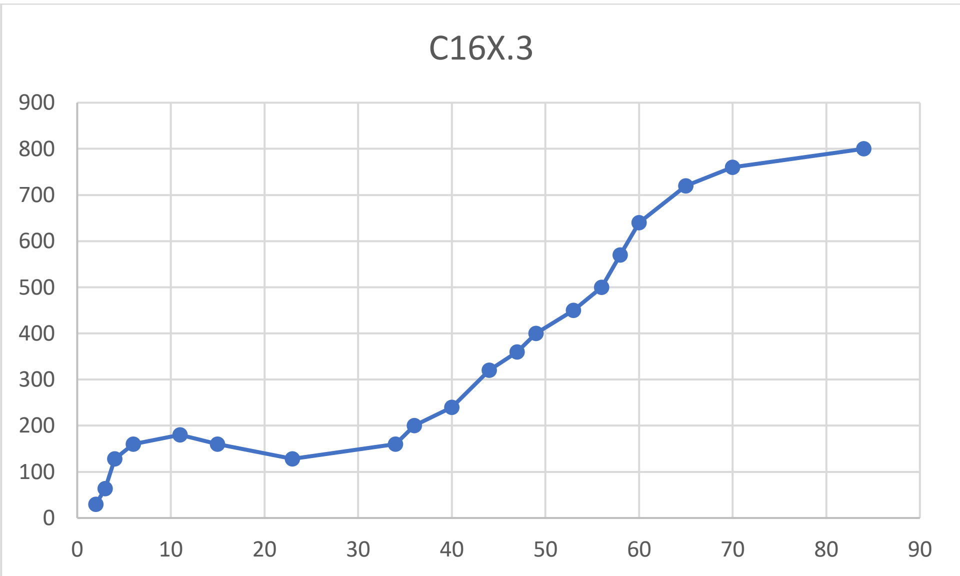
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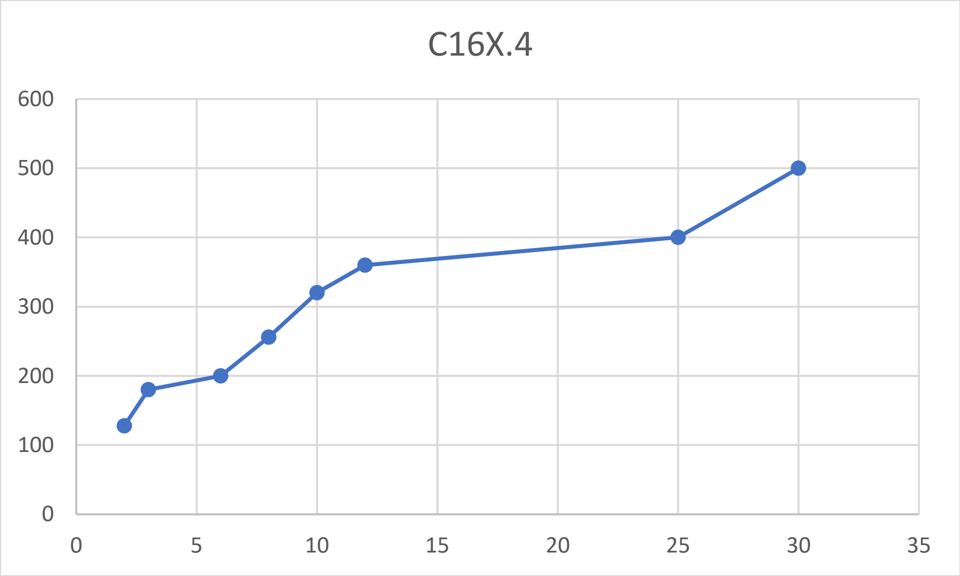
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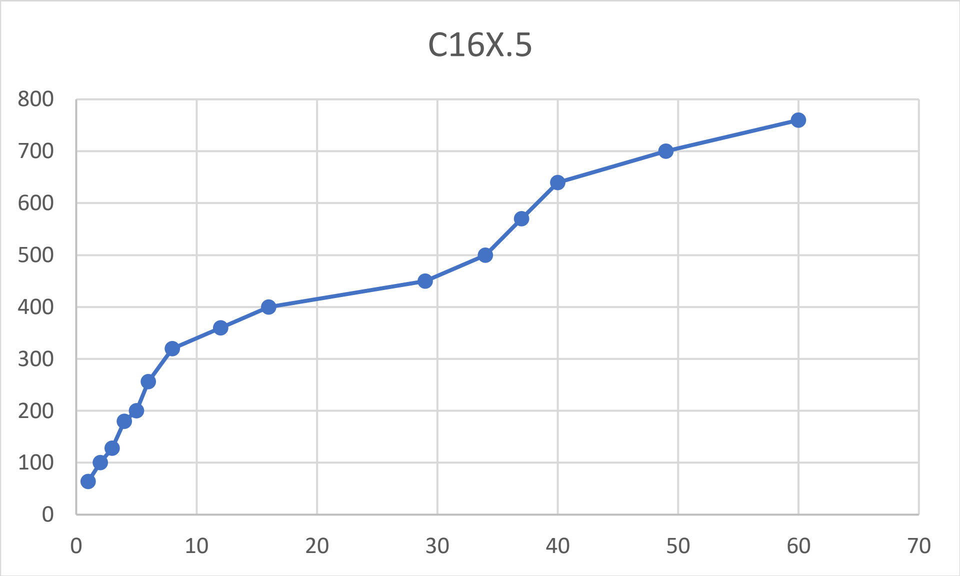
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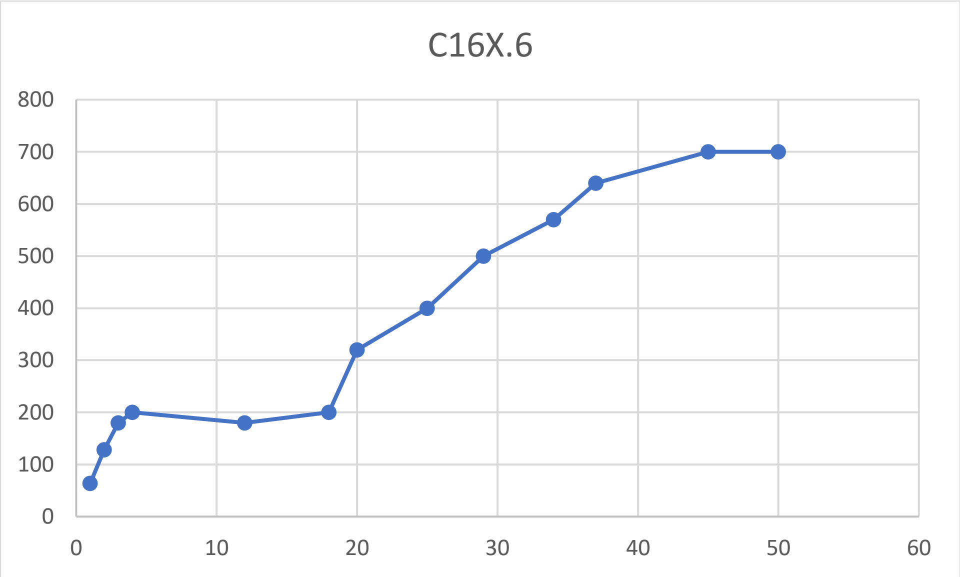
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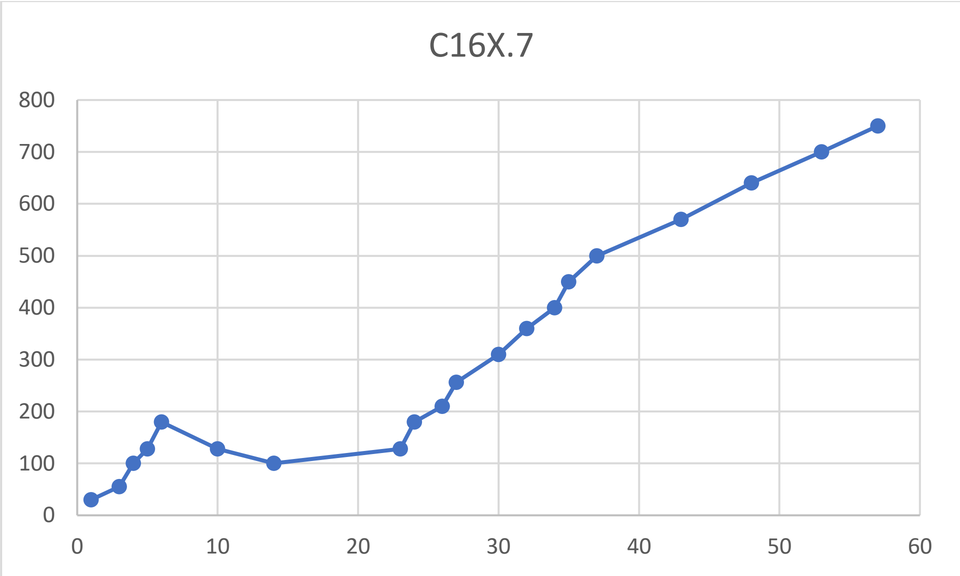
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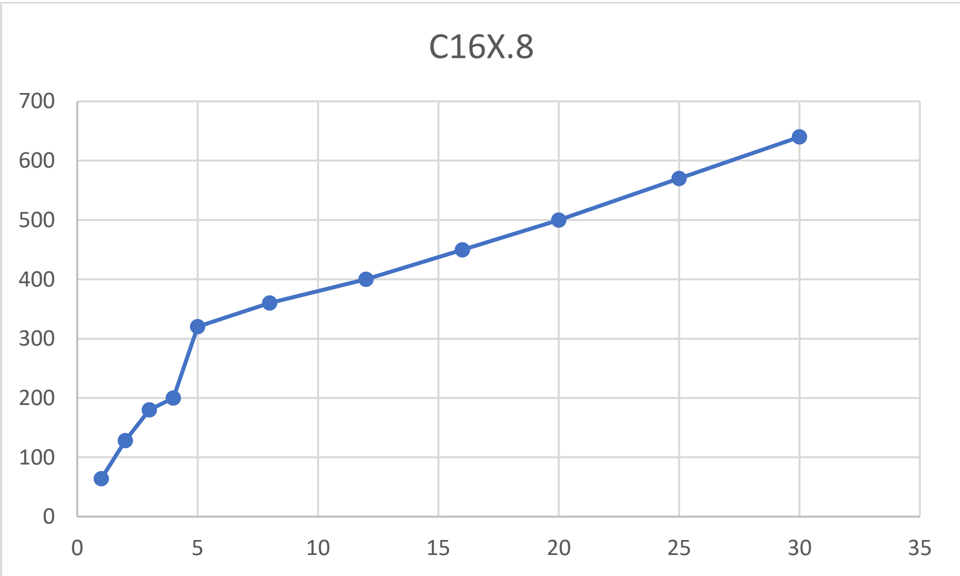
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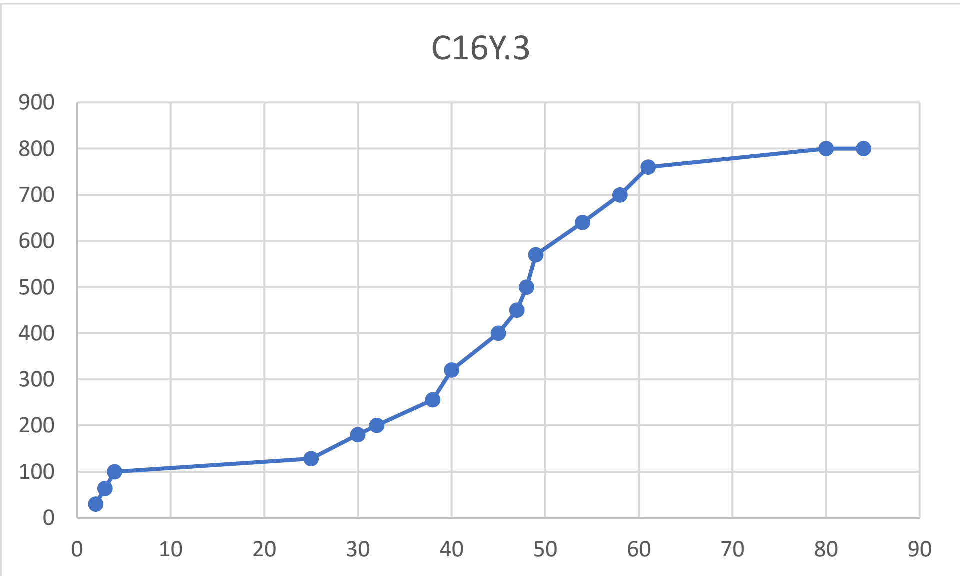
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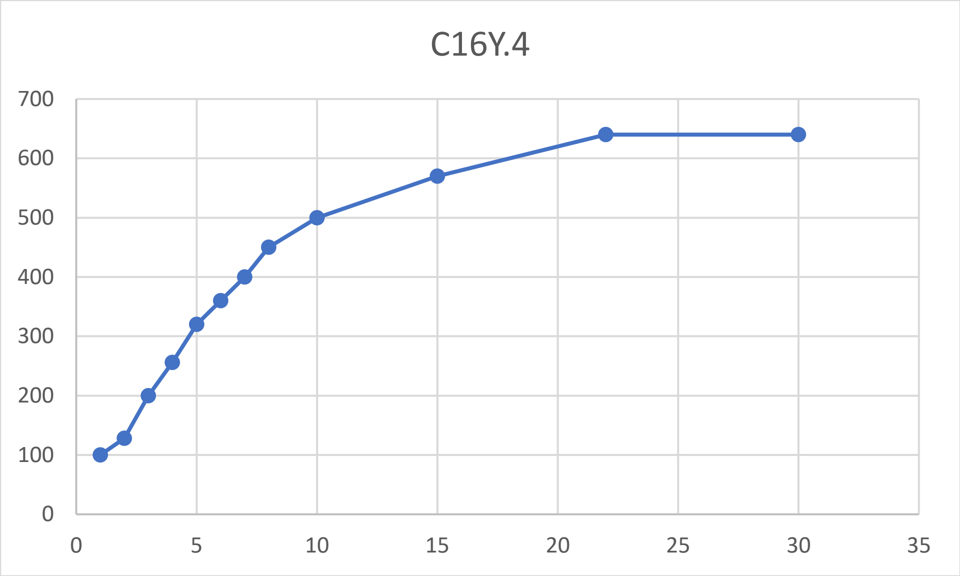
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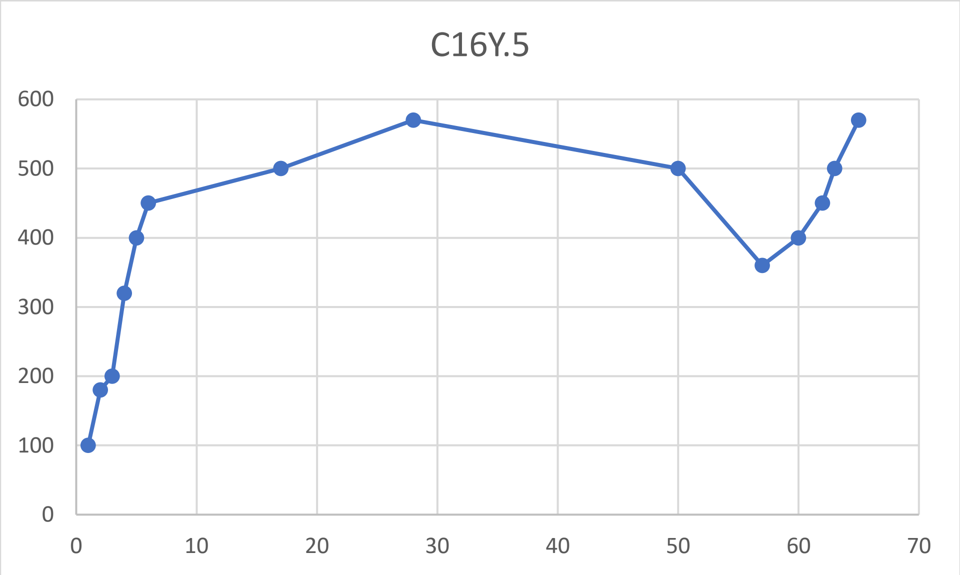
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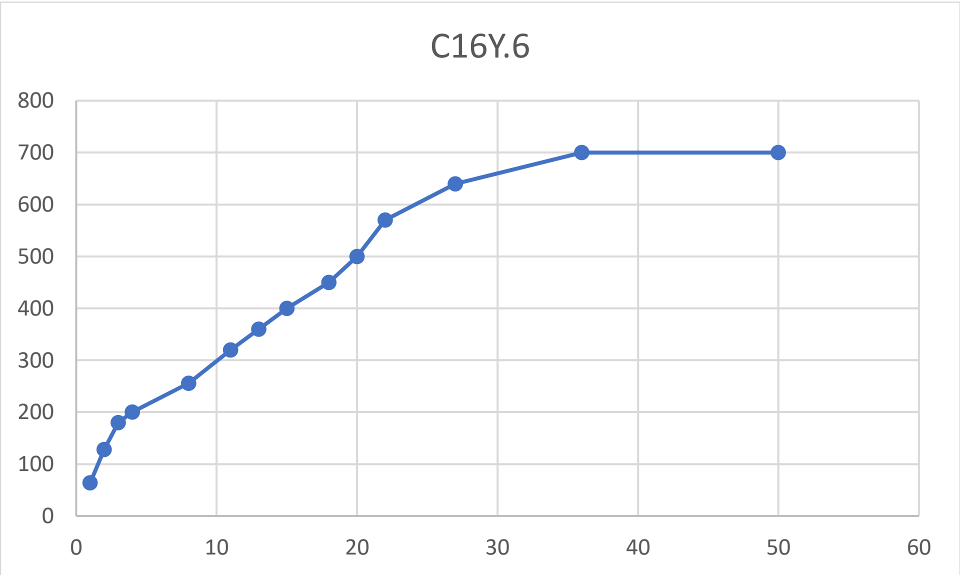
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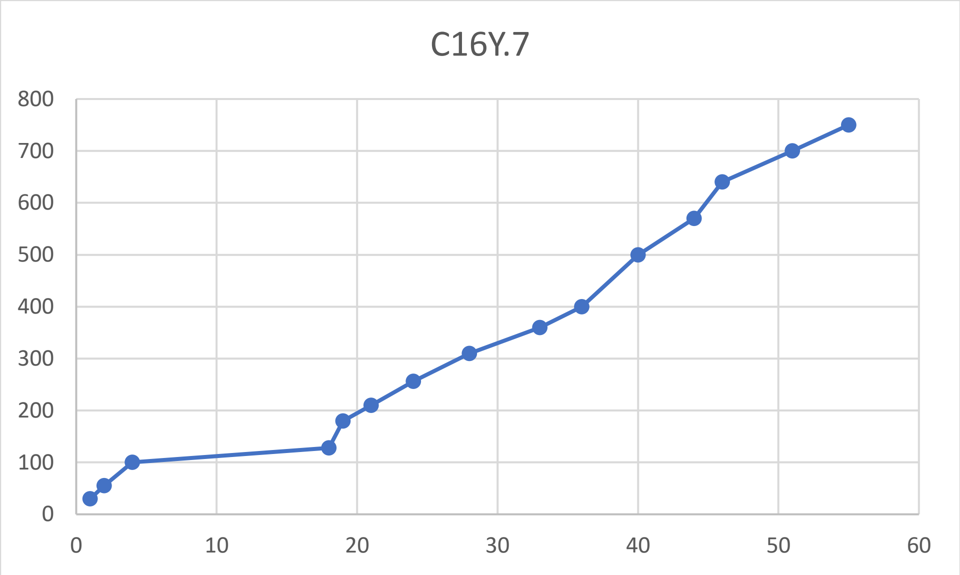
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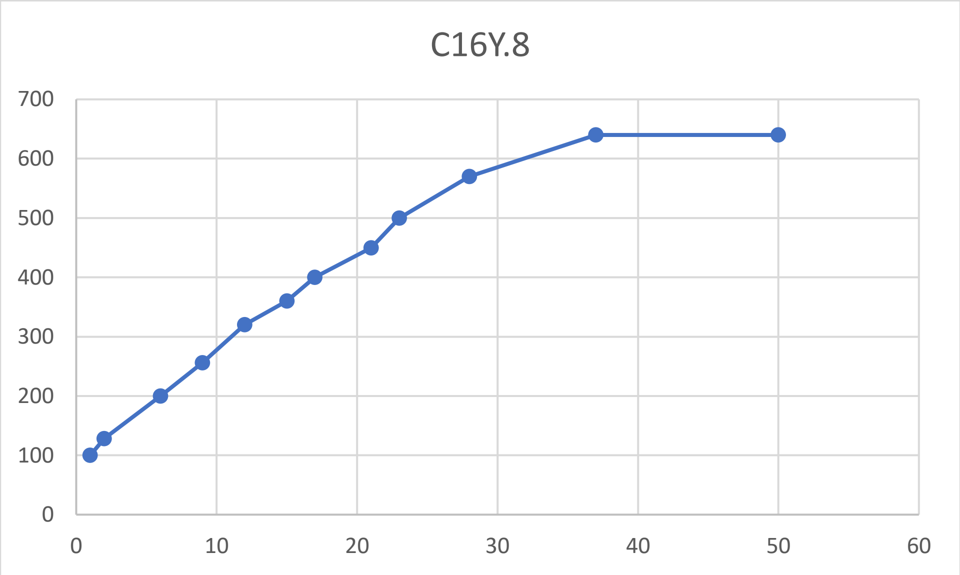
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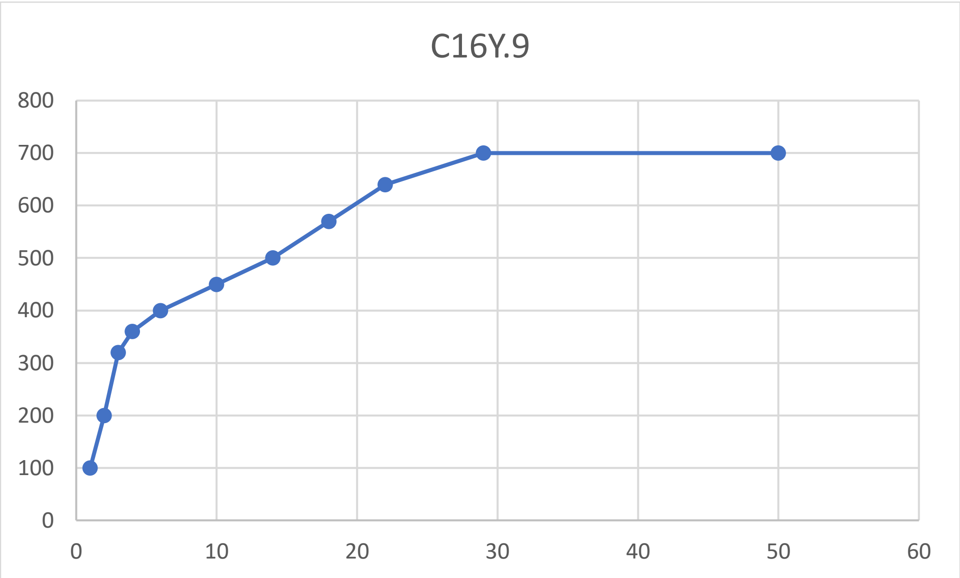
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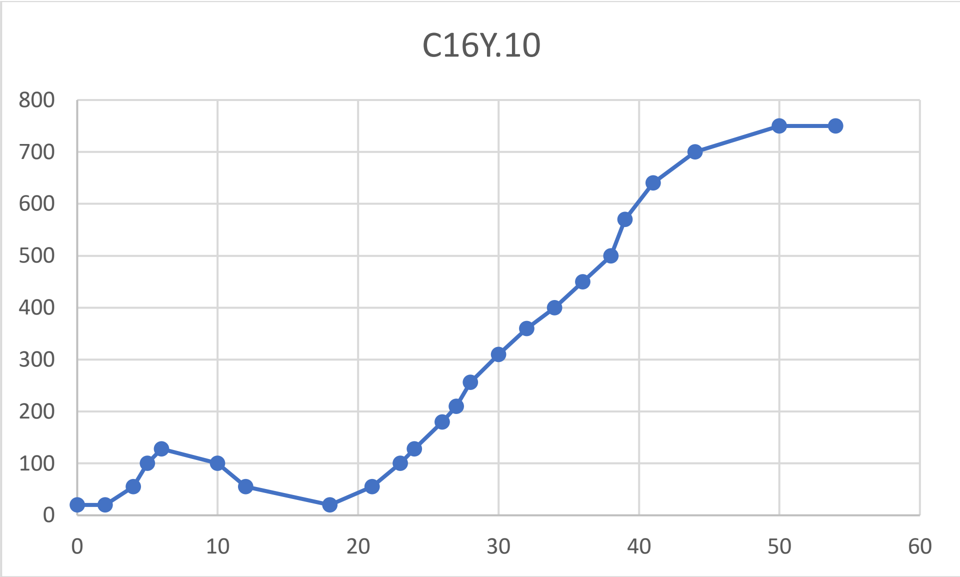
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