Preface

This M.Sc. thesis is written during spring 2010 by Henrik Worren, who is graduate student from the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU) in Trondheim.

The dissertation is initiated by Wallem Shipmanagement Norway and proposed solutions related to their vessels. Professor Harald Valland and Principal Research Engineer Lars Kolle (M.Sc.) has been the main contributors and advisors. The thesis has been written in Trondheim, where guidance and assistance were easy available.

In autumn 2009 I wrote a project thesis on the same subject where the topics were studied on a general basis. This project thesis highlighted EU Directive 2005/33/EC in general terms and the essence in it. In this M.Sc. thesis I investigated challenges related to low sulphur fuel and how engine components are affected. Preventive measures for operators are also suggested.

Finally, I would like to give my gratitude to Harald Valland and Lars Kolle for great assistance and inspiring inputs. In adition, I would like to give my thanks to Wallem Shipmanagement Norway that also contributed with valuable information and clarifications.

Trondheim 11.06.2010

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Henrik Worren

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Abbreviations

AUX - Auxiliary Engine
BTC – Before Top dead Centre
CCI - Calculated Cetane Index
cSt – Centistokes, 1 cSt = 1 cm^2/s
DMA - Marine Distillate fuel, grade A.
DNV - Det Norske Veritas
DNV PS - DNV Petroleum Services
EEA - European Economic Area
HFO - Heavy Fuel Oil
HSHFO - High Sulphur Heavy Fuel Oil
LSHFO - Low Sulphur Heavy Fuel Oil
MDO - Marine Diesel Oil
MGO - Marine Gas Oil
ME - Main Engine
MGO - Marine Gas Oil
IMO - International Maritime Organisation
MT - Metric Tons
PS - Port Side
PSC - Post State Control
RORO - A vessel type where cargos are rolled on and off.
SB - Starboard Side
SECA - Sulphur Emission Controlled Area
SFOC - Specific Fuel Oil Consumption
SOLAS - Safety Of Life At Sea
TC - Time Charter
WSMN - Wallem Shipmanagement Norway AS

Summary

The objective of this diploma thesis is to assess the technical and operational challenges EU Directive 2005/33/EC will introduce. This is done using fundamental knowledge about naval architecture and marine diesel engines. Experiences on 0,1 % sulphur fuel in the maritime industry is limited, established standards and practices are few and is now being developed.

EU Directive 2005/33/EC is dictating vessels to use fuel with a maximum sulphur content of 0,1 % while in EU port. MGO (type DMA) is the only fuel available with a sulphur content below 0,1 %. Vessels managed by WSMN are calling an EU port frequently and have to do necessary modification to their vessels for safe compliance to the directive.

Today their vessels are carrying HFO and MDO, after complying with the directive, they shall carry HFO and MGO; MDO will be exchanged with MGO.

MGO got different properties from MDO. The main difference is low viscosity. Low viscosity can be compensated by cooling the fuel before use, installing a cooler before engine inlet. Poor lubricity is also an area of concern, lubricity additives available on the market may be used. Poor lubricity properties is from the production process in the refineries, hydrotreating is used to achieve 0,1 % sulphur content and is removing the fuel's natural lubricity.

Marine fuels are tested against ISO 8217. This standard has several deficiencies and missing vital information on ignition/combustion properties. C/H (carbon/hydrogen) ratio is the most accurate indicator on this area. It is therefore recommended to upgrade a normal fuel sample analysis to include C/H ratio.

Equipment most affected by the new properties is pumps; injection pumps and booster-/supply pumps. Lower viscosity can increase the internal leakages and delivered flow and pressure will decrease. How each vessel is affected it mainly determined by the injection system's condition. The better the condition is, its ability to deal with low viscosity fuels is better

On a general basis, manufacturers and class societies shall be consulted and modifications approved.

1 Introduction

The "carbon footprint" for a pair of shoes shipped form China to Europe by sea would be 372 grams. To take those shoes another 20 km by car from shop to home would produce 10 times more carbon gases.

MAERSK Line Chief Executive Eivind Kolding to Bunkerworld 9 November 2007.

Shipping is the most economic way to transport large amount of goods, this is why 95 % of world international trade is transported by ships. The unit cost of sea transport has also decreased greatly through technological improvements. Figure 1 shows the small transportation costs by sea in relation to its retail price [1]. Since almost all goods of international trade are seaborne carriage, means that the fuel consumed is depending on world trade. The world trade and the world economy have gone down the last year because of the financial crisis.

- The typical cost to a consumer in the United States of transporting crude oil from the Middle East, in terms of the purchase price of gasoline at the pump, is about half a US cent per litre.
- The typical cost of transporting a tonne of iron ore from Australia to Europe by sea is about US $12.
- The typical cost of transporting a 20 foot container from Asia to Europe carrying over 20 tonnes of cargo is about the same as the economy airfare for a single passenger on the same journey.

Typical Ocean Freight Costs (Asia-US or Asia-Europe)

	Unit	Typical Shelf Price	Shipping Costs
TV Set	1 unit	$700.00	$10.00
DVD/CD Player	1 unit	$200.00	$1.50
Vacuum Cleaner	1 unit	$150.00	$1.00
Scotch Whisky	Bottle	$50.00	$0.15
Coffee	1 kg	$15.00	$0.15
Biscuits	Tin	$3.00	$0.05
Beer	Can	$1.00	$0.01

Figure 1: Cost of transporting goods by sea.

Since 1950 and up to 2006 the worlds total export has increased annually 6,0 % on average, see figure 2. Within this period there have been several financial crises like we have today. This supports that the world economy and the world trade will continue to increase in the future. This increase of goods produced will mainly be transported by sea and further the emissions from shipping will increase. We therefore need rules and regulations to control ship emissions.
In the recent years there has been a lot of interest for alternatives to fossil fuel. For sure there has come up many good ideas but I do believe that marine fuel as we know it today will be the ruling source for ship propulsion for many years to come.

Shipping and its pollution is less regulated compared to land based industry and has a definitive environmental improvement potential. Studies have shown that these pollutions can be reduced by 80-90 % [2]. To achieve this, the emission from the shipping industry has to be regulated through rules and regulations. Sulphur is today eliminated from road transport fuels, not only because of the harmful effects, but to enable exhaust treatment technologies. Sulphur interfere exhaust cleaning technologies for NO_x, CO and PM.

IMO's purpose is to regulate marine safety, security of international shipping and to prevent marine pollution. Air pollution as this thesis is about, is regulated through IMO and their Annex VI: "Prevention of Air Pollution from Ships".

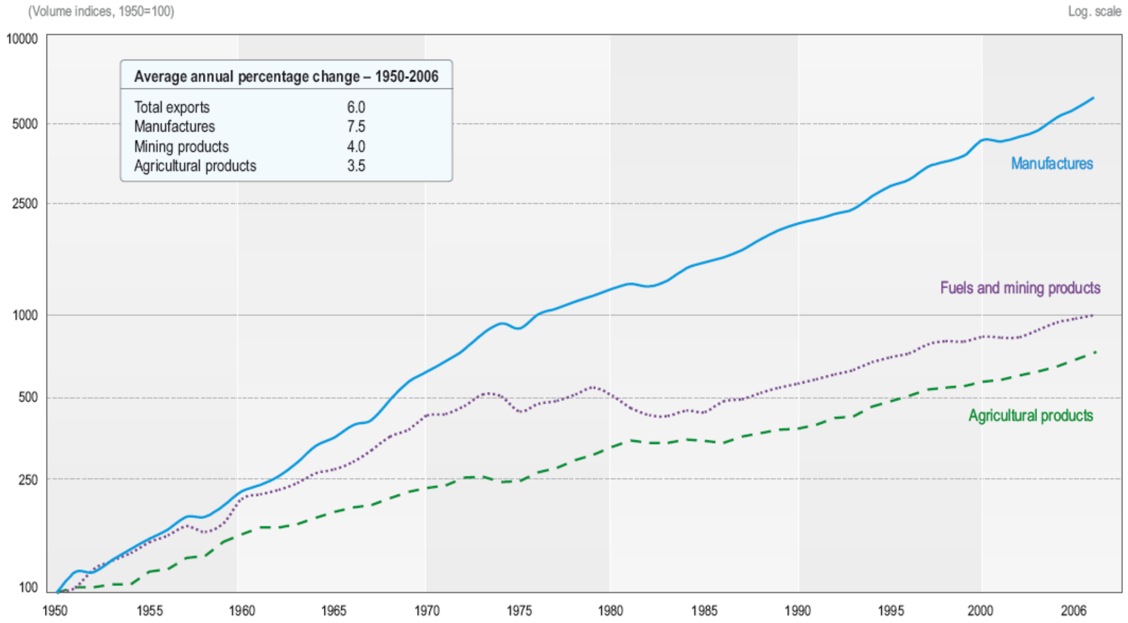

Figure 2: Merchandise trade volume by major product group, 1950-2006 [3].

The main pollutants from a vessel are the emissions from the combustion of fossil fuel. High emissions from carbon dioxide (CO_2), particulate material (PM), sulphur oxides (SO_x) and nitrogen oxides (NO_x) are the most concerning topics today. If the emission development up to year 2000 should continue, the emissions will be very high in the future [2]. CO_2 has a global impact and contributes to the greenhouse-effect. CO_2 emissions are linearly to the quantity of fuel burned and not easy to reduce. Sulphur emissions cause a haze for the environment and also to human beings. Such emissions can lead to e.g. acid rain and acidification of the ocean. This will be more described in chapter 5.5. There is also a clear connection between sulphur emissions and PM. A reduction in the sulphur emissions will therefore reduce the PM [4].

In Annex VI there has been established Sulphur Emission Control Areas (SECA). In Europe we have the North Sea SECA (into force November 2007) and the Baltic Sea SECA (into force May 2006). In both these SECA areas there is a maximum permissible sulphur content of 1,5 %. In this case, vessels use LSHFO (Low Sulphur Heavy Fuel Oil) which is a HFO, and therefore it has almost the same properties as HFO.

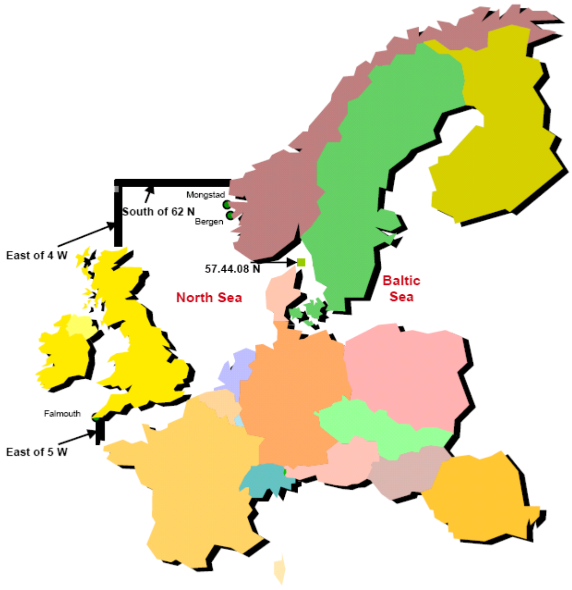

Figure 3: SECA areas today.

Another hot topic today is the question about new SECA areas. IMO have a global target of 0,5 % sulphur in marine fuels by 2020. On this way there will definitely come several local restrictions. There are discussions about a Mediterranean-, North America- and South East Asia SECA.

Date	Area	Sulphur [% by mass]	Regulation
May 2006	Baltic SECA	1,5	IMO
August 2007	North Sea + English Channel SECA	1,5	EU
January 2010	All EU Ports	0,1	EU
July 2010	All SECA	1,0	IMO
January 2012	Globally	3,5	IMO
January 2015	All SECA	0,1	IMO
January 2020	Globally	0,5	IMO

Table 1 Sulphur emission control calendar [5].

A serious market player (charterer) should have focus on reducing its emissions and choose a shipper that can provide tonnage with emission abatement technology. At the same time, shipper will attract customers with strong financial capabilities that are able to pay for this extra benefit (oil majors). When ship owners are presenting their vessels for a special trade to a charterer, their environmental profile and performance can be taken into consideration. Today's financial crisis has made a delay in this demand, this will be requested in the future and will be done as a strategic decision for charterers.

1.1 Structure of thesis

The structure of this thesis is shown in figure 4 below. Initially it is necessary to deeply study EU Directive 2005/33/EC. It turns out that a new type of fuel is introduced, with new properties and characteristics. Next step is to find out how the new properties affecting existing machinery and potential problems. In the final part, preventive measures for operators are suggested. This thesis also discusses how EU Directive 2005/33/EC is implemented and lessons learned from this process.

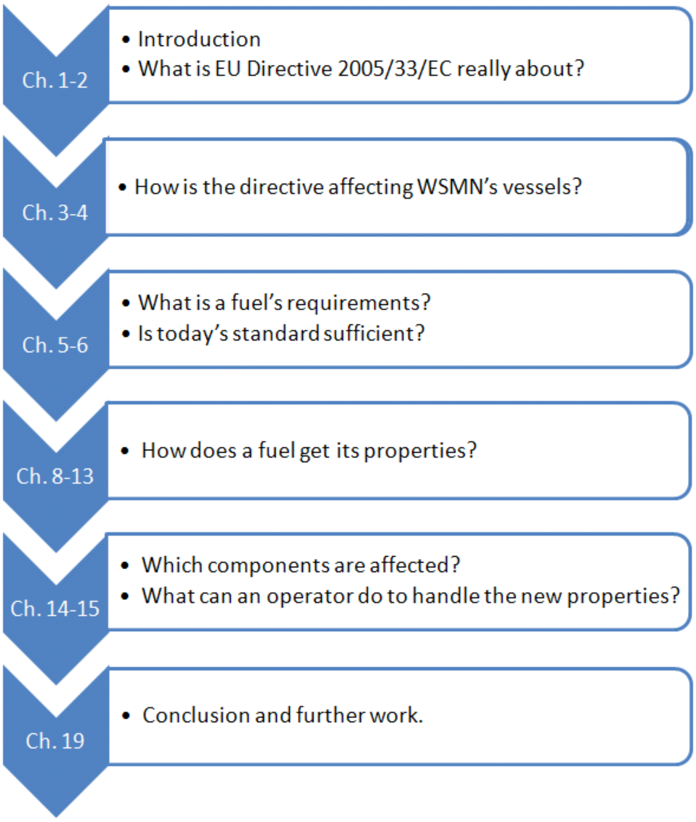

Figure 4: Structure of thesis.

From a technical part of view, EU Directive 2005/33/EC is mainly concerning marine diesel engines and boilers. This thesis is mainly focused on marine diesel engines.

2 Summary of EU Directive 2005/33/EC

IMO is through MARPOL (Annex VI) controlling air pollution from ships. In many years it has been a consensus in the maritime industry that IMO controls emission from international shipping. In addition to IMO rules, each nation can make rules applicable for their national waters. Now, for the first time – EU has given stricter regulations and goes ahead of IMO and issued EU Directive 2005/33/EC.

All EU member states shall comply with Directive 2005/33/EC (amending Directive 1999/32/EC) [6]. The directive also includes EEA countries, Norway and Iceland will therefore be included [7]. From January 1th, 2010, a dramatic point (article 4b) in the directive came into force. In short terms, it means that all ships in an EU port shall not use fuel with sulphur content above 0,1 % by mass. It is also stated in the directive that member states shall not sell MGO exceeding 0,1 % sulphur after January 1th, 2010. The directive requires that the fuel change-over operation shall be carried out as soon as possible after arrival and late as possible prior to sailing.

Vessels may avoid complying with article 4b if the vessel fulfils one of the below listed points:

- Will stay in port for less than two hours.
- Turns off all engines (and use shore power).
- Achieves emission reduction which is at least equivalent as using fuel containing 0,1 % sulphur.

The first point is impossible for bulk carriers and tankers; they will stay in port for normally 1 to 3 days. The second point is not either possible, power needed for discharging cargo is more than it can receive from shore power. Vessels don’t have electricity system designed for receiving large amounts of shore power. Discharging of a tanker is done by steam and the boilers are not driven by electricity.

The last point is a “open” possibility, it does not state which kind of technology or how the vessel shall achieve these low emissions (equivalent to emissions from burning 0,1 % sulphur fuel). The only possible solution is to use scrubbers[1] and then a scrubber that can clean the exhaust gas down to 0,1 % sulphur content. The scrubber has to be approved by class and its performance must be proven. The whole idea is to burn HFO and then avoiding more expensive MGO. The price difference between HFO and MGO is around USD 170 per MT. It is necessary to emphasize that scrubbers are complex and under development. **Hence, the easiest way to reduce the sulphur emission is therefore to use fuel with less sulphur content.**

Prior enforcement date for the directive, it was several rumours in the market, indicating that the directive’s enforcement date will be postponed. Ship owners were not ready to burn 0,1 % sulphur fuels since necessary modifications to equipment were not executed. The experience of using MGO is limited and safety aspects were not proper assessed. These arguments were also supported by class societies.

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[1] A short explanation of a scrubber is given by Wartsila here: http://www.wartsila.com/Wartsila/global/docs/en/about_us/in_detail/2_2007/SOx-scrubbing-marine-exhaust-gases.pdf

December 21th, 2009, ten days prior enforcement date, there came a legal note from the EU Parliament [8]. It was not a postponement of the directive but a recommendation to EU member countries. The most important points in the recommendation are:

Member States may consider the existence of an approved retrofit plan when assessing the degree of penalties to be applied to non-complying ships.

…for these ships that have not undergone the technical modifications, completion of the whole process should not take more than eight months.

The recommendation was understood in the maritime industry as a postponement of the enforcement date for eight months. A “retrofit plan” means a statement from manufacturer that necessary parts are ordered. This is only a **recommendation** to EU member states; it is up to EU member states how to enforce the directive.

It turns out that each EU member state made their own local enforcement, some more strict than other. March 11th, 2010 Port of Trieste in Italy was first out with heavy fines for non-compliance vessels. Fines for non-compliant vessels were €15.000 to €150.000. Repeat offenders would be banned from entering all ports in Italy [9].

Today, June 2010 there is different practices on each EU member states. Ship owners are forced to do necessary modifications and comply EU Directive 2005/33/EC. Experiences from burning 0,1 % sulphur fuel is limited and are now being collected.

3 Fuel qualities

With one new fuel quality there are several new answers that needs to be answered and challenges to be assessed.

When vessels are built, they are built for its trade with the current regulations. EU Directive 2005/33/EC came in 2005 (July 6th), it should be rational to think that vessels built after this date is prepared for known, coming requirements. This is not the case, this directive has only been on ship owners mind the last year. This directive dictating vessels to use fuels with a maximum sulphur content of 0,1 % while berthing in EU. Which kind of fuel vessels shall burn is not stated.

Vessels built in the period up to the start of 2010 were designed for HFO use as the main fuel and some MDO in addition. It turns out that either HFO or MDO were available with a sulphur content of 0,1 % and a “new” fuel quality were needed. A natural question is how MGO will be used, will MDO be exchanged with MGO completely, or partly. It will in this first part be examined how this can be done.

3.1 Assessment of needed fuel qualities

Different vessels have different fuel oil tank capacity. For tanker and bulkers, fuel oil tanks are limited. They carry cargo with a high specific gravity and the cargo therefore has to be stored with a low centre of gravity position (under the water line) due to the vessel’s stability. For a container and roro-vessel, the cargo has a low specific gravity and can therefore be loaded higher up in the vessel. This releases more capacity for fuel oil tanks and it is more flexible in fuel oil tank configurations.

The main question here is to find out which kind of fuel is needed to carry. This thesis is limited to tankers managed by WSMN. Today they are carrying HFO and MDO. Because of new regulation as described in chapter 2 they shall now also carry a new type of fuels with a maximum sulphur content of 0,1 %.

Figure 5: The different loading configurations due to the cargo and its specific gravity.

Normal configuration on tankers and bulkers is that 85-95 % of the fuel oil tanks are designated for HFO and the rest for MDO. All HFO tanks are normally in connection to each other since they are heated.

Marine fuels are regulated through ISO 8217[10]. Several of the fuels listed, are not common and seldom sold. This standard is now under renewal and the new version it is expected to be released in June/July 2010. Changes in the standard are discussed in chapter 6.3.

In the literature, marine fuels have many different names. We will start to clarify what their real name is and its characteristics. Marine fuels are classified from its viscosity and density, it can be found in many sulphur content variations. Normal used fuels are presented in table 2.

Fuel quality (common used names)	**Fuel quality, (ISO 8217)**	**Price (22.02.2010) [US$/MT]**	**Viscosity at 50°C [cSt]**	**Viscosity at 40°C [cSt]**
Heavy Fuel Oil (**HFO**)	RMG 380	455	MAX 380	
Heavy Fuel Oil (**HFO**)	RME 180	469	MAX 180	
Marine Diesel Oil (**MDO**)	DMB	614		MAX 11-14
Marine Gas Oil (**MGO**)	DMA	644		1,5-6,0

Table 2: Normally used marine fuels.

In table 2 there is listed the most common types of marine fuel, all of them available world wide. HFO is the most common due to its price. These prices is for “normal” fuels, when ordering low sulphur fuels there are a mark-up of USD 20 to USD 70 [11]. The most significant difference (except from price and viscosity) is that HFO are residual fuel and MDO and MGO are distillates. This is from the refinery process, crude oil is heated and different components will evaporate at different temperatures. MGO is the lightest one and will evaporate first. After MGO, MDO will evaporate. They are therefore both distillates. HFO will not evaporate until we reach very high temperatures, HFO are therefore called residual.

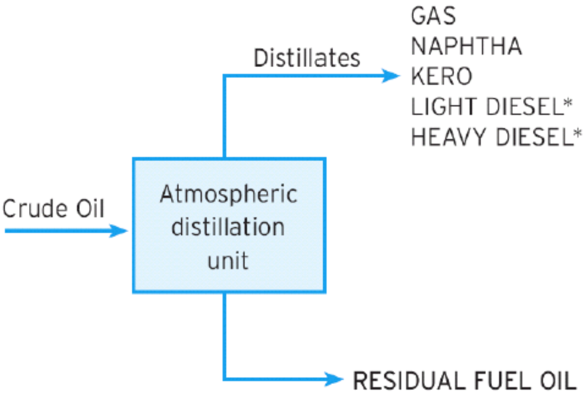

Figure 6: The refinery process (simplified).

Manufacturers of engines and boilers recommend a fuel viscosity interval of 2-20 cSt. Residual fuel needs therefore to be heated to reach this viscosity. 380 cSt HFO needs to be heated to a temperature interval of 120-150 °C. The reason why there is residual fuel available in 180 cSt and 380 cSt is because not all vessels have the heating capacity needed for 380 cSt fuel and have to use 180 cSt. 180 cSt fuel is a bit more expensive relative to 380 cSt fuel, and typical used on old or small vessels.

The sulphur content is listed but there are several versions of the fuels listed. E.g. HFO are also sold as low sulphur HFO for use in SECA areas, 1,5 % sulphur content. Sulphur content is also the reason for MGO is presented as fuel for marine engines and boilers due to its low sulphur content. **MGO are the only fuel available that fulfil the criteria of 0,1 % sulphur content by mass.** Later in this chapter there is explained one exemption.

MGO is new for the industry since it has not earlier been used as a commercial marine fuel at large scale. The short answer is that there were none regulations or requirement to use it. It is also the most expensive of marine fuels.

From ISO 8217 there are only one type of MGO, DMA. In real life there are 4 types of MGO, all of them with different characteristics. This will be more explained in chapter 10.

	HFO / RMG 380	**MGO / DMA**
Boiling Point [C^{o}]	150 – 600	170 – 390
Flash Point [C^{o}]	> 60	> 60
Auto ignition temperature [C^{o}]	> 230	> 230
Density [kg/m^{3}]	< 991	< 890
Viscosity [cSt]	< 380	1,5 – 6,0

Figure 7: Main differences of HFO and MGO[10].

For most vessels trading mainly the in EU / SECA, MDO will be eliminated. There is normally only tank capacity for two fuels; this will be HFO (1,5 % sulphur content) and MGO (0,1 % sulphur content). HFO to be used for normal steaming in international waters, and MGO in ports. Such a solution will result in scepticism from ship owners. Running ME on MGO is new for the industry and experiences are few.

Before doing overhauls or longer period with stand still it is normal to clean the engine by running a short period on MDO. MDO and MGO are very close, only significant difference is the viscosity. According to MAN B&W's recommendation prior layup/standstill of vessels it is sufficient to run ME on full load for one hour, two hours if the load is 75 % [12]. With a viscosity above 3 cSt (MGO's viscosity has been stable on 3 cSt in 2009) there should not be any problems if it is relevant running for a short period as described above.

One solution if MDO shall not be eliminated is to split existing tanks. Such steel work has to be done at a yard which may result in off-hire for the vessel. It is also an expensive solution.

If the vessel has several MDO tanks, one tank can be dedicated for MGO. The vessel will then be carrying three fuel types; HFO, MDO and MGO. This solution may also result in yard stay due hot work (new pipes, valves etc.) and the complexity of three fuel types versus two is huge. Routines for switching between these three fuels shall be established and the engineers onboard shall keep them separately at all times. The price difference between MDO and MGO is around 30 USD/MT and does not justify the complications involved.

There are some fuel qualities fulfilling 0,1 % sulphur and in the same time has the same properties as HFO. Shell WRD (Wide Range Diesel) is strictly a heating oil but its properties are good in respect of its low sulphur content. Today the fuel is available in small quantities in Norway (e.g. Mongstad) and Sweden. Because of the limited availability, ship owners cannot rely on this fuel and have to modify for use of DMA. More information about Shell WRD is found in a Project Thesis written prior this M.Sc. Thesis by undersigned [13].

4 Trading patterns

Tankers that WSMN got technical management of are on long TC to Shell and TOTAL. This means that charterer (Shell and TOTAL) are giving instructions on the vessels trading pattern. New regulations means in most cases unforeseen expenses. Further the question is raised: who is going to pay for what? When the SECA areas were introduced in 2005 there came a clarification on this point[14]. It states: "…the vessel shall be able to consume fuels of the required sulphur content". The same legal statement is applicable for EU Directive 2005/33/EC. Such statement leaves all doubt; owner shall ensure that the vessel can use MGO.

EU Directive 2005/33/EC is only applicable in EU ports while WSMN's vessels are sailing wherever charterer decide. To find out how often and when the respectively fuels are needed, it is necessary to identify the vessels' trading patterns. This is found out in co-operation with representatives from WSMN[15-16].

The thesis will be simplified to only dealing with four vessels. The two sister vessels MT "Kronviken" and MT "Solviken" (Aframaxes) and the other two sister vessels MT "Erviken" and MT "Storviken" (Suezmaxes).

4.1 MT "Kronviken" and MT "Solviken" (Aframaxes)

Figure 8: Aframaxes MT "Kronviken" and MT "Solviken" [17].

The Aframaxes are only trading in the SECA areas. The main reason is because they are built to ice class standard. Ice classed vessels have special building requirements. There are rules related to engine output, hull structural design, gears, propeller, shafts, rudder and steering arrangements. All of the listed areas are made extra strong and robust. Ice classed vessels are more expensive to build but will give more trading flexibility and higher rates.

Figure 9: Vessel sailing in heavy ice.

MT “Kronviken” and MT “Solviken” have both the classification notation “ICE-1A”. They shall therefore manage to sail at minimum 5 knots when the ice is 1,0 meter thick [18].

These rules are regulated by costal states’ rules. In the in the Finnish gulf, Swedish Maritime Administration made a “Finnish-Swedish Ice-Class Designations” (from 2003). The rules are:

Ice Class	For navigation in	Metres ice thickness
IA Super	extremely difficult ice-conditions	> 1,0 m
IA	difficult ice-conditions	0,5-1,0 m
IB	moderately difficult ice-conditions	0,3-0,5 m
IC	easy ice-conditions	0,15-0,3 m
II	very easy ice-conditions	0,1-0,15 m[2]

Table 3: Finnish-Swedish Ice-Class Designations[19].

Both vessels are annually sailing 280 days and the rest at berth. LSHFO are used for ME and AUXs at steaming while MGO has to be used at berth. While steaming consumption are 55 tonnes HFO per day, at berth they are using 30 tonnes HFO per load/discharge. For them the case is pretty obvious. They should only carry HFO with low sulphur (1,5 %) content for steaming, and MGO in ports.

4.2 MT “Erviken” and MT “Storviken” (Suezmaxes)

The Suezmaxes are bigger and have different trading patterns. They are transporting crude oil for long distances. Their trading patterns can be seen as a triangle pattern and is shown in figure 10.

For the Suezmaxes the normal trading patterns are:

- From West-Africa to Europe
- From Europe to U.S. Atlantic Coast.

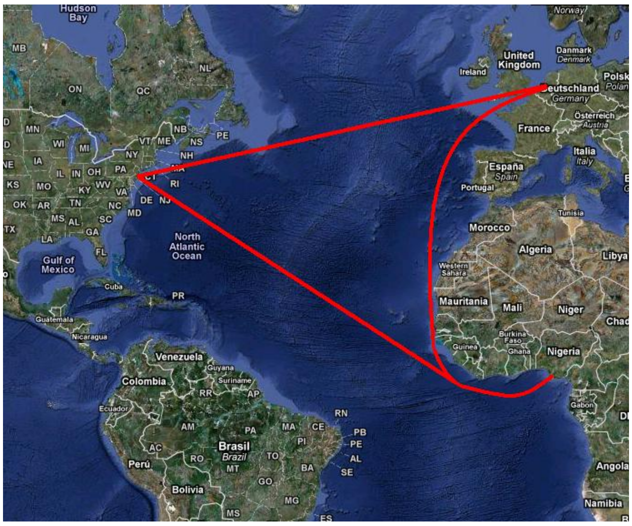

Figure 10: The suezmaxes' triangular trading pattern.

In Europe the most visited port is Rotterdam. In Rotterdam cargoes are gathered from many small shipments and further transported in large vessels for long distances such as United States (normally Philadelphia). In West-Africa loading are done in offshore loading terminals outside of Nigeria and Angola. MT “Erviken” and MT “Storviken” are calling 2-3 ports per month while these ports are in EU every second month. Either Philadelphia, Nigeria or Angola got any emission regulations.

HFO are used for ME and AUXs at steaming while MGO has to be used at berth. While steaming, consumption is 75 tonnes HFO per day, at berth they are using 40 tonnes HFO per load/discharge.

The Aframaxes has to carry two types of fuel HFO (1,5 % sulphur content) and MGO (0,1 % sulphur content). This gives no problems with the tank capacity since they will use MGO in the MDO tanks and LSHFO in the HFO tanks.

The suezmaxes will use HFO (4,5 % sulphur content) for steaming, while in EU ports they have to use MGO. MDO will not be used since this is not any requirement.

For both vessel types there are separately MDO/MGO and HFO service tanks, this means that the two types of fuels will not be blended as the trading pattern is today. The vessels are on long TC and it cannot be neglected that the charterer will change the trading patterns. Risk of unforeseen expenses, from legislations as EU Directive 2005/33/EC and others, during a (long) time charter, rests on the ship owner.

In this thesis there will also be discussed the occurrence in mixing HFO and MGO. This will be a topic sooner or later, mixing either by an accident or by purpose.

5 Fuel requirements

World wide there is sold over 200 millions tonnes of marine fuel annually. These fuel deliveries are sold in accordance to the ISO 8217 standard. There is taken samples from fuel received onboard. These are further sent to a laboratory for analyses. To get a sample analysed by a recognized fuel oil analyse company as DNV PS or FOBAS costs around USD 500, including freight costs.

I will in this chapter go through the standard and which parameters that are checked in a fuel analysis. There are also some additional specification that should been taken in; *fuels that are within the standard are sometimes unfit for purpose*.

5.1 Density

Density is measured to correct weight and quantity of fuel that has been delivered. One of the aspects is to have a density that differs from water. Water and other particles shall be removed in the separator. The separator separates liquids/particles from the oil, based on their density differences. If the density changes from "normal" it should be taken into considerations to change the gravity disks in the separator. HFO (RMG380) got a maximum density limit of 991 kg/m^3 and fuels received are very close to this limit. DMA got a density limit of 890 kg/m^3, MGO fuels received to WSMN's vessels are in the area 830-860 kg/m^3 and is presented in Appendix A.

A fuel pump is only delivering a specific volume, this concludes to 10 %[3] reduced energy to the engine per engine stroke/revolution if the fuel is exactly to its density limit. To deliver the same power output with a reduced density, an increased fuel rack position is necessary. Fuel sample from MV "Utviken" shows MGO density down to 834 kg/m^3. For a vessel operating on HFO with density close to its limit and switching to MGO with a density of 834 kg/m^3 results in a decreased fuel input of 16 %. According to WSMN[16], no changes are observed, everything operated and working as normal. Bunkering receipt and analysis results for MV "Utviken" are presented in Appendix A.

Odfjell have the same situation on their vessels, machineries are working as it should. Experiences from engineers onboard telling that the leakage from injection pumps is a bit higher, but working properly [20].

Lower heating value or net calorific value is a value of the energy/heat released from a medium under a complete combustion. This is when all hydrocarbons are converted to CO_2 and H_2O. To determine this value we need a bomb calorimeter and it is not a test that can be done in full scale to all fuels received in a laboratory. Therefore it is not a criterion for fulfilling ISO 8217 but it tells us the energy in a fuel. For HFO and MDO this is in the area 42,7[21] MJ/kg. For light diesel (diesel used for trucks) the lower heating value is a bit higher, around 43,2 MJ/kg. Exact lower heating value for DMA with 0,1 % sulphur content were not found. It is reason to believe that it is a bit higher than HFO and MDO, but below or close to light diesel/truck diesel.

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[3] $\frac{(991-890)\bullet 100\%}{991}=10\%$

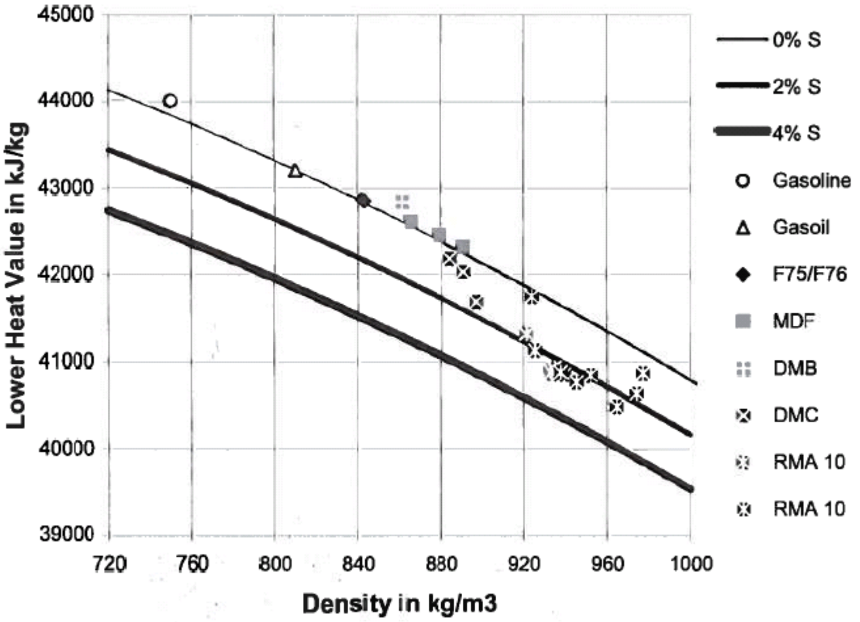

Figure 11: Relationship between density and lower heating value[22].

The difference in lower heating value from HFO or MDO to MGO is around 1 % and the difference in density is in the area 10 – 16 % [4]. There is therefore a clear reduction in the amount of energy when using MGO fuels and it is not compensated by increased lower heating value. An increased fuel rack is needed and the fuel pumps have to deliver a higher amount of fuel so that the engine can deliver the same engine output. There is no reason to believe the expressed opinion from either WSMN or Odfjell, a so huge reduction in density *will* require a higher fuel flow and increased fuel rack. There may be communication problems or misunderstandings.

None of engine builders have mentioned this air/fuel change. Boiler manufacturers are the only one dealing with this topic. When they are doing necessary modifications making their boiler capable using MGO, they are adjusting air/fuel ratio. It should be emphasized that air/fuel ratio is easier to change for a boiler than for a diesel engine. To change air/fuel ratio on a diesel engine include changing of turbo/turbocharger etc.

5.2 Viscosity

This is the oils most important characteristics. Viscosity will affect the flow and also the strength and thickness of the oil film on surfaces; these are important characteristics for lubrication oils but also on fuel oils. Poor oil thickness can give metal-metal contact and will cause wear. Low viscosity fluid in an injection pump can give direct contact with the plunger and the cylinder, further, the injection pump can seizure. The same critical occurrence can happen when we got temperature fluctuations, generates uncontrolled thermal expansion of plunger/barrel (changeover from hot HFO – cold MGO fuel, and vice versa).

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[4] $\frac{(991-890)\bullet 100\%}{991}=10\%$ $\frac{(991-834)\bullet 100\%}{991}=16\%$

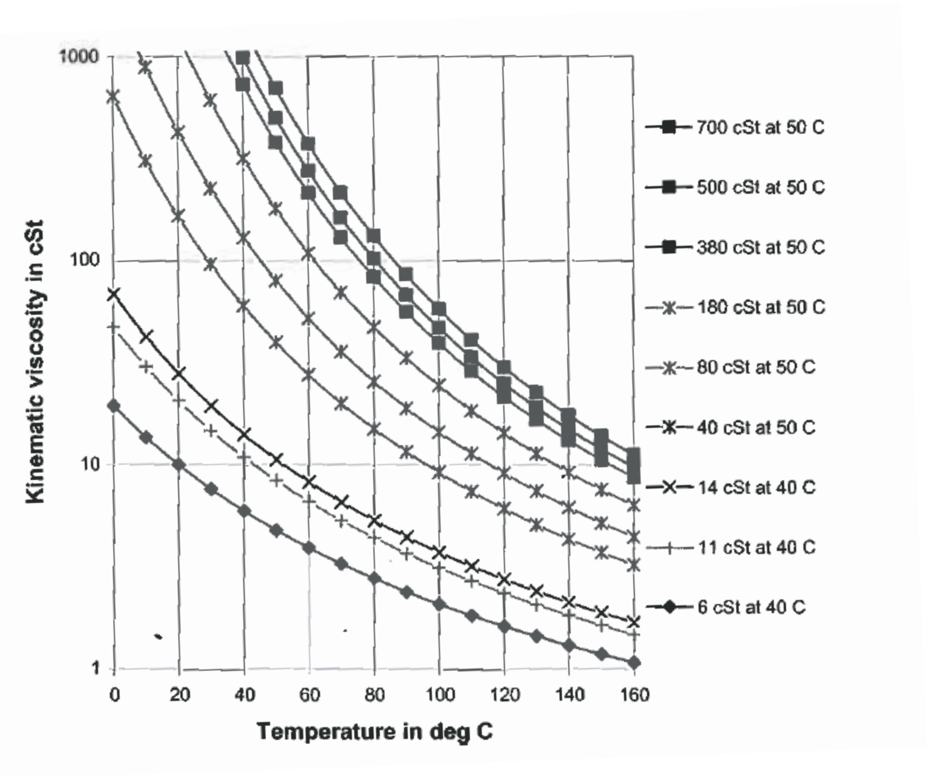


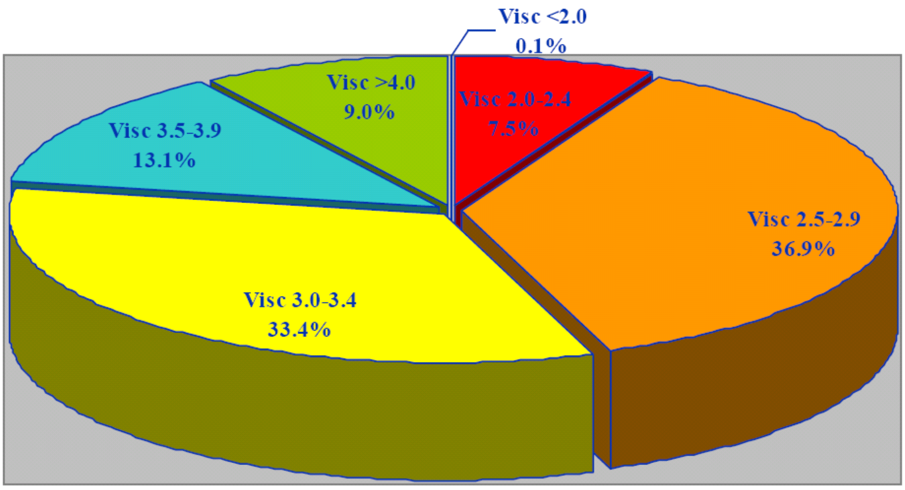
Figure 12: Viscosity - temperature diagram. [22]

For distillate fuels, viscosity is measured with both a maximum and minimum limit at 40 ^{0}C. DMA got a viscosity interval of 1,5 – 6,0 cSt. For residual fuel there is only a maximum limit, low viscosity residual fuel are unprofitable for the fuel producer. 50 ^{0}C are the measuring temperature for residual fuels. From known viscosity, engineers onboard know how much they have to heat up the fuel (residual fuel) before use. Normally the viscosity are close the maximum limit, some times a bit higher.

For piston- and screw pumps, the pumpable fluid is the lubricator. It prevents metal-to-metal contact and works as a sealing. Lower viscosity increases the risk of increased wear and tear. In worst cases, breakdown can occur. Fuels made for automotive use have a lubricity criterion. The same does not apply for marine fuels. There is little experience in use of low viscosity fuels for marine engines. Lubricity can be expressed in *Summerfeld number*, also called *bearing characteristics number[23]*. This is only applicable for journal bearings (not piston pumps). Changes in Summerfeld number are proportional to changes in the viscosity.

For distillate fuels the viscosity shall also have a lower limit, if the viscosity is too low, it can be problems with pumps and injectors. This will result in reduced fuel oil pressure, in many cases this can be “solved” with giving some more load (increased fuel rack). The potential consequences related to reduced fuel oil pressure are very serious. If fuel injector pumps don’t deliver its maximum pressure the engine will not deliver max output, in extreme cases it can be difficulties to start up the engines. Worst case scenario is engine stop and blackout onboard.

The same critical occurrence can happen when we got temperature fluctuations (changeover from hot HFO to cold MGO fuel, and vice versa). Injection pump may stop due to sticking piston. This is more described in chapter 7.



Viscosity at 40˚C (mm²/s)

Figure 13: Statistics on viscosity levels of MGO fuels delivered January to November 2009[24].

Ship owners are afraid to get distillates with a very low viscosity, this because of the lower viscosity limit of 1,5 cSt from ISO 8217. Most injection pumps for diesel engines and boilers have a lower viscosity limit of 2 cSt. If the viscosity is below this limit, ship owners cannot be sure that proper fuel pressure and quantity are delivered to its consumers. Statistics shows that as good as all fuels delivered in 2009 had a viscosity levels above 2 cSt.

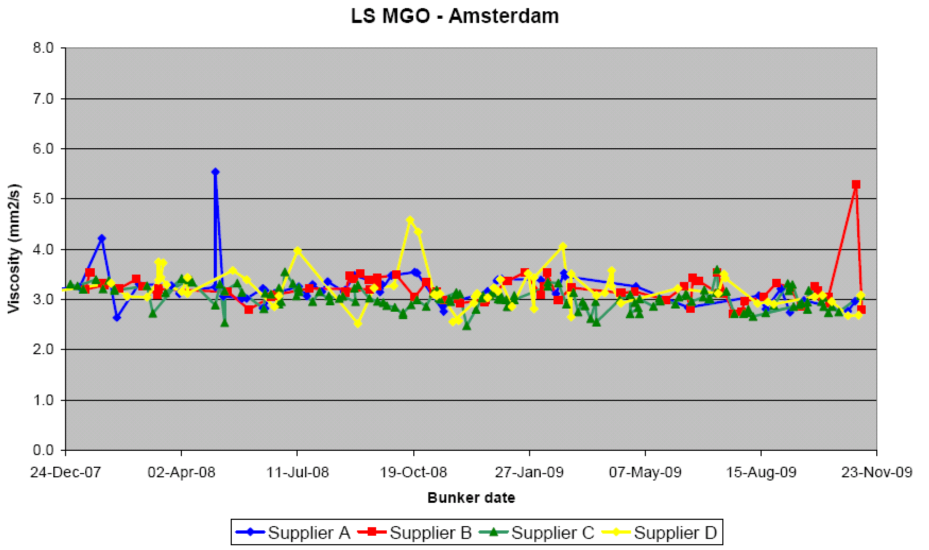


Figure 14: The trend on viscosity for MGO delivered 2008-2009 [24].

MGO’s viscosity for 2008-2009 was stable on 3 cSt. Figure 14 shows four different suppliers in Amsterdam, the trend is the same for ports in America, Australia and Asia [25]. When demand for low sulphur fuels and DMA rises, there is a concern in the industry that refineries will “blend” out DMA with truck-diesel (which got viscosity of 1 – 2 cSt). So far, this is not observed.

As a rule of thumb, the condition of the fuel oil system and its components (especially injection pumps) are critical. The better the condition is, its ability to deal with low viscosity fuels is better.

5.3 Micro carbon residue

The fuel is burned within a test where mass are measured before and after burning to determine the percentage of mass remaining. Remaining mass is determined as residue carbon. A high carbon residue can involve deposit formation under high temperatures (combustion). Under combustion, high carbon residue fuels can be difficult to burn completely and will be remaining as deposit formation on exhaust valves and exhaust spaces. Micro carbon residue limit for distillates are 0,30 % and for residual fuels around 20 % (mass percent). When micro carbon residue is measured for distillates, it is a check for contaminations of residual fuel. This is seldom a problem today.

5.4 Water

Water can come from many sources, mainly it comes from water in the oil initially, and from condensation in the fuel oil tank. Water content is often stated on the bunker receipt from supplier and is also stated in the fuel analysis results. Normally these numbers are pretty close. You are only paying for fuel and not the water.

Most of the water will be taken out in the settling tank and also in the separator. This volume, will not pass the OWS (Oily Water Separator) and have to be treated as sludge. Disposal price for sludge is 2-3 times the price of HFO.

The fuel injection pump works “pump vise” and will make pressure reduction in the fuel system (on its upward stroke). When the pressure drops we can get cavitations/steam in the fuel system and further the injection pump will not work properly. This will be more described in chapter 7. Presence of water will also reduce the fuels specific energy, fuels with water will burn less efficiently. Water will vaporize and harm injection equipment and cause corrosion to exhaust valves, turbocharger and exhaust spaces. If water is well emulsified in the oil it can be hard to remove. This will make the effective energy content of the fuel decrease and fuel consumption will rise.

5.5 Sulphur

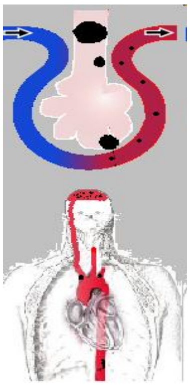


Figure 15: PM is being taken up in the lungs.

Sulphur regulation world wide is 4,5 % for marine fuels. Sulphur is regulated for environmental reasons. The essence in EU Regulation 2005/33/EC is use of 0,1 % sulphur containing oil. Because there are several local sulphur regulations all over the world, as a result, sulphur will be removed from the new ISO 8217. Sulphur content shall be up to prevailing local regulations to decide e.g. North Sea SECA, Baltic SECA CARB etc.

One of the main reasons for the huge attention for ship pollutions is the health damage. Through some “conversions” we can say that smokestack pollution from shipping kills people and cause the society a huge amount of money.
In the technical paper “Air pollution from ships“ there is claimed: *“Smokestack emissions from international shipping kills approximately 60,000 people a year, including 27,000 in Europe, at an annual cost to society of more than 200 billion euro”.* The paper is published jointly by several highly reputable organisations such as European Environmental Bureau (EEB)[2]. If the society believes in the numbers or not doesn’t really matter, there is a fact that smokestack pollution has consequences for the society. To eliminate these problems is not possible, but a noticeable

reduction can be done with relative small and easy technical modifications. A stricter regulation regime to the shipping industry will come sooner or later as the reduction potential is huge.

PM stands for Particulate Matter and is the same as particle pollution. Fine particles (mainly from unburned fuel and lubrication oil but also from NO_x and SO_x) are mixed in the atmosphere. These particles are also known as aerosols. The particles are further taken up in the lungs and gets in your blood. These particles can lead to asthma, lung cancer, cardiovascular issues and premature death. There is still ongoing research on the topic, it may be that there are other particles that contributes more dominantely than SO_x in the formation of aerosols [26].

Aerosols plays an active role in the production of clouds, as small particles that water can stick to and further becomes clouds. Clouds reflects sunlight and counteract the greenhouse effect. It is a public understanding that the health issue goes in front of the greenhouse effect.

Anyway, EU has a clear opinion, their statement in EU Directive 2005/33/EC leaves all doubt behind:

"…aims to achieve levels of air quality that do not give rise to unacceptable impacts on, and risks to, human health and the environment."

Sulphur emissions are proportional to the sulphur content in the fuel, assumed that there is no exhaust gas cleaning equipment installed onboard. After combustion, SO_x and NO_x combines with water droplets in the atmosphere. We get this back as acid rain and it ends up in the ocean. Some ecosystems have enough buffering capacity to handle this change in the acid concentration. In many ecosystems where there is not enough buffering capacity, a small change in the pH will harm fishes and plants significantly.

NO_x also increases the ground-level ozone. This will damage vegetation, human health and contributes to global warming.

There are several ways to regulate the sulphur content for marine use:
- Regulate the refineries: Dictate them to produce or sell marine fuel with given sulphur content.
- Regulate emissions: Dictate vessels to discharge exhaust gas with given sulphur content.
- Regulate fuels burned: Dictate vessels to burn a specific fuel.

EU Regulation 2005/33/EC is a combination of these three points and is summarized below:
- MGO sold in EU after January 1th, 2010, shall have a sulphur content of maximum 0,1 %.
- Vessels shall not burn any fuel with a sulphur content above 0,1 % by mass, it is not stated in the directive which kind of fuel vessels shall burn.
- The directive can be avoided if the vessel got any technology that makes them pollute similar to a vessel that burns 0,1 % sulphur fuel. The only possible solution is then to wash any "dirty" fuel with a scrubber. Scrubber technology/solutions are still in the development phase and there are not any standard products available.

This is the reason for using MGO (lighter fuels), residual fuels are not available in such a low sulphur content as dictated in EU Directive 2005/33/EC (0,1 % sulphur). Sulphur content alone doesn't harm the engine noticeable, but when fuels are going through a desulphurizing process we get problems. This process will reduce the fuel's lubricity. This is more described in section 10.4.1.

5.6 Sediments

Fuels can be stored for a long time and can be contaminated by dirt, rust and other inorganic matter. The fuel's sediment content is a measurement of how "clean" the fuel is. Fuels are not tested on their compatibility for each other but for the cleanliness for one fuel sample alone. This test is different for distillates and residual fuel. Total Sediment Potential (TSP) is measured for residual fuels[27]. The fuel is heated to 100 ^{0}C for 24 hours and then filtrated. Sediments remaining in the filter are then measured. It simulates storage and handling properties of a fuel.

For distillate fuels, Total Sediment Existent (TSE) is measured[27]. The test procedures are almost the same, but it is not necessary to heat it for a long time. A sample are heated up to 100 ^{0}C and filtrated as for residual fuel.

For both residual fuel and distillates, sediments is seldom a problem and it not always taken in a fuel sample analysis.

When we are talking about incompatibility problems between fuels, sediments will fall out of the fuel mixture as asphaltenes. A sediment test is not telling anything about their compatibility for each other but sediments that can fall out if the fuel bursts.

5.7 Ash, Vanadium and Sodium

Ash can have different constituent parts like vanadium, nickel, sodium, aluminium and silicon. During the combustion, vanadium and sodium will react and oxide to sodium vanadyl vandates [28]. At high temperature these species can make deposits in the exhaust gas system (exhaust gas valves, turbo charger etc.). These deposit formations can result in inefficient operation of valves since they will not close properly. Deposit formation will likely stick on turbine blades and nozzle ring, both will result in decreased turbo charger efficiency. This will also influence the scavenging, less air flows through the engine and its thermal load will increase. Limit for the species responsible for deposit formation are for HFO 0,15 % and MGO 0,01 % (mass percent).

5.8 Aluminium + Silicon

Aluminium and silicon correlates to aluminium- and silicon oxides from the refinery process. This is to check the fuel for remaining catalysts. Such particles are very hard and have an abrasive effect. Engine components can wear out in short time. The maximum limit from ISO 8217 is 80 mg/kg for residual fuel. Some of these amounts will be removed in the centrifugal separators. There is no limit for distillates, this because these remaining catalysts will remain in the "bottom" of the refinery process, it will remain together with residual fuel and not with distillates. This is more described in chapter 10.4.2.

5.9 Flash point

Flash point is related to safety and not combustion/ignition properties of the fuel. This limit is regulated through SOLAS and IMO. Flash point is the temperature that the oil will vaporize and *can* make an ignitable mixture with air. For ignition to occur, an ignition source is needed. Flash point shall not be confused with autoignition temperature. Autoignition temperature is the temperature that makes the fuel to ignite by itself, any ignition source is not necessary.

Autoignition temperature for MGO is above 250 ^{o}C [29] for gas oils and even higher for residual fuels. If the flash point is below 60 ^{o}C for any fuel, the fuel shall not be used and a claim shall be sent to the fuel supplier. If fuel is received with a flash point below 60 ^{o}C, class society shall be contacted for advices. If the vessel decide to use the fuel, it will be suspended by class and its insurance will not be valid. DNV PS has reported that 7 % of the MGO/MDO fuels they tested from Rotterdam in the period January to September 2009 had a flash point below 60 ^{o}C. For Piraeus in the same period, the share was 2 %. When comparing viscosity and flash point there is a dramatic change when viscosity is below 3 cSt. This can be related to the refineries' utilization of the crude. A small change in flash point can make refineries to utilize more light products from the crude.

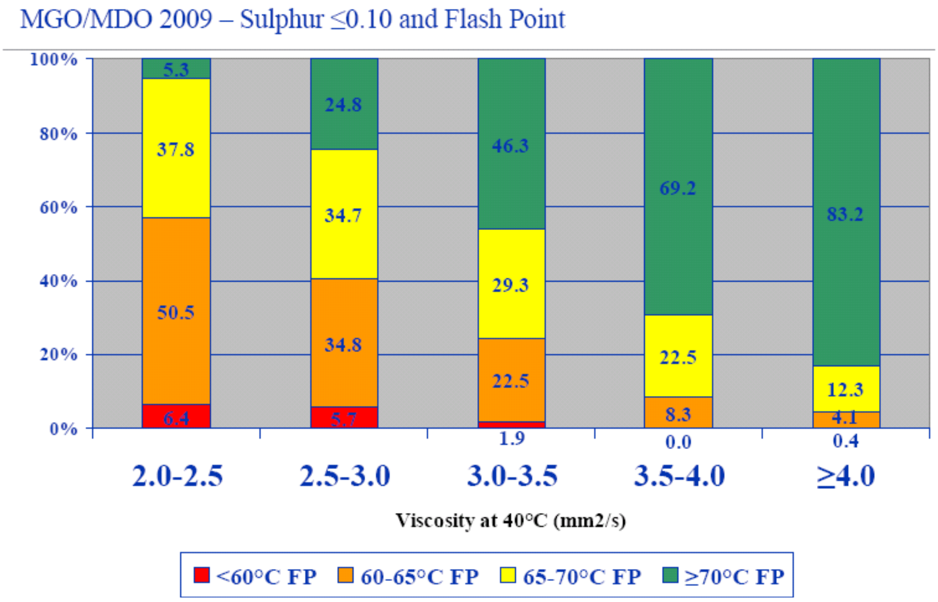


Figure 16: Statistics on flash point and viscosity [30].

5.10 Pour and cloud point

Pour point is the temperature when the oil is no longer pumpable, below this temperature the oil ceases to flow. For residual fuel the limit is 30 ^{o}C and 0 or -6 ^{o}C for distillates.

Cloud point is the temperature when it may break out wax crystals in the oil. The fuel is no longer completely soluble and its appearance is observed as a cloudy. These wax crystals thickens the oil and can block filters, injectors and starve the engine.

MT "Kronviken" and MT "Solviken" are as mentioned ice-classed and operates in cold environment (winter season). As long as the heating coils are used, this should not be a problem. The only area of concern is when the fuel is chilled/cooled in the fuel system. Too keep the viscosity for distillates above a certain limit there may be need to cool it down. At such situations where residual and distillate fuel are mixed in the pipe and further cooled, the temperature of the mixture can get below 30 ^{o}C which is the pour point for residual fuel. This is more described in chapter 14.3.

5.11 Calculated cetane index (CCI)

Cetane[5] number or cetane index is measured for marine distillates. Cetane is a molecule with good ignition properties. In comparison, we got octane numbers for gasoline. Their mission is to ensure the fuel will not self-ignite too easily and engine knocking can occur. Cetane number/index is almost opposite; it should be a figure of how easily the fuel/air mixture will self-ignite after injection.

This is a calculated value and based on a physical test. It is based on API gravity[6] and the mid-boiling point (50 % evaporated)[21]. Because it is only 50 % evaporated and its API gravity part, its reliability is vague. It only tells us how a fuel *ignites*, that there is presence of light fractions in the fuel. A fuel that will ignite does not necessary *burn* (in relation to combustion) well. To determine the actual cetane index it is necessary to burn the fuel in a test engine with variable compression ratios. This is too advanced and time-consuming to be done in a normal fuel sample analysis.

CCI is only a calculated number from a fuel sample, this is just an indicator and not a parameter that can be trusted fully. It only tells us that the density is reasonable and there is light fractions presents (when 50 % vaporized). It tells us nothing about the remaining 50 % for the sample. This can be heavier fractions that will ignite late and burn poorly, making the combustion to occur over a longer time. It is not taken for granted that the remaining 50 % will be burned completely, higher particle formation and deposit formation can be a result. I will summarize to say that cetane index is an "ok" indicator of ignition/combustion but nothing more.

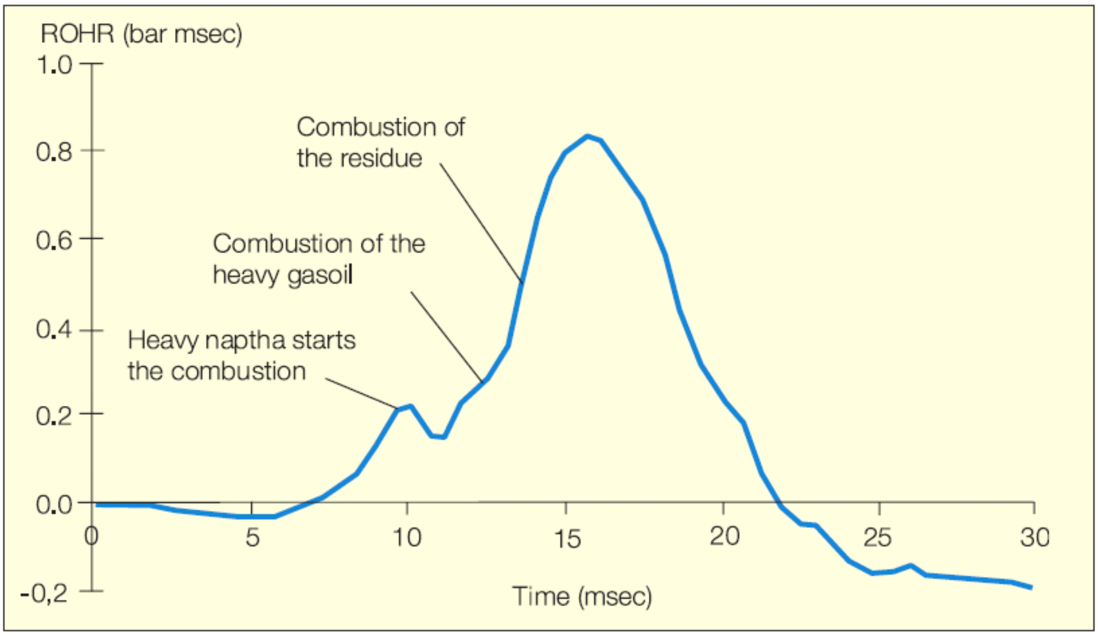


Figure 17: ROHR (Rate Of Heat Release) when the different fractions ignites[31].

On the test result for residual fuels there is a figure called CCAI (Calculated Carbon Aromaticity Index) or CII (Calculated Ignition Index). Both of them are calculated values. Each of them with a

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[5] Cetane (n-hexadecane, $C_{16}H_{34}$)

[6] API Gravity: is a measure of how heavy or light a petroleum liquid is compared to water. If its API gravity is greater than 10, it is lighter and floats on water; if less than 10, it is heavier and sinks

formula[32] consisting of density and viscosity. CCAI were introduced by Shell in the 1980s and their mission was to detect cycle oils. CCAI should give us information in the ignition performance of the fuel by testing the aromaticity of a liquid fuel. Ignition happens when the fuel is vaporized/atomized. The composition and properties for vapour, does not need to be the same as for liquid.

Today, refineries are so complex that this method cannot be used. On a fuel sample result, this is only a misleading indicator in the ignition quality of the fuel. The fuel sample result says nothing about the fuel's ignition or combustion properties. It is necessary to emphasize that CCAI and CII are not a part of ISO 8217 but it is normal to have on the fuel sample results and maintains a misunderstanding indicator for the operator. MAN also says that CCAI and CCI are not reliable.[31]

5.12 Appearance

A DMA grade MGO have an appearance requirement that is shall be clear and bright, whilst MDO do not have such a requirement and can to some extent be blended with HFO.

5.13 Zinc/phosphorus/calcium

Such particles are used as additives in lubrication oils to improve its properties. Used lubrication oils cannot be used to anything and in old days fuel suppliers dumped ULO (Used Lube Oil) in marine fuels.

If these particles are detected in a fuel sample analysis, it indicates that used (or new) lubrication oils have been added to the fuel. This is rarely a problem today.

6 Deficiencies in ISO 8217

Fuels tested at a laboratory at a analysis company, is tested to meet the standard ISO 8217. Even dough the fuel is determined as “met” the fuel does not necessary give the good combustion in an engine as desired. To know what each test parameter in ISO 8217 really tells us, is not straight forward. Some of the parameters are intuitive to understand, others more complicated. Increased demand for low sulphur fuel will require better understanding and knowledge on the topics in the ISO 8217 standard.

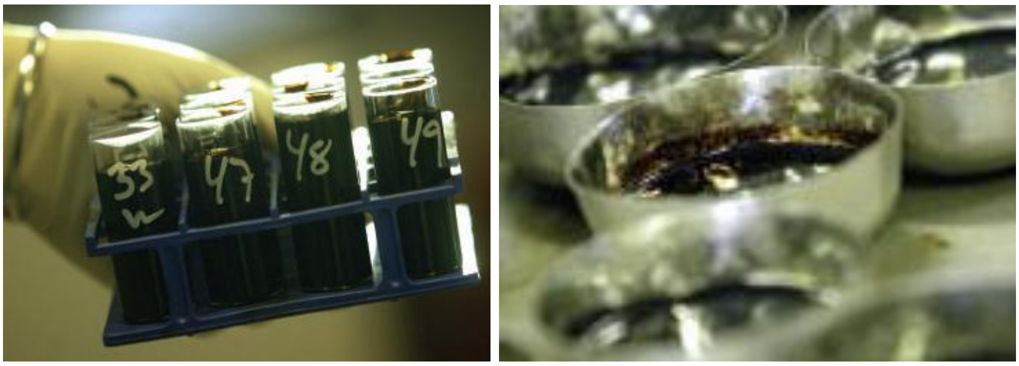


Figure 18: Fuel analyses.

Normal procedures when loading fuel, is to take a fuel sample (from the vessel’s manifold). This newly received fuel shall be stored in a separate tank. The fuel sample are further sent to a laboratory e.g. DNV Petroleum Services (DNV PS). DNV PS is the largest actor in the market for fuel testing; they got 70 percent of the market share. DNV PS will further analyze the fuel sample up against ISO 8217. Normally DNV PS will send the results within one day (normally) to the vessel and to the vessel’s manager. The test results are presented as “met”or “not met”. An example is presented in Appendix A.

Another fact that only 50-60 % of HFO and only 15-20 % of distillates are tested on a world basis is a frightening number. There are some clear points of improvements in ISO 8217, in the same time it is better than nothing. When machinery claims are taken to court fuel sample analysis is a vital evidence. When receiving fuels, its origin and composition are unknown. The jeopardizing of not analysing fuels, compared to the price of a sample and possible problems/accidents related to bad fuel is incomprehensible.

One other weakness in ISO 8217 is that several fuels can be similar e.g. a DMB with low density can be classified as a DMA (with clear and bright appearance) and with high density it can be classified as a DMC. DMB and DMC has none lower viscosity, they can easily be classified as a DMA if viscosity and density are low.

When fuel samples are determined as “not met” it is normal to give some short advises. E.g. if the content of deposit ash is too high it is advised to emphasize proper separator cleaning. If there is repeatedly occurrence of the same parameters there should also be some kind of system that monitor each vessel and previous fuel sample results. A corresponding system should also monitor each supplier to detect sub standard suppliers.

Marine fuel shall have five main properties:

- Appropriate fluidity (viscosity)
- Excellent combustibility
- Thermal and storage stability
- Stability when dissimilar oil is blended
- Lubricity

Fuel oil tests does not always describe the oil's properties, especially not when it comes to ignition and combustibility. Several of the parameters don't give any added value to the fuel analysis. After having examined ISO 8217 there are two obvious defects:

- Ignition/combustion: For distillate fuels the parameter Calculated Cetane Index as an ok parameter. Residual fuels got CCAI number. CCAI are only applicable for straight run fuels and is only a calculated value. CCAI is therefore a very vague parameter.
- Lubricity: There are none parameters about a fuel's lubricity, either for residual or distillate fuels. With de-sulphurization processes applicable today this should be introduced as a criterion. Lubricity can be measured in a High Frequency Reciprocating Rig (HFRR).

There are several portable hand-set available on the market. Such products make it possible to do a simplified analysis of the fuel received onboard. Unfortunately, fuel tests done onboard are not normal to perform. There is a consensus in the industry that fuels brought today are of a good quality and "fit for purpose".

A normally practice is to store the new bunkered fuel and not use it before the test results are given. After bunkering it takes 1-2 days before you know if the fuel specifications are met or not. If the vessel comes from a (remote) area where 0,1 % sulphur fuel is not possible to find, and the vessel are heading for an EU port, the vessel have to bunker 0,1 % sulphur fuel *at once* it calls the port. The fuel shall also be used immediately. There is in such a situation not possible to verify if the fuel is fit for purpose or not. In some cases, the fuel sample goes astray or the results are delayed. In these examples the situation is the same as above, you don't know the quality of fuel used.

6.1 Can deficiencies in ISO 8217 be connected to accidents?

Fuel ignition quality is a suspected area, for operators, class and insurance companies. In general terms we can say that fuel with poor combustion properties will lead to carbon deposit (unburned or partly burned fuel) on vital engine components like cylinder heads, valves, piston crowns, top lands, ring grooves. These are long term damages that will result in reduced performance and will come to view when engine is dismantled for maintenance.

Figure 19: Deposit formation on exhaust valve.

Poor fuel qualities can also have more dramatically damages as will lead to full stop and further costly repairs needed. These damages will be reported to class and further insurance companies may take the expenses, fully or partly. In this relation, inferior fuel quality is a suspected area.

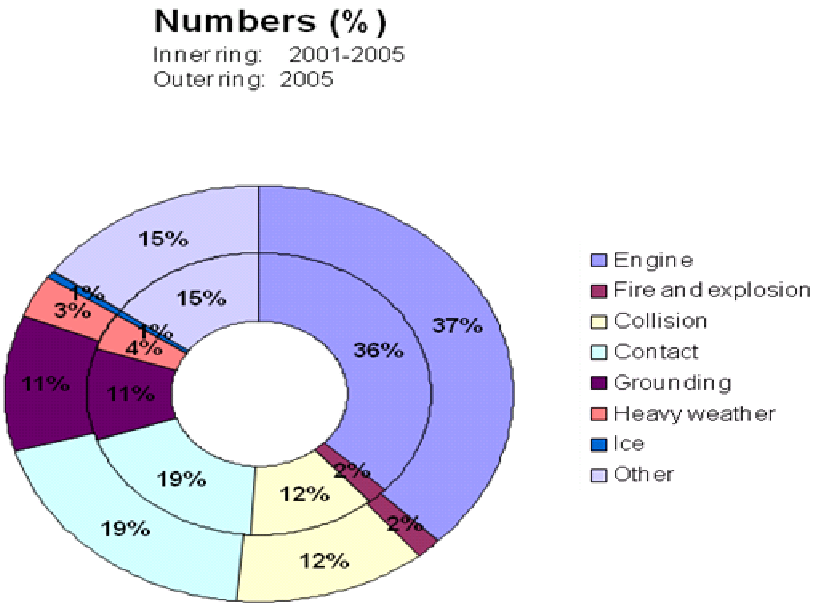


Figure 20: Claims divided into categories[33].

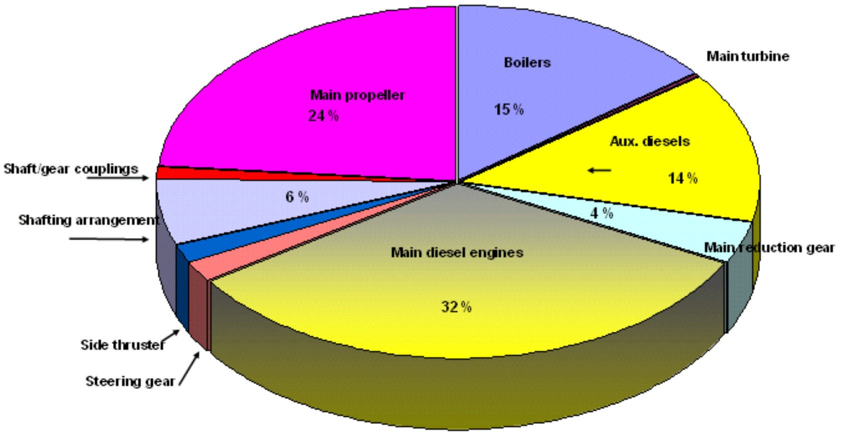


Figure 21: Engine related claims divided into sub-categories[34].

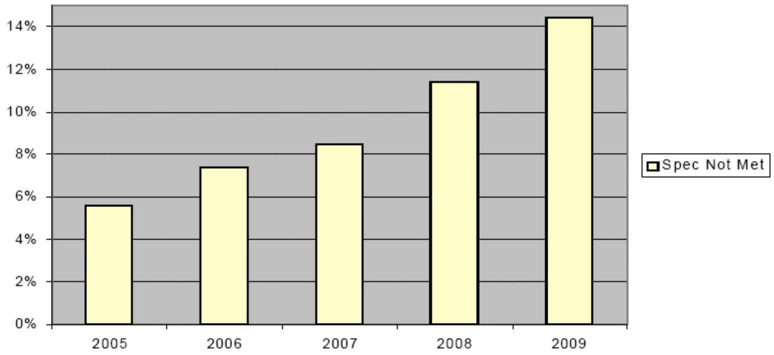


Figure 22: Distillate fuels off specification 2005-2009 [34].

In the period 2001-2005 36 % of all claims to CEFOR were engine related claims[33]. Statistics from DNV [30] shows that these damages are 46 % are from ME and AUXs . Damage investigations according to DNV have some surprising findings on the root-cause of engine related claims [30]:

- Accidents from off-spec fuel: 1-3 %
- Component failure: < 5 %
- ***Poor combustion / ignition + the human touch: The remainder.***

Fuels off-spec are relatively low but increasing. In 2009, around 14 % of fuels tested were off specification. With statistics from class and insurance companies there is reason to believe that there is something wrong or missing in today’s fuel standard (ISO 8217) and test methods since only 1 – 3 % of accidents can be directly linked to off-spec fuel.

There is reason to believe that the fuel quality can be held responsible for many unsolved and ambiguous engine related problems and accidents. Low sulphur fuels cannot be excepted in this relation. DNV has already got some experiences on this from customers [30].

Connection between the many inexplicable engine problems and inferior fuel is not clear, but it cannot be excluded.

6.2 FIA 100

To get the real answer of a fuel's ignition/combustion properties a physical combustion has to be done. FIA 100 and CRU is an apparatus where a fuel is tested for its properties related to combustion/ignition. Fuel is heated up to 500 ^{0}C and 45 bar and injected to a chamber where it self-ignites at constant volume. This process is done several times for one type of fuel and several parameters are taken. The most important result is the ECN (estimated Cetane Number). This is the most realistic and reliable figure for ignition/combustion. DNV has done research on which parameters that correlates to ECN.

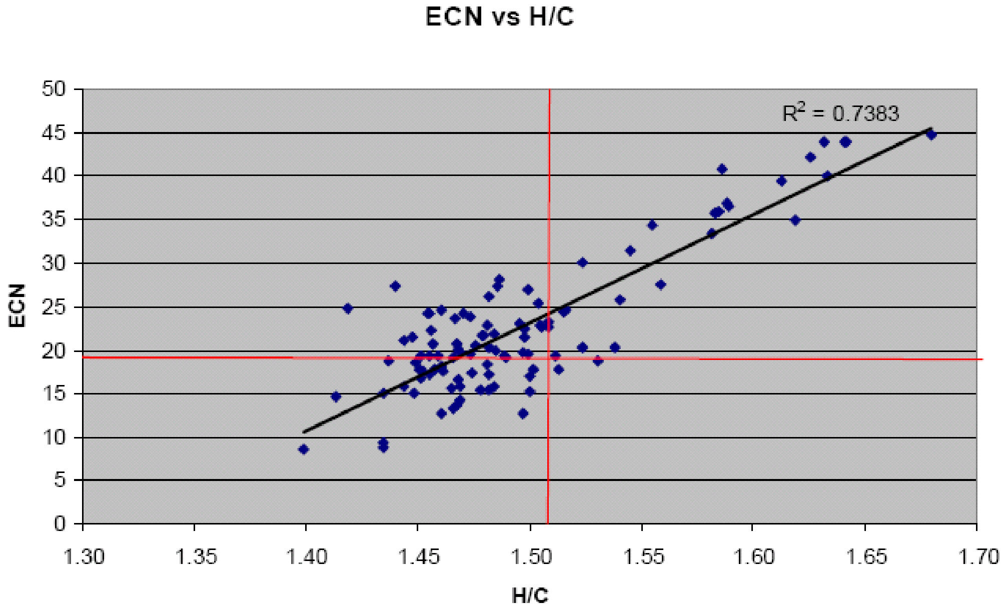


Figure 23: Relationship between ECN and H/C ratio [25].

As figure 23 shows, the hydrogen/carbon ratio it the most promising indicator. This will be further explained in chapter 10. Results from FIA 100 also confirm that CCAI and CCI is a vague indicator for ignition/combustion.

A normal fuel sample analysis costs as mentioned USD 500. H/C ratio can also be measured, by request. This will cost around 40 % extra [25] and will bring such analysis to a new level.

I will therefore in chapter 10 go deeper into how a fuel gets its properties, finding out how fuel is produced and which methods are used.

6.3 The new version of ISO 8217

The ISO 8217 standard were first launched in 1987. With 9 years interval it was revised in 1996 and 2005. Now in 2010, after 5 years after last revision there is a new version coming. The official version will most likely be released July 2010.

Several market players as ship owners, fuel producers, engine manufacturers and class societies are involved in the development of the new version.

The most important changes is represented below [35]:
- Maximum limits of Al+Si, ash, vanadium and sodium is reduced, but not to any drastically limits.
- CCAI will be included in the specification for all residual grades. CCAI is normally tested by fuel sample analysis companies today. This change is therefore only a formal introduction of CCAI to the ISO 8217 standard.
- New, alternative test methods for ignition and combustion are considered, which method is not decided. This is a very welcomed parameter to the standard and will improve the standard greatly.
- A new grade is presented, DMZ. This grade is identical to DMA with a lower viscosity limit of 3 cSt. In 2008-2009 DMA's viscosity were stable om 3 cSt, the DMZ standard will prevent a viscosity reduction in MGO. Today's DMA has a lower viscosity limit of 1,5 cSt, operators can today receive a DMA with such low viscosities, most likely it will give problems to engine and fuel system. When ordering DMZ one can be sure that the fuel holds a viscosity above 3 cSt.
- A lubricity test is introduced. This is only required for marine fuels with a sulphur content below 0,05 %. EU Directive 2005/33/EC is concerning fuels with a maximum sulphur limit of 0,1 %. As long as fuel producers are delivering fuel with a sulphur content in the interval 0,05 to 0,1 %, this requirement is avoided. It is difficult to improve a fuel's lubricity without adding expensive additives, it is therefore reason to believe that fuel producers will aim to produce MGO that got a sulphur content 0,05 – 0,1 %. This is the case in around 50 % of the 0,1 % sulphur MGO fuel deliveries to WSMN [16].

Main deficiencies in today's ISO 8217 standard, combustion/ignition and lubricity properties are tried to be rectified. It is a step in the right direction; unfortunately, the new standard does not rectify today's shortcomings. Changes seems to be hard to be implemented and there is much politics in the renewal process of ISO 8217. CCAI were introduced in the 1980s while implemented to the standard in 2010.

7 Injection system on a medium/high speed diesel engine

Marine fuel with its properties, as described in the chapter above, is injected to the engine combustion chamber. It is therefore decided to explain how this is done and important properties needed.

Finely atomized fuel shall be injected into the cylinder during the piston's upward stroke. Increased temperature and pressure makes the fuel self ignite. Fuel is directly injected to the combustion chamber, therefore the term *direct injection*. There is one injection unit per cylinder in comparison to common rail systems where there is one common injection pump. The main parts of the injection system are injection pump and nozzle, illustrated in figure 24 and 25. The fuel is injected by a jerk/piston pump at high pressure, which is camshaft driven. Compressed fuel goes further through the pipe and nozzle. This high pressure making the nozzle to open and injects the fuel to the combustion chamber. Typical injection pressure is 1300-1800 bar and injection time 0,004 – 0,010 seconds. These figures are depending on engine revolutions, high rpm give highest pressure and lowest injection time.

High pressure, short time interval, small clearances and long lifetime requirements, emphasize the importance of *precision* to injection components and *cleanliness* of the fuel.

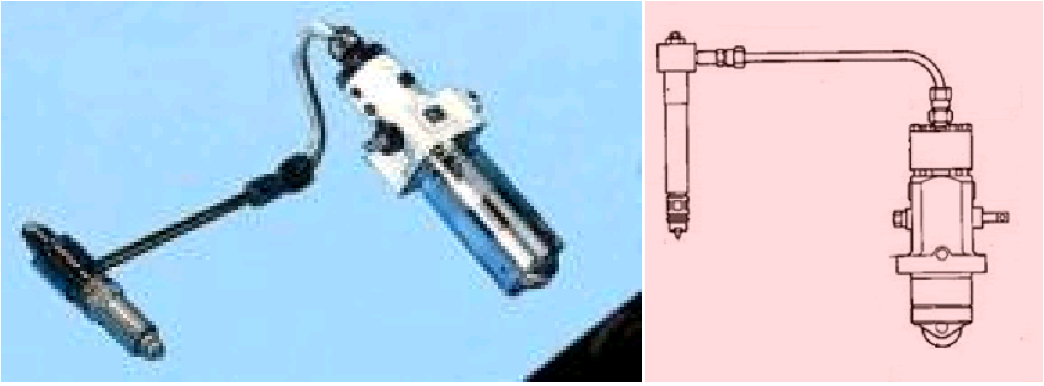


Figure 24: Injector and injection pump as components.

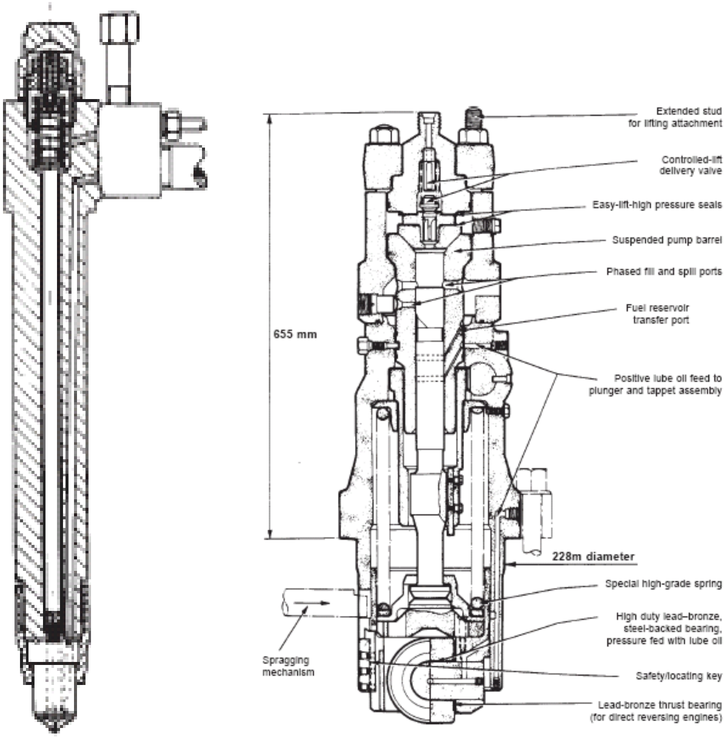


Figure 25: Injector and injection pump, cut through view.

The injection period should be short and end sharply. Any droplets *after* the injection will result in smoke and incomplete combustion. Viscosity is the vital key for proper injection and atomization. If HFO is received with a viscosity a bit too high there is not a problem, it just requires a bit more heating. On the other range, if viscosity is too low, internal leakages can occur and delivered pressure and quantity will be decrease. In this case, it is necessary to cool the fuel for achieve correct viscosity. This is a potential problem for the DMA type of MGO that got a lower viscosity limit of 1,5 cSt at 40 C. In an engine room the temperature can easily be 60 °C and lower viscosity limit for injection pumps is normally 2 cSt.

For a good combustion, fuel shall be proper atomized; every droplet shall be exposed to a minimum amount of air. Fuel and oxygen as reactants shall produce carbon dioxide and water.

Fuel injection pumps are cam shaft driven and therefore, high rpm gives high injection pressure. Further, high pressure gives best atomization of the fuel and best fuel economy. Fuels of poor quality will therefore easies be burned under high load.

The clearance between the barrel and the plunger is very small; around 4-16 µm, depending on plunger diameter. Metal to metal contact can be a factum if viscosities are too low. Incompatibilities occurred in pipes can precipitate asphaltene which is of a size above the clearance between plunger and barrel. Further, a fuel injector can get stuck, and then it will in most cases the unit is beyond repair.

Figure 26: Dismantled injectors.

The injection system is also sensitive for poor lubricity; pumping medium (fuel) is giving lubrication to the injector pump. As a rule of thumb, thick pumping medium, high viscosity, gives better lubrication than thinner medium. If the viscosity is too low, metal-to-metal contact will occur. Worst case scenario is a sticking fuel pump which can result in full stop of engine.

Low sulphur MGO may give worse lubricity than HFO. If this is only from the reduced viscosity or processes from the refinery, is not clear. This is more described in chapter 10.4.1. Lubricity can be measured in a high frequency reciprocating rig. Today, fuels tested are not going through such a test. Fuels shall be tested for this and limits should be established. I think this will be a standard in 5 to 10 years.

8 The origin of marine fuels

All fuel oils are complex solutions consisting of several chemical constituent parts. In comparison, LNG and LPG are “clean” gasses which consists of one or a few types hydrocarbon structures. I will here explain their structure and properties, and will also highlight the potential hazard moments in each of them.

It all starts with crude oil being refined. In short term we can consider that as crude oil is being heated up and different fractions will be removed at its boiling point. The lightest fractions boil up first as gasoline, kerosene, diesel etc. These are called distillates. Heavier materials with large molecules will remain since their boiling point is very high. These are called residuals. The residual fraction is, by definition, the material that will not boil at atmospheric pressure. Further heating in the refinery process can make larger molecular materials that have even higher boiling point. Before selling this as bunker fuel, producers are diluting this residual with distillate to meet sales specifications (viscosity, density, sulphur etc.).

How much that are made/refined of each part from crude is market driven. A refinery makes fuels that will pay best of. If a refinery wants to maximize their production of gasoline, it will have consequences for the remaining fuels made from the same crude.

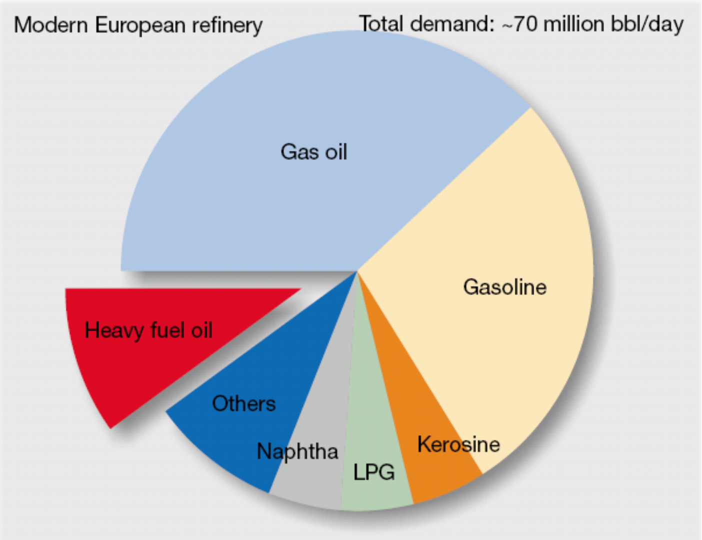


Figure 27: Example of cut of a typical crude oil barrel [28].

The last product from a crude is asphalt, used for road surfacing. It is very difficult to separate the different fractions in crude precisely; there will always be some fractions of unwanted products. Residual fuel shall be as free from asphalt as possible, but this is not the situation today. Fractions of asphalt are present in all fuels and the concentration is highest in residual fuel. The chemistry compositions (by weight) of asphalt are: 80% carbon, 10% hydrogen, 6% sulphur and the rest oxygen and nitrogen. Carbon to hydrogen ratio is very high, this will be further explained later. The compounds are classified as asphaltenes and maltenes. This is from their solubility in hexane or heptane. Asphaltenes got high molecular weight and are not soluble in hexane or heptane, while maltenes got lower molecular weights and are soluble.

One other essential topic in the relation of fuel quality is the origin of the crude. Different origin contains different amount of light and heavy fractions that can be separated by atmospheric distillation. The distinctive features are that Africa and Middle East crude got a high portion of light fractions while China and Alaska is poor on light fractions. Figure 28 is from 1999 but the crude's composition is the same.

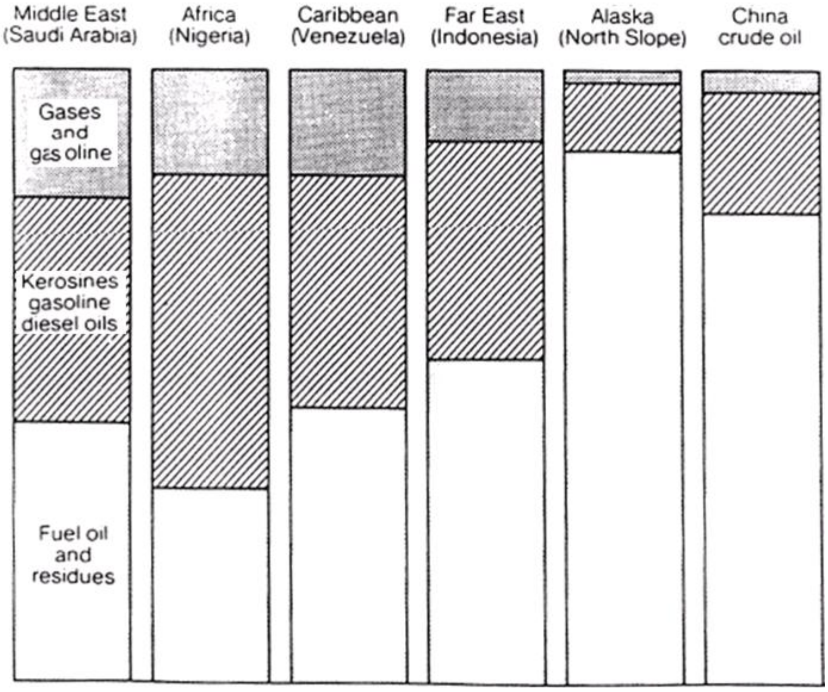


Figure 28: World wide composition of crude's fractions.

Initially crude got low sulphur content. Statistics from Statoil shows that the average sulphur content in their crude oils were 0,36 % in March 2010 [36]. Statoil is a major player and got worldwide operations so I do believe that this is a reliable number. One can then wonder why marine fuel got so high sulphur content. The reason can be explained from the refineries. Fuels for road and aviation use are refined free from sulphur content. The remaining part, marine fuel, will then have higher sulphur content.

8.1 History of marine fuels

In the 1960s, the use of marine fuels was a pretty straight forward process. The fuel was received and stored, purified and burned. At that time the refineries were a simple distillation process [37]. Residual marine fuel consisted at that time around 50 % of the original crude oil that was put into the refinery, meaning a high percentage of light fractions.

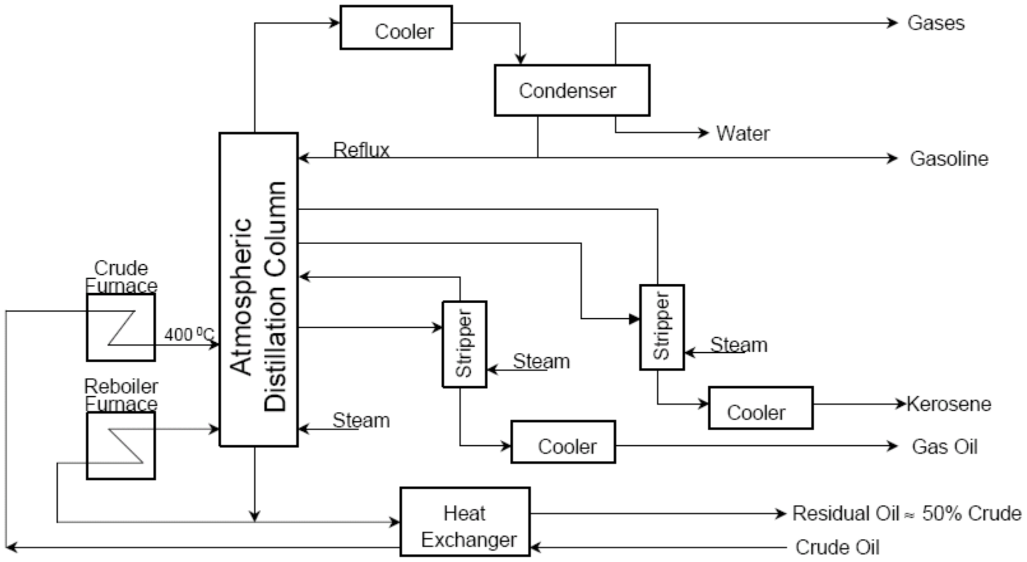


Figure 29: Simple crude oil distillation process.

8.2 Marine fuels today

As the worldwide demand for oil rises, refineries became more and more advanced to make more fuel out of the crude, here their production methods became further more sophisticated. There are different interests in the market of fuel production. Fuel manufacturers/refineries seeking low process costs while ship owners want clean fuel at low cost. On the sideline, engine builders strive to make engines that can operate smoothly on fuels that are cheap, but to too dirty. With such conflicting interests from market players it is essential to ensure fuel is of a proper quality. Fuel analysis companies are of course happy with this situations, more analyses, more earnings.

A refinery wants to make as much light oils possible out of the crude oil. Of course, because lighter oils are better paid. A modern refinery process is shown in figure 30. Today’s residual fuel consists of around 16 % of crude oil that came to the refinery. In comparison to 1960s when it was around 50 %, it means that something is removed, and resulted in a worse quality of residual fuel. Operators experienced more challenges in fuel handling and combustion.

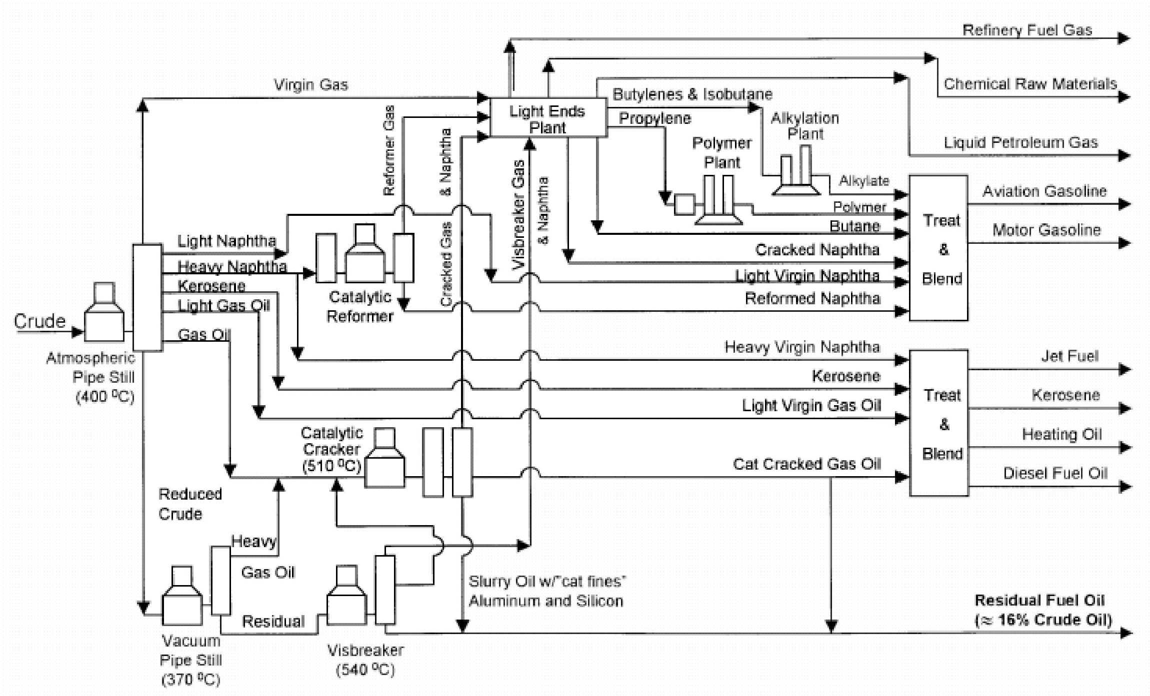


Figure 30: Modern crude oil distillation process.

The lightest fuel is methane (CH_4). Here the carbon-hydrogen ratio is very low 1:4. This is a very clean fuel that will easily vaporize and mix good with oxygen in the combustion. With respect to heating value, there is a clear relationship. Fuels with **low** carbon-hydrogen ratio has in general a **high** heating value.

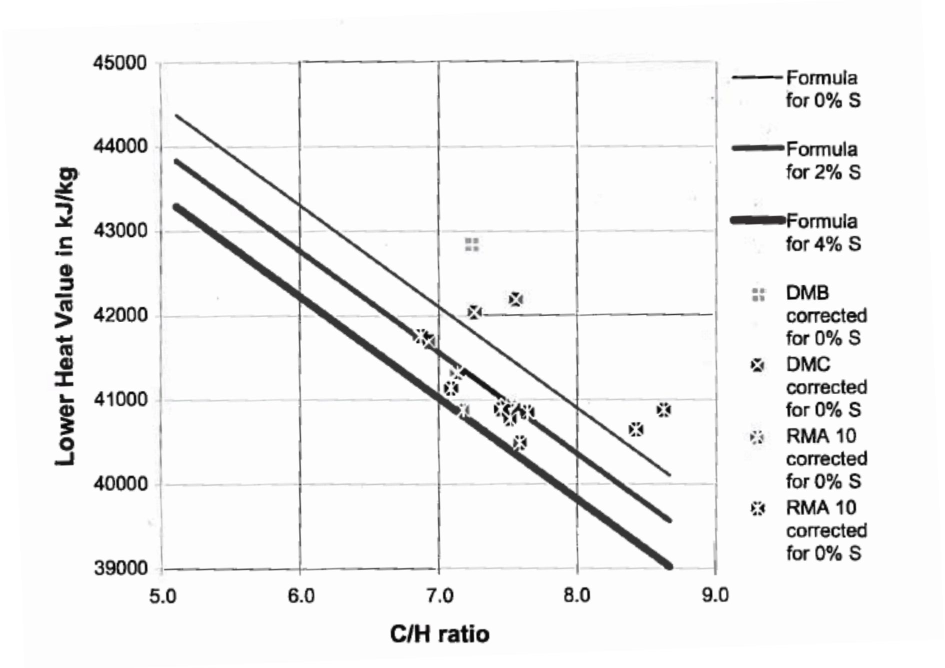
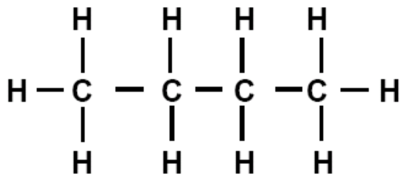


Figure 31: Picture showing relationship of C/H ratio and lower heating value.[22]

In a refinery crude oil is used as the "base" and transformed into other oil by heating. They are separated by their boiling point. First, small and light molecules like those in propane gas, naptha, gasoline for cars, and jet fuel are taken up. All of these molecules have short carbon-chains. Automobile fuel got 4-12 carbon atoms per molecules. Residual fuel (HFO) have in comparison 20-70 carbon atoms per molecules. Residual fuel are rich on carbon and poor on hydrogen. The “unclean” parts, (asphaltenes, sulphur, vanadium, sodium and trace metals) from the crude oil will remain in residual fuel. These unclean parts are also known as sludge.



$$\begin{array}{ccccccccccc} & & H & & H & & H & & H & & \\ & & | & & | & & | & & | & & \\ H & - & C & - & C & - & C & - & C & - & H \\ & & | & & | & & | & & | & & \\ & & H & & H & & H & & H & & \end{array}$$

Figure 32: n-butane C4H10

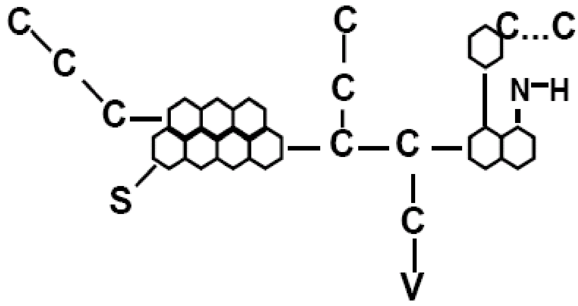


Figure 33: Asphaltenes and contaminant are combines in residual fuel.

As the length increases, marine fuel become more and more complex and it can easier take up contaminants. The ignition quality became also worse and the risk of ignition delay increased. This is illustrated in figure 34. 3,3-diethyloctane which is a short hydrocarbon chain burns easily (and got high cetane number) while aromatics doesn’t burn well and god poor ignition performance.

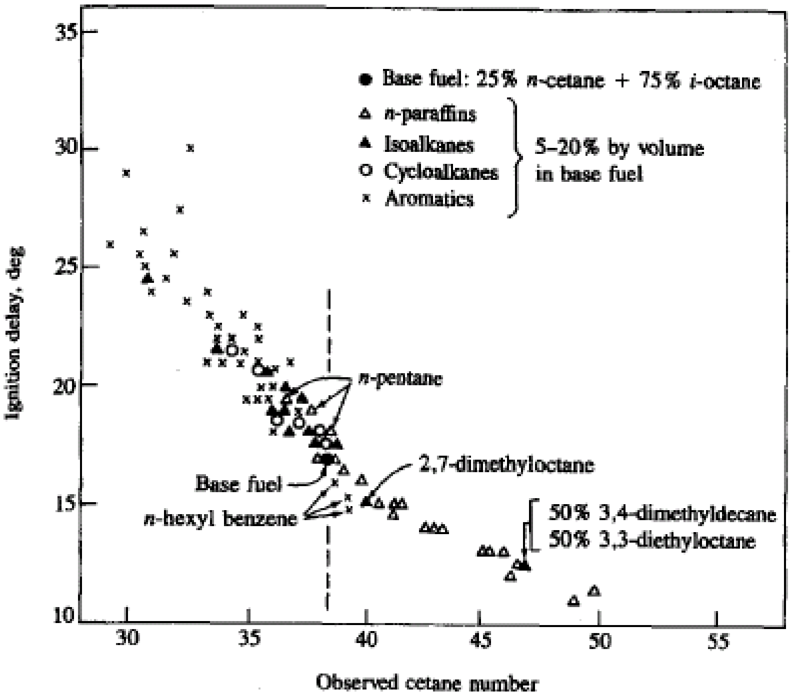


Figure 34: Ignition delay and cetane number (observed) as function of crank degrees [21].

9 Heavy Fuel Oil (HFO)

HFO are blended from various refinery processes such as distillation and cracking (these two concepts are explained in chapter 10). The fuel is viscous and requires heating for storage and combustion. It is a complex mixture of high molecular compounds (around 20-70 carbon atoms per molecule) and has a typical boiling point of 350 – 650 ^{o}C. HFO is a dirty fuel, the next product from the refinery process are asphalt. HFO has to be settled and cleaned. After this cleaning process the fuel is still “dirty”, but useable. HFO has a high content of sediments. These sediments are bounded in the aromatics in the fuel and are therefore only “potential sediments”. When mixing fuels (as we have to when switching fuels) the fuel can burst. The aromatics cannot longer hold on the potential sediment to the mixture. These sediments will then fall to the bottom of the tank and will be treated as sludge. This sludge has to be removed from the tank physically and very expensive to deliver (2-3 times the price of HFO).

Sludge cannot be used to anything and needs to be treated specially. The origin of the crude oil HFO are made from, will decide its quality and properties. Off course, the refinery process is also important to the quality. If the crude oil’s properties are close the sale specifications, less refinery processes are necessary to achieve desired HFO.

To get more valuable products from a refinery, “cracking” is necessary. To cut a long story short; cracking is the process of breaking long chain hydrocarbons into short ones. How this process is carried out, determine the products’ properties. The refinery processes will be explained in detail below.

10 Marine Gas Oil (MGO)

To get deeper into MGO it is necessary to examine how it is produced. As explained in chapter 3, MGO are the only fuel from ISO 8217 that will be delivered in 0,1 % sulphur content. Due to the refinery process, there are four types of MGO. I will classify them after their production method. This means finding out how they are produced and which refinery processes that are used. In general we can say that MGO consists of 10-25 carbon atoms per molecule. Typical boiling point is 150 – 450 ^{o}C, with this wide boiling point it can be difficult to separate each fraction. This will again, also be depending on the crude’s origin.

10.1 Straight run gas oil

This is the easiest form for MGO. Atmospheric distillation of crude oil physically separates different fractions from their boiling point. MGO will start evaporate at a temperature just above 150 ^{o}C. The crude is heated up to 350 ^{o}C, after this temperature its chemical composition changes and we moves over to thermal cracking which is explained in chapter 10.3. Vaporised fractions are separated in fractionating column. The column is progressive cooled towards the top and each fraction begins to condense at its boiling point. Each composition of the crude are in this way separated.

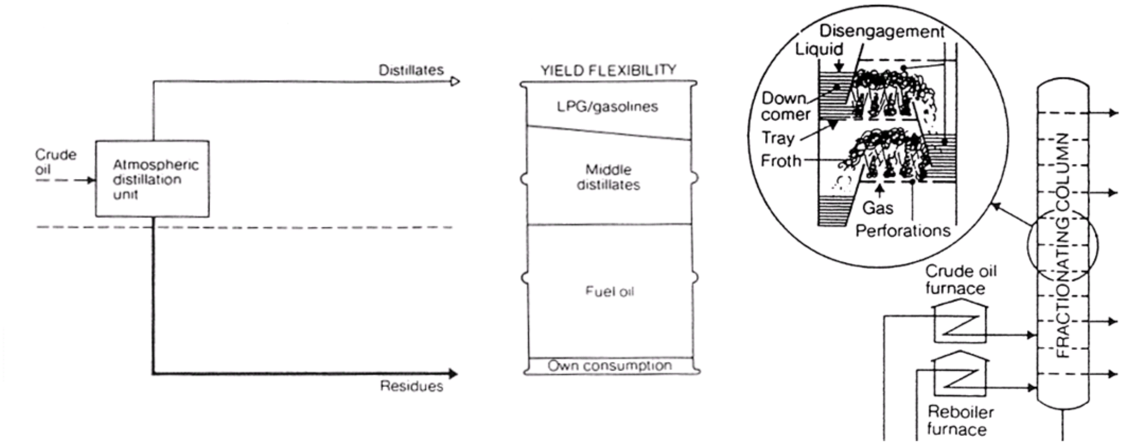


Figure 35: Atmospheric distillation and distillation column.

The disadvantage of atmospheric distillation is that there is limited scope of to change the proportion of distillates and residue; it is determined by the crude itself. This means that the refinery cannot utilize market demand and maximize the production of the best paid fuels.

10.2 Vacuum gas oil

To recover more distillate products, further processing is necessary. The principle is almost the same as for atmospheric distillation but when vacuum is achieved, less temperature are needed to achieve the fractions boiling point. Products extracted from vacuum distillation are: vacuum gas oil, waxy distillates, wash oil. These products are normally sent further to thermal and hydrocracking. Residual fuel from vacuum distillation is often classified as *short residue*.

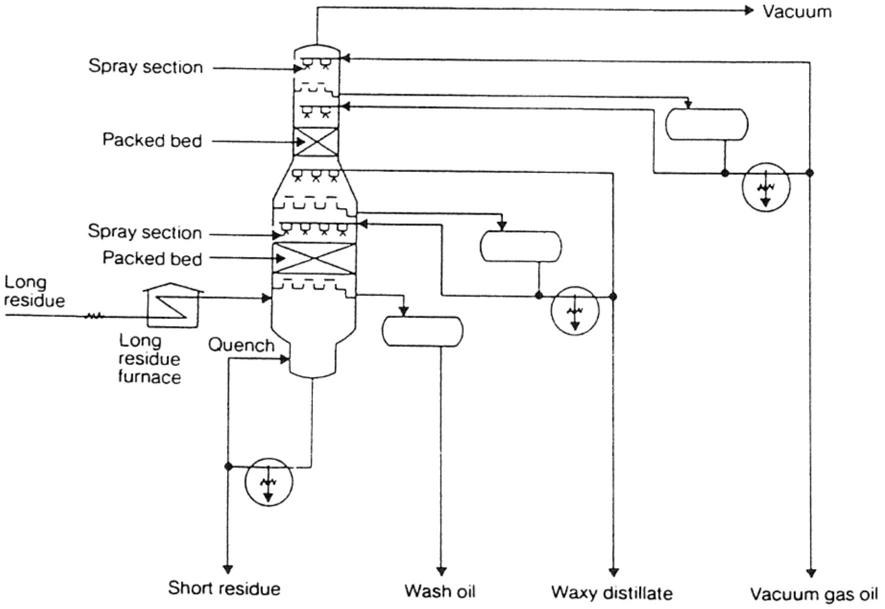


Figure 36: Vacuum distillation.

10.3 Thermally cracked gas oil

As the name says the mixture is heated up to high temperatures (450-750 ^{0}C) and high pressure, normally 5 to 10 bar but in some cases up to 70 bar [38]. The feedstock resides in the drum for a period of 5 minutes. At these circumstances, large hydrocarbon molecules will become unstable and make smaller molecules. The process can occur in furnace coils or in a drum where lighter fractions are vaporized and recovered separately[39]. Feedstock to this process can be from straight run or vacuum gas oil, or both of them. Thermal cracking has three major applications[40]: visbreaking, a thermal gas oil and coking.

Visbreaking is the most interesting method. Visbreaking got the name from its purpose; you wish to break down the viscosity of viscous oils. In the same time, a small quantity of distillate products is also produced. Visbreaking is a non-catalytic thermal process, it converts residues through thermal cracking to lighter, better paid fuels as gas, naphtha, distillates. One other benefit is that visbreaking reduces the sulphur content.

Another way visbreaking method is the soaker method. In the furnace coil/drum the feedstock are normally heated for high temperatures for a short time (5 minutes) while soaker is opposite, long time (15 – 20 minutes) and relatively low temperatures. Coking is the last method, it aims to maximize the amount of distillates. It impoverish all hydrogen so the residual part becomes coke. Coking is not so widespread in today's refineries.

	Density [kg/m3]	**Viscosity at 100 ^{0}C [cSt]**	**Sulphur content [weight %]**
Before visbreaking	1,020	930	4,0
After visbreaking	1,048	115	4,7

Figure 37: Example of visbreaking [38].

As we can see from the table above, the viscosity is greatly reduced while density and sulphur content are almost unchanged. From being a residue crude oil that could not be sold, the fuel will now meet specifications of marine fuel and can be sold.

One of the main limitations of visbreaker operations is to make a fuel with good stability. Heavy visbreaked fuel have a tendancy to produce sediments that will fall out when the fuel is stored. The light, low viscosity fuel made has a tendency to take up aromatic species. Longer hydrocarbon chains are broken down and at the side-chains aromatic compounds takes its place.

Further, the aromatics/asphaltenes become meta-stable, this means that the chemical bounding will only hold for a certain time, after that the blend becomes unstable and the asphaltenes will fall out as sediments. As fuels are sold and stored in speculations on fuel price fluctuations, long-storage-life for fuels are important.

On a fuel sample result it is stated "Total Sediments, potential". This defines the total amount of inorganic and hydrocarbon sediments or sludge. Total sediment is an indicator of the fuel's stability/compatibility. There is a limit of how much sediments a blend can hold on, when this amount is high, this limit are getting closer.

Figure 38: Clogged separator.

Fuel stability can be checked through test methods called ASTM D7157, ASTM D7060, ASTM D7061 and ASTM D7112. This test can be performed by using portable devices[41]. All fuels sold today (both residual and destillates) are with a total potential sediments of 0,1 % by mass. All mobile devices I could find needed a total sediments of 0,5 % by mass. For this reason they cannot be used on fuels fulfilling ISO 8217.

It is reasonable to believe that refineries will increase its use of such methods to make lighter and higher valued oils from their residual part of crude. There are coming several new regulations that will require more and more vessels to use lighter oils and less HFO (residual fuel).

10.4 Catalytic cracked gas oil

Catalytic cracking is the major process in the petroleum refining industry. As the name says, a catalyst is added to the feedstock in the mission to make long hydrocarbon chains to shorter ones. There are two main types of catalytic cracking used today depending on which catalyst that are used, hydrogen and zeolite.

10.4.1 Hydrocracking /hydrotreating

Crude can be classified as *sour* if it contains much sulphur (in H_2S) or CO_2 and *sweet* if their quantities are small. If crude comes from an area that makes its sour, it can be necessary to reduce the sourness (desulphurized the feedstock) before it can be sold. In respect to very low sulphur fuel (as 0,1 % sulphur gas oil) such process are done in most cases.

Feedstock (atmospheric or vacuum distilled crude) are pre-heated and mixed with hydrogen under high pressure, the mixture are then heated to a desired hydrocracking temperature[42]. The hydrogen atoms reacts with sulphur to form hydrogen sulphide (toxic), the nitrogen compounds are converted to ammonia (in reaction with hydrogen) and the aromatic compounds are saturated.

The high pressure feedstock also contains an aqueous amine solution which absorbs the hydrogen sulphide (from removed sulphur) and allows it to be removed. The ammonia produced (from removed nitrogen) is dissolved in the process water which is removed as "sour water". This process is usually done in several steps.

The result is saturated hydrocarbons (from aromatic hydrocarbons) and the hydrogen/carbon ratio is increased. Further will contaminants as sulphur, nitrogen and metals be removed as hydrogen atoms are taking their place. The result is a higher valued and cleaner fuel. Major products from hydrocracking are jet fuels and diesel (including MGO). This type of diesel, with its low sulphur content, is perfect for use in sulphur restricted areas.

A fuel got its natural lubricity through "minor species" such as nitrogen, oxygen and polyaromatic species. These linked species are directly responsible for the overall natural lubricity of the fuel. When these species are removed, the fuel’s natural lubricity will be decreased. Lubricity properties for marine fuels is a new topic and is not regulated through ISO 8217. Gasoline and diesel for automotive use, there are limits for lubricity, not for marine fuels.

Lubricity properties for marine fuels is a vague topic and new for the maritime industry. After the introduction of distillates having low sulphur and low viscosities for marine engines, there has been a topic of lubricity in the fuel system. It is not determined if it is lubricity nor viscosity, or a combination of those that is the major contributor to lubricity in the fuel system components (mainly injection pump).

There are additives on the market that can improve a fuel’s lubricity. Infineum is a joint venture of ExxonMobil and Shell. They have launched Infineum F7451[43] that shall improve the combustion chamber clean-up and lubricity when operating on distillates. FOBAS (Lloyds Register’s answer to DNV PS) has even verified Infineum F7451 as a lubricity improver in desulphurized fuel[44]. Since major market players have verified lubricity additives there is an indication on that lubricity is a vital property.

There are several additives available on the market, with varying effects. Some of them shall improve combustion, ignition, improve lubricity and clean the engine in many ways. Engine builder MAN on the other side, does not recommend using additives of any kind under the engine’s guarantee period[45]. Such statement gives reason to be critical in use of additives.

This sulphur removal process not only affects the fuels lubricating qualities but can also affect the ignition quality. This is more explained in chapter 12.

10.4.2 Cracking using zeolite

In other applications, zeolite can be used as catalyst. This is also described as FCC (Fluid Catalytic Cracking).Pre-heated feedstock is sprayed in *very* hot catalyst (around 700 °C). The hot catalyst will now make the feedstock to vaporize. Zeolite is used as catalyst because of its very special characteristic; zeolite forces the hydrocarbon molecules to be presence in small spaces[46], this will break long hydrocarbon chains into shorter ones. This is due to a very regular pore structure of molecular dimensions. The vapour will flow upwards and further be separated in cyclones. The catalyst-free hydrocarbons are routed to a fractionator where they are separated into gas oils, LPG, gasoline and naphtha. This process will occur as the temperature decreases in the fractionator. The catalysts that have been used in cracking reactions, will have developed coke deposit on the surface of the catalyst. Steam is further used to separate catalyst from the cracked hydrocarbons. We will then have separated catalyst (which are reused) and lighter hydrocarbons that are separated from the feedstock and can be sold as high valuable fuels.

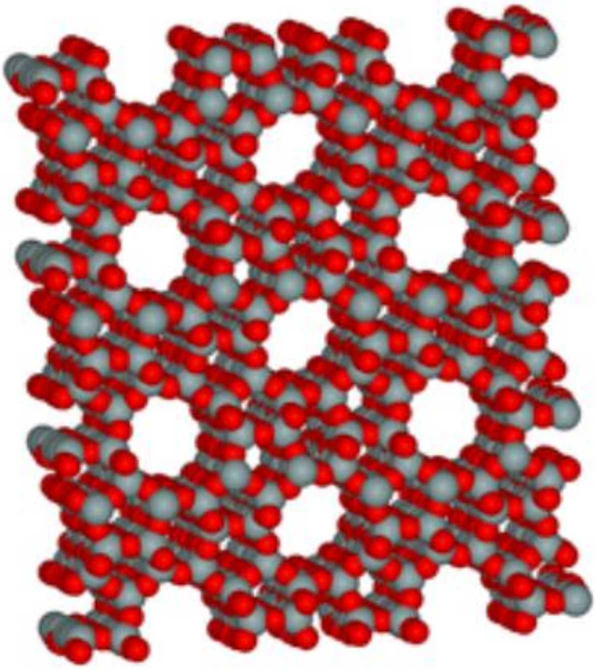


Figure 39: Molecular structure of zeolite

The zeolite type used in catalytic cracking is composed of silica and aluminium. They have a tetrahedral structure with a silicon or a aluminium atom in the middle and oxygen on the four corners. They are making a lattice, making only hydrocarbons of a certain size to flow through. When a fuel is tested for aluminium + silicon they are tested for remaining catalyst (zeolite). This is also called catfines, from catalytic fines.

If there are traces of zeolite they can harm the engine seriously. Compounds of silicon and aluminum are highly abrasive and can damage vital engine parts in short time. Catfines are very hard (close to the hardness of diamonds), for this reason they have a very damaging abrasive effect to moving engine parts that get in contact with the fuel[47].Parts as fuel pumps, injectors, piston rings and liners can be damaged in short time and total engine failure is highly possible. Al+Si particles are small, typical diameter in the area 1-50 microns [48-49] and *may* pass a separator. These catfines can be separated in the settling tank or in the separator. A separators ability to detect catfines have been a challenge of a long time[50].

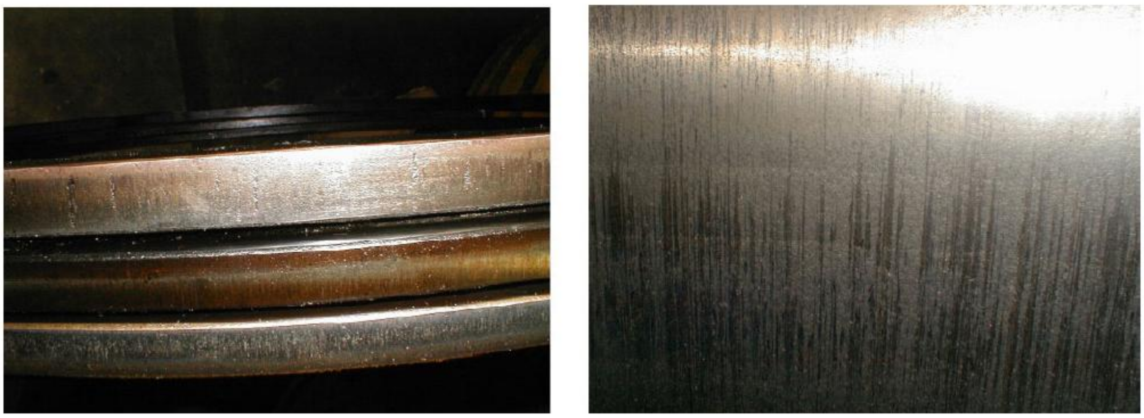


Figure 40: Abrasive effect on cylinder from catfines[45].

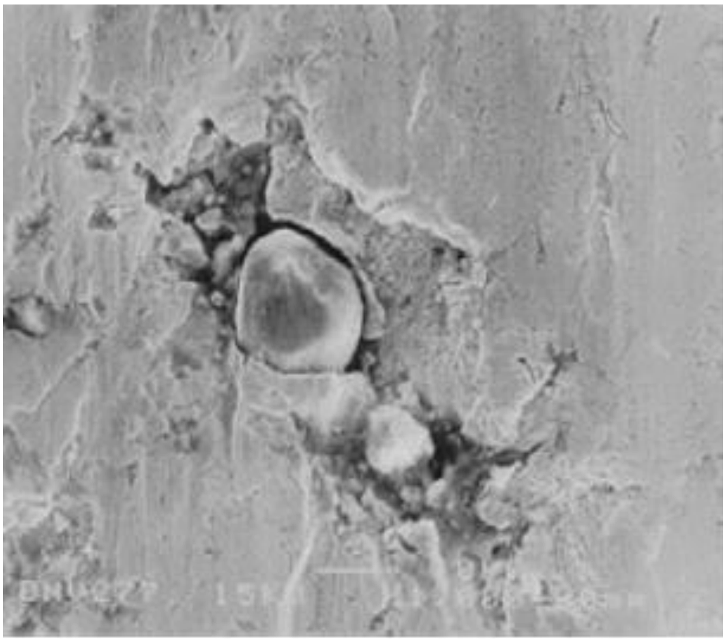


Figure 41: Catfine embedded in liner.

The limit for catfines (aluminium + silicon) is 80 mg/kg or 80 ppm for residual fuel (from ISO 8217). Engine producers advice their engines to use fuel with a maximum of 15 ppm catfines content[51]. This means that fuel treatment onboard shall be able to clarify up to 81 % of Al+Si particles [7].

Another catalytic cracking are steam cracking. This is a process where steam are used to make finer products as (ethane, LPGs and naphtha) to even finer products as ethylene, propylene, and butadiene. Since this process is not applicable for production of MGO it is not further explained.

In March 2008, DNV PS reported high levels of catfines; only 7 months after North Sea and English Channel SECA were introduced. If there is a high amount of aluminium + silicon, it tells us that it has gone through catalytic cracking where zeolite is used and not removed properly. If there is a relationship between demand for residual marine fuels and slipshod in the refinery business is not known.

There is a relationship between sulphur content in HFO and catfines[52]. As the sulphur content decreases, concentrations catfines increases. A natural question is how catfines will be in very low fuels, 0,1 % sulphur MGO.

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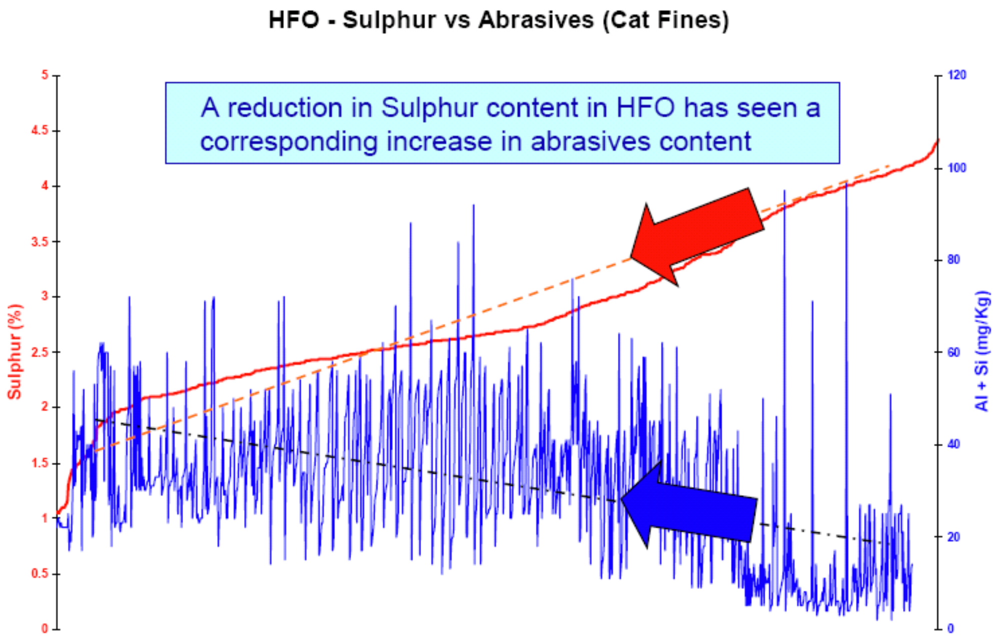
[7] $\frac{(80-15)\bullet 100\%}{80} = 81\%$



Source: DNVPS database (of 1,012 analysis results from October 1st – November 10th 2007)

Figure 42: Sulphur vs Catfines[52].

Catfines (Al+Si) from catalytic will be remaining in the bottom of the refinery process. Light distillate fuels as 0,1 % sulphur MGO will **not** have concentrations of catfines. The relationship of sulphur content and catfines is applicable for HFO and **not** for MGO.

10.4.3 Cycle oils

Cycle oils are an unwanted bi-product from catalytic cracking. Cycle oils can be divided into LCCCO and HCCCO (Light/Heavy Catalytic Cracked Cycle Oil). The oil got low viscosity and their density are high. Their properties make them excellent in blending relations. HCCCO is used for blending in residual fuels and LCCCO in gas oils, they reduces its viscosities greatly. The only drawback is that they don't burn well. This is also confirmed in figure 52 where HCCCO were burned in a test engine. The tested fuel got properties of density is close to 380 cSt HFO and viscosity low, good properties for blending and reduction of high viscosity HFO. HCCCO is high on aromaticity and has a long ignition delay.

Cycle oils got originally a high content of Al + Si from the catalytic cracking which is very harmful for the engine as shown in figure 40 and 41. Al + Si has to be removed in the same principles as described in chapter 10.4.2 and are then determined as *clarified* or *decanted cycle oil [49]*.

The fact that cycle oils don't burn well can be explained in their amount of aromatic hydrocarbons. Around 70 % of the aromatic hydrocarbons in cycle oils are two-rings aromatics[53] (e.g. benzene, toluene, xylen -ring)[54]. The rest are even split between one- and three-ring. Two- and three ring aromatics have poor combustion quality, with a cetane number 15 to 25. In comparison, a straight run distillate from the same crude will have a cetane number 40 to 60. Gasoline got normally not more than one benzene ring. A gasoline's octane rating is related to its content of branched hydrocarbons, too few of these, the octane rating and its anti-knocking properties are getting worse. Aromatic hydrocarbons are related to the same. In marine fuel highly aromatic hydrocarbons contribute to poor ignition performance.

The purpose of CCAI was to detect marine fuels with a high amount of cycle oils. The empirical formula for CCAI is developed by Shell and is presented below.

$$CCAI = D - 140,7\log(\log(V + 0,85)) - 80,6 - 483,5\log(\frac{t+273}{323})$$

D = density at 15 ^{o}C (kg/m^{3})   V = viscosity (cSt)   t = temperature (^{o}C)

Equation 1: CCAI formula.

CCAI was, and is, only applicable for straight run fuels. This was highly emphasize when CCAI were launched, today this application is more or less forgotten. The situation today is that you never know if fuel purchased is straight run or not.

11 Summary of the different types of MGO

As the complexity of the refinery process increases, sources for potential fuel problems increase. It is necessary to emphasize that MGO delivered can be a mixture of all of the four types of MGO as described above.

After assessing the different types of MGO there is a clear conclusion; **straight run MGO is the preferred type of MGO**. Its high amount of light fractions gives high possibilities for good ignition/combustion properties.

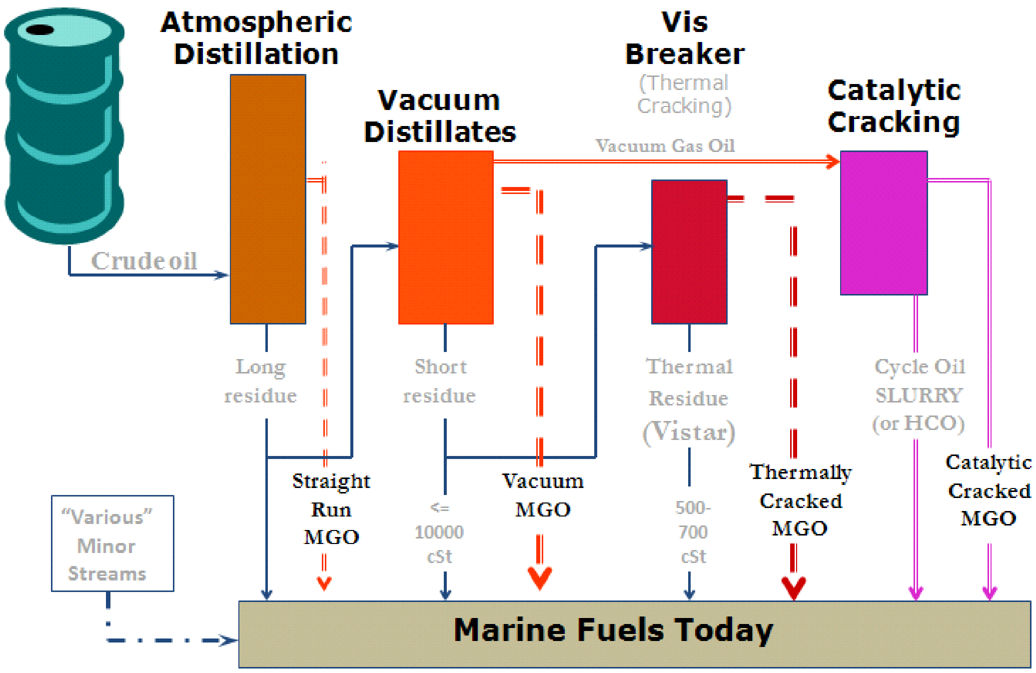


Figure 43: Four manufacturing types of MGO.

From research in this thesis there are none relationship in sulphur content and fuel quality in respect of ignition and combustion. Fuel quality is determined by source, manufacturing method and composition of the blended components.

To achieve 0,1 % sulphur MGO, hydrotreating is the most applied method [55]. This process will most probably affect the fuel's natural lubricity.

Refineries got the main responsibility to achieve high quality fuel, interest group can influence and affect standards (ISO 8217) but there will always be possibilities for cut capers. Where in the world the crude comes from is less important, refineries decide a fuel's properties.

CONCAWE has done research on each of the four types of MGO. They have found typical concentration ranges of the four types of gas oil that can be found in distillate marine fuels. This is presented in table 4. Distillate marine fuels can be MGO and MDO. As described earlier, both of them can be found with properties to meet the 0,1 % sulphur regulation.

Refinery process stream	**Distillate marine fuel** (all figures in % v/v)
Straight-run atmospheric gas oil	
- light	40-100
- heavy	0-50
Vacuum gas oil	0-20
Thermally cracked gas oil	0-30
Light catalytically cracked gas oil (cycle oil)	0-40

Table 4: Typical gas oil concentrations in distillate marine fuels.[56]

As table 4 shows, the main component is straight run gas oil. This is the "best" component and has the best ignition/combustion performances. Their report is from 1996, from that time there have come several regulations, forcing refineries to tweak their products to meet demand and maximize their profits. Since this report is 14 years old, the numbers are uncertain but the main trends should be unchanged.

Aromaticity is related to the fuels carbon/hydrogen rate. The easiest aromatic hydrocarbon is benzene (C_6H_6). For gasoline there is normally only benzene as aromatic hydrocarbons. The carbon atom are arranged in a hexagonal structure, see figure 44. When we are dealing with less valuable fuels, the aromatic hydrocarbons consist of longer chains.

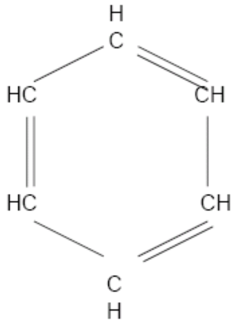


Figure 44: The simplest aromatic hydrocarbon, benzene.

Aromaticity can either be measured in *carbon aromaticity* (the percentage of the carbon atoms incorporated in aromatic rings) or as *hydrogen aromaticity* (the percentage of the hydrogen atoms attached to aromatic rings). Both these factors shall be as low as possible. When many hydrogen atoms are bounded up in aromatic rings (also multiple rings) there are few “free” hydrocarbons that will ignite first.

The most preferable fuel is straight run MGO, this is because this has a good carbon-hydrogen ratio (ignition/combustion performance) and the deposit potential is limited. When further refinery stages as described above are applied, the fuel oil quality will deteriorate.

How much a refinery tweaks its production will have a negative effect on the products. An easy indicator can be the ratio of residual and distillate from the crude, compared to the ratio residual and distillate that the refinery produces. If a refinery forces to make a high amount of distillate products when the crude delivered to the refinery is poor on light fractions it have to go through several complex refinery processes as described above. It can also be measured in the form of carbon/hydrogen ratio; this has to be done in a laboratory.

The most problematic area is ignition/combustion quality and lubricity properties. How to handle such problems are further discussed below.

12 Ignition delay –what to do?

Without further explanation, ignition happens when finely atomized fuel are sprayed at high pressure (1300-1800 bar) into to the cylinder during its upward stroke. The high temperature from compression (close to 200 bar) makes the fuel/air mixture to burn and the combustion is started.

A fuel needs both ignition and combustion qualities. With bad ignition quality there will be none or very late combustion. If the combustion is not good there will be unburned fuel and deposit formation will occur on engine parts.

Ignition quality can be expressed as ignition delay. This can be measured through advanced cylinder pressure measurements. Ignition delay is the time (in milliseconds) from the start of fuel injection (lifting of fuel injection needle) to the start of combustion. This is illustrated with figure 45.

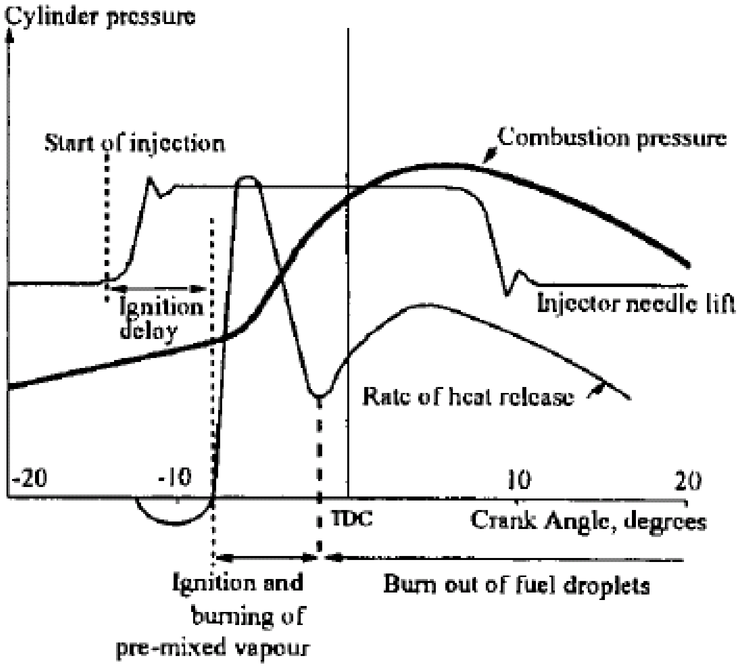


Figure 45: Combustion characteristics as a function of crank angle.[57]

In general terms, ignition delay is different for low, medium and high speed engines. This is from the bore/stroke ratio, large engines (low speed, two-stroke) have a low bore/stroke ratio and will increase temperature and pressure greatly and fuel will ignite easier. The aux engines for all four vessels of concern use MAN B&W's 5L28/32H running at 720 rpm. One millisecond ignition delay relates to 4,32 crank degrees. As the engine running at this high rpm, some milliseconds will cause problems. Low ignition quality will most noticeable at start-up and on low loads when the engine has not reached sufficiently working temperature.

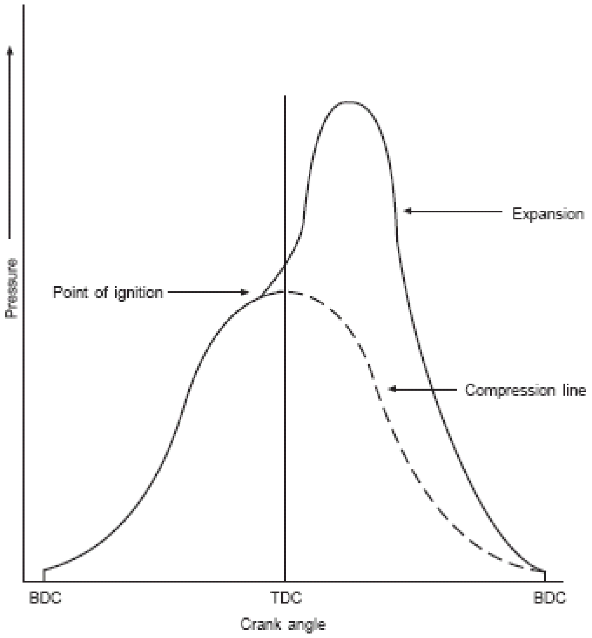


Figure 46: Cylinder pressure as a function of crank angle[58].

Ignition starts when the light fractions will ignite, when the mixture first ignite, the remaining will burn easier. The suspicion is that as the light components in residual oil are removed and sold as higher valued fuels. The remaining components will ignite later and all at the same time.

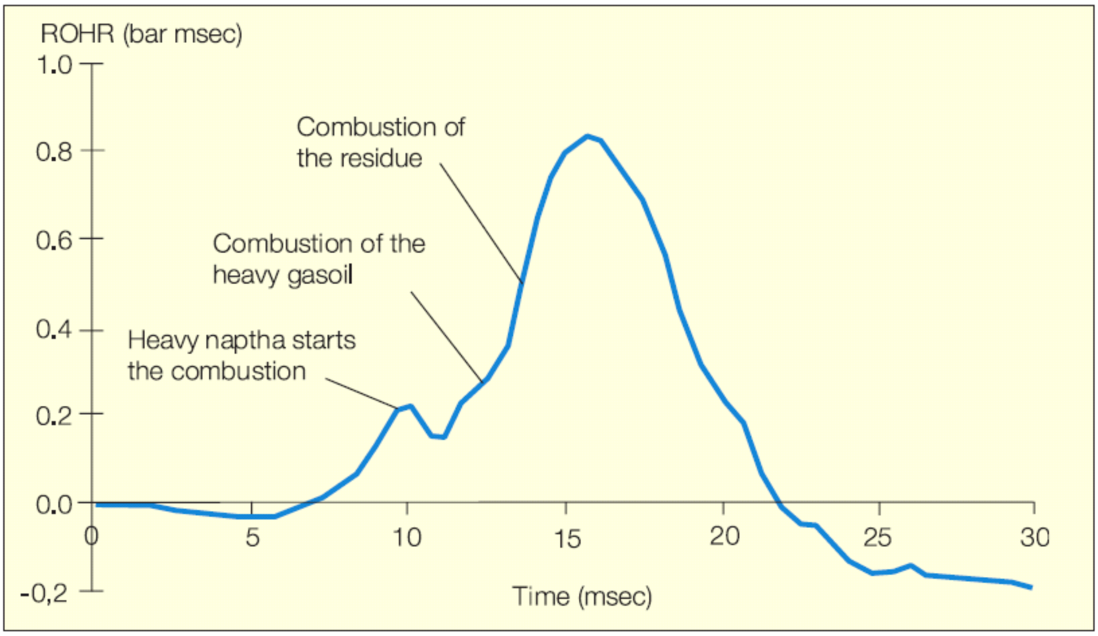


Figure 47: ROHR (Rate Of Heat Release) - when the different fractions ignites.[31]

To identify the amount of light fractions are done when performing a cetane-test as described in chapter 5.11. To get a clear picture of a fuel's components, a gas-chromatography analysis has to be performed. Such test will identify and quantify each component. Straight run fuels will be rich on the light fractions, making the fuel ignite and burn properly. On the other side, we have heavy cracked fuels. They may be poor on light fractions and rich on heavy fractions, making them ignite and burn poorly.

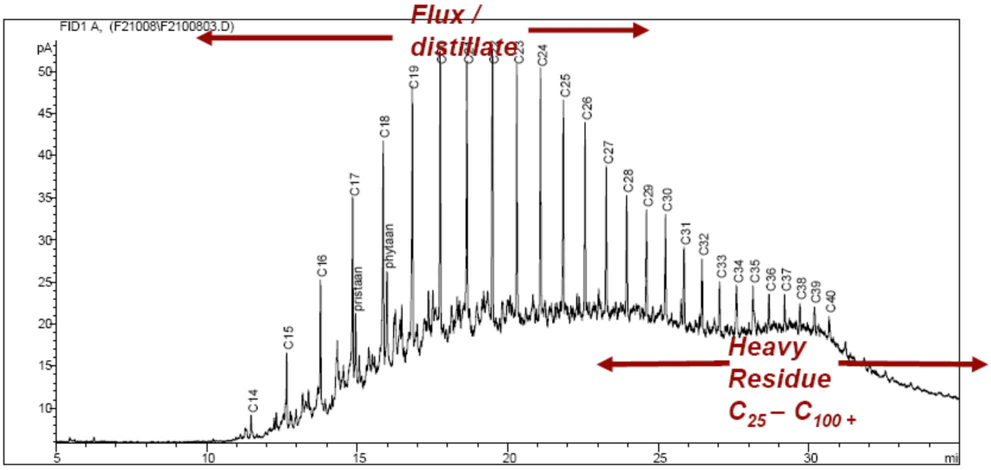


Figure 48: Gas-chromatographic analysis of 180 cSt HFO [59].

Low ignition quality (long ignition delay) forces the combustion to occur in a short time interval. The result is a high pressure increase (combustion hardness) and a higher maximum pressure. See figure 49. Increased combustion hardness causes higher forces exposed to engine parts.

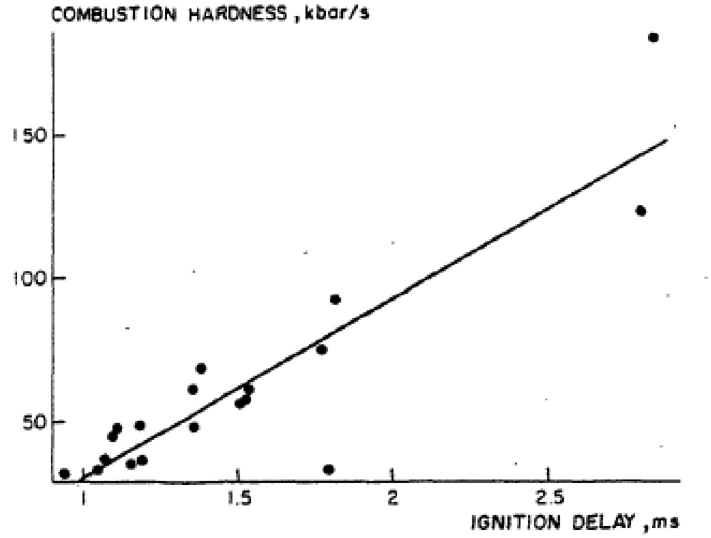


Figure 49: Relation between combustion hardness and ignition delay [38].

A lot of literature available on marine combustion engines is from 1980s. At that time injection pressure were lower than today. Modern marine engines got injection pressure around 1200-1800 bar[58]. This will improve the injection spray and atomization of the fuel. Therefore, modern engines will not be very sensitive to a small reduction in injection pressure. The atomization related to area per volume gets higher (the droplets gets smaller and increases) and digest of inferior fuel gets easier. Smaller droplets vaporize more readily than larger droplets.

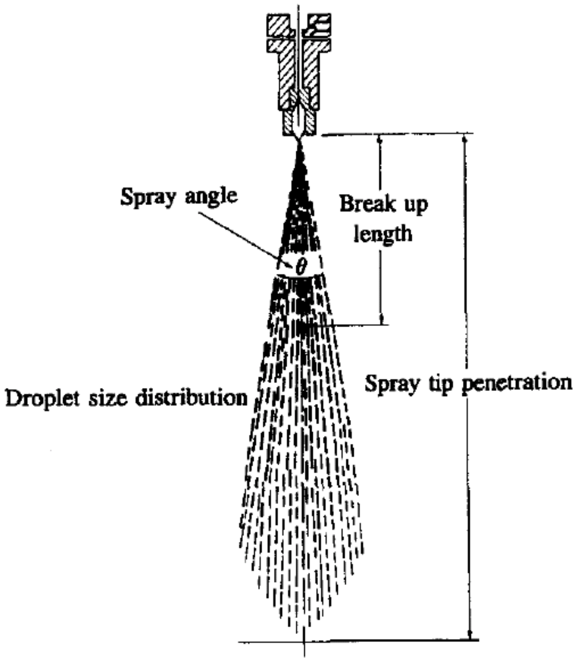


Figure 50: Schematic of diesel fuel spray defining its major parameters [58].

There is also an increased possibility for unburned or partly burned fuel, as all the fuel shall be burned at the same time interval as a “normal” fuel. Uneven and partly burned and fuel will lead to carbon deposits on engine parts as piston top, exhaust valves (and the rest of exhaust system), turbine nozzle ring and turbine blades. We will get decreased turbocharger efficiency, thermal efficiency and the fuel economy becomes worse. The engine will also be exposed for a higher thermal load on the engine which is damageable in the long run. Poor and uneven ignition/combustion will expose engine components for fatigue forces. Ignition delay related damages are in most cases revealed over time and is observed in poor liner and piston ring condition.

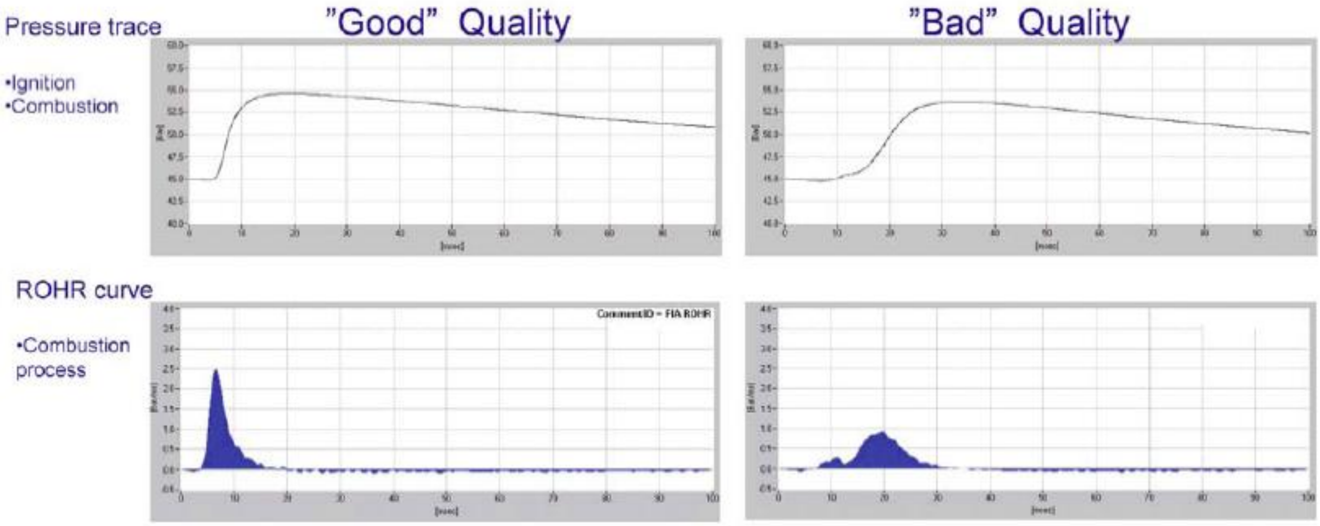
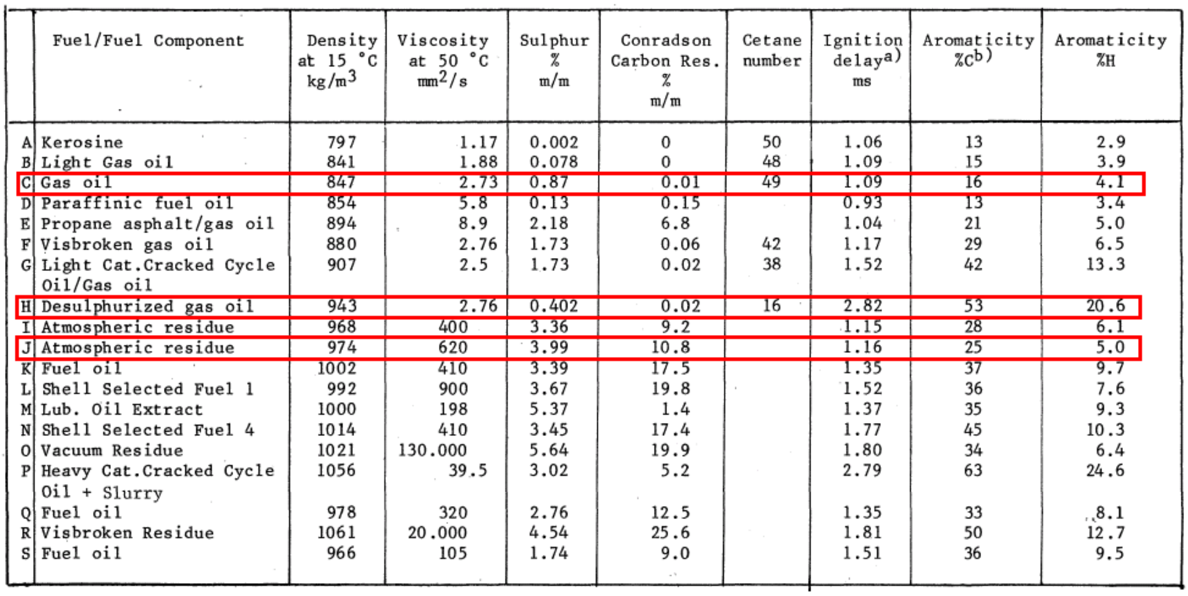


Figure 51: FIA analysis of "good" and "bad" fuel (HFO) [31].

There has been research on this topic, comparing ignition quality with other parameters (CIMAC 83, Paper D13) [38]. Their mission was to find a reasonable indicator for ignition on marine fuel. In their research they tested several fuels (including MGO and desulphurized MGO). As a test engine they used a one cylinder MAK 1M 281 AK, 4 stroke medium speed engine (1.000 rpm). This engine is quite similar to WSMN's AUXs.



	Fuel/Fuel Component	Density at 15 °C kg/m³	Viscosity at 50 °C mm²/s	Sulphur % m/m	Conradson Carbon Res. % m/m	Cetane number	Ignition delay a) ms	Aromaticity %C b)	Aromaticity %H
A	Kerosine	797	1.17	0.002	0	50	1.06	13	2.9
B	Light Gas oil	841	1.88	0.078	0	48	1.09	15	3.9
C	Gas oil	847	2.73	0.87	0.01	49	1.09	16	4.1
D	Paraffinic fuel oil	854	5.8	0.13	0.15		0.93	13	3.4
E	Propane asphalt/gas oil	894	8.9	2.18	6.8		1.04	21	5.0
F	Visbroken gas oil	880	2.76	1.73	0.06	42	1.17	29	6.5
G	Light Cat.Cracked Cycle Oil/Gas oil	907	2.5	1.73	0.02	38	1.52	42	13.3
H	Desulphurized gas oil	943	2.76	0.402	0.02	16	2.82	53	20.6
I	Atmospheric residue	968	400	3.36	9.2		1.15	28	6.1
J	Atmospheric residue	974	620	3.99	10.8		1.16	25	5.0
K	Fuel oil	1002	410	3.39	17.5		1.35	37	9.7
L	Shell Selected Fuel 1	992	900	3.67	19.8		1.52	36	7.6
M	Lub. Oil Extract	1000	198	5.37	1.4		1.37	35	9.3
N	Shell Selected Fuel 4	1014	410	3.45	17.4		1.77	45	10.3
O	Vacuum Residue	1021	130.000	5.64	19.9		1.80	34	6.4
P	Heavy Cat.Cracked Cycle Oil + Slurry	1056	39.5	3.02	5.2		2.79	63	24.6
Q	Fuel oil	978	320	2.76	12.5		1.35	33	8.1
R	Visbroken Residue	1061	20.000	4.54	25.6		1.81	50	12.7
S	Fuel oil	966	105	1.74	9.0		1.51	36	9.5

Figure 52: Fuels tested with its parameters.

According to their results, there is a clear correlation on cetane number and ignition delay. High cetane number gives short ignition delay. For MGO that have been catalytic cracked or desulphurized there is a clear ignition delay. *Especially* for desulphurized MGO.

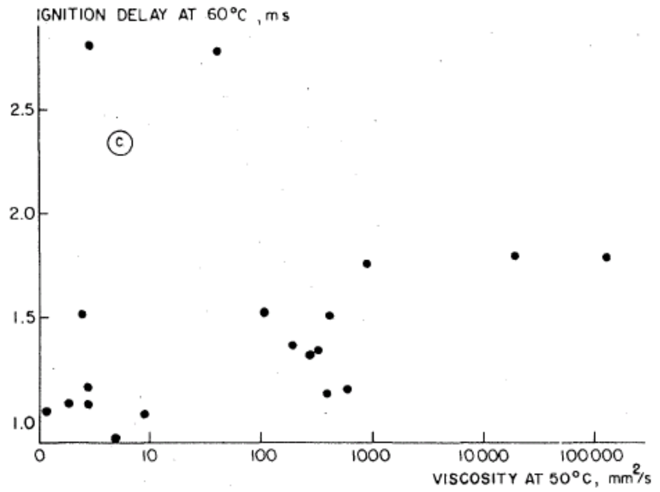


Figure 53: Relation between ignition delay and viscosity (logarithmic scale on x-axis).

As a general opinion that lower viscosity will give a longer ignition delay is not correct. There were none correlations on this. See figure 53.

Residual fuels cannot be measured in cetane number since it is not possible to measure a middle boiling point. It is a clear correlation between ignition delay and aromaticity (both carbon- and hydrogen aromaticity).

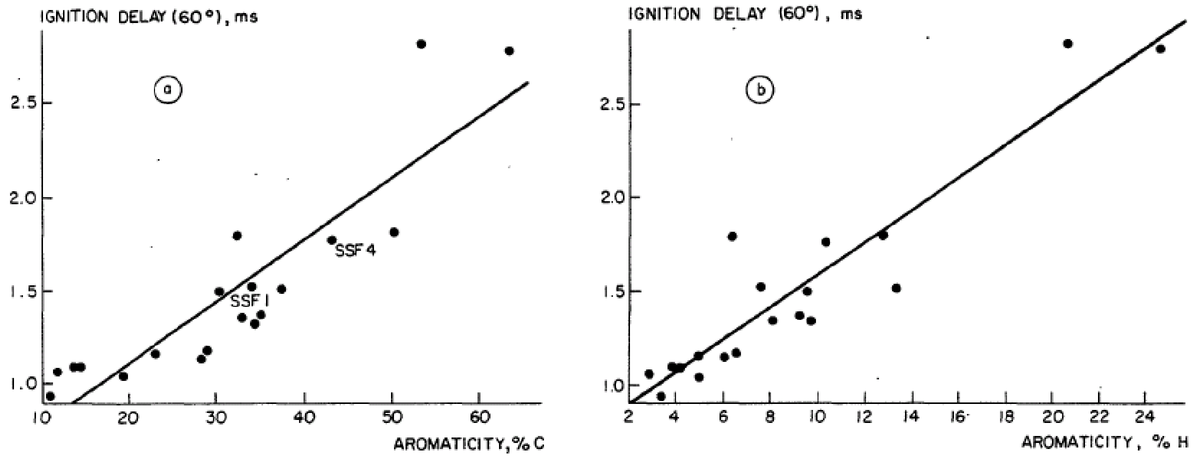


Figure 54: Relation between ignition delay and aromaticity of different fuels [38].

The same research also concludes that CCAI correlates to aromaticity. This correlation will in this thesis be rejected. This research is from 1983 and from that time the refineries has changes highly and possibilities to avoid CCAI-trapping can be done easily.

As shown above, the combustion starts later than it should. In addition it takes longer time. With longer combustion time, we get another topic: NO_x formation. The purpose of EU Directive 2005/33/EC is environmental purposes and from inferior fuel qualities, forced by this directive, may be leading increased NO_x emissions.

Ignition delay can be divided into physical and chemical properties. Chemical by the fuel's ignition performance in light fractions presence, and physical by better the physical conditions that promotes ignition conditions. Below the most affecting properties will be discussed and proposed solutions presented.

One solution is to pre-heat the charge air. When the combustion happens at a higher initial temperature there is less heat (from compression) necessary to reach ignition condition. As an example, using numbers from figure 54 and 52, an increase of charge air by 15°C, relates to an earlier ignition of 0,3 - 0,5 ms[8]. This ignition delay due to pre-heated intake air is equal to the ignition delay difference from MGO to desulphurized MGO. It can therefore be advised to operators to throttle the cooling water for charge air cooler if there are ignition suspicions.

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[8] This size is also confirmed in *Heywood* (page 548).

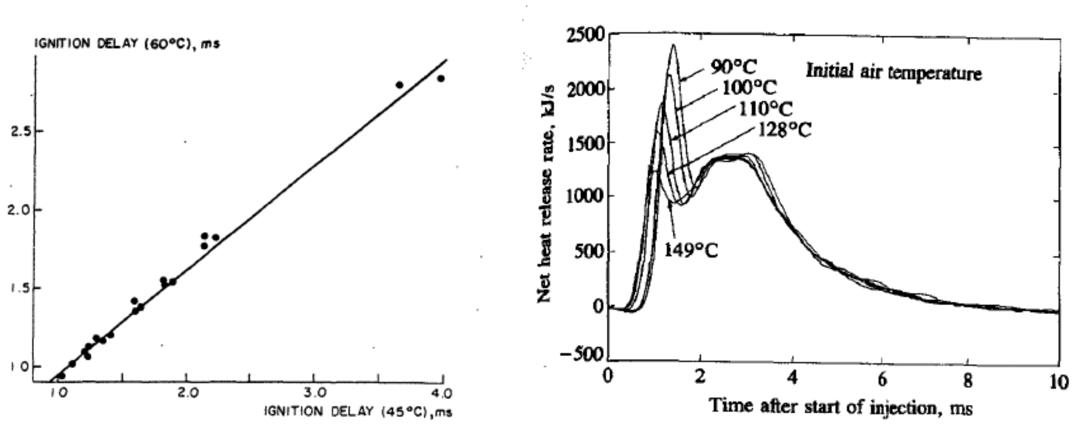


Figure 55: Ignition delay at 45 and 60 ^{0}C for various fuels[21, 38].

Increased charge air temperature will also affect the net heat release. As figure 55 shows, a temperature increase of 40 – 60 ^{0}C will give a smoother rate of net heat release. The high peaks when initial air temperature is 90 ^{0}C gives a higher pressure gradient resulting from a higher amount a fuel ignited, it also contributes to an ignition delay.

Another solution is earlier injection timing (if possible). Medium to low speed engines shall have injection in the area 10-15 ^{0} BTC[21]. The limits for advanced ignition timing is limited, it can move the injection spray into an air charge at a lower temperature and have an opposite effect. If the fuel injection is too early it will be mixed with cold air and have worsened the fuel spray. The ignition delay will be further delayed and combustion hardness will increase. Injection should happen when the charge air got a high temperature (late in the compression). In most cases changing the injection timing will not be a topic.

Engine load is an important factor. As engine load increases, the compression time (temperature change per time and pressure per time) gets shorter and ignition delay decreases, it is also from increased injection pressure as described in chapter 7. The relation is close to linear. This is shown in figure 56. As load increases, increase also the engines temperature, it heats up charge air and ease ignition conditions. This can be an explanation why vessels as described in chapter 14 experienced difficulties at low engine load. AUXs are seldom runned full load, electricity consumers as cranes, pumps etc have a on/off modus. High output is typically needed for a short time. Therefore, normally two or three AUXs are running on low load (around 50 %) to take care of high outputs, when necessary.

The optimal operational solution in relation to ignition delay is to have few AUXs running and at high load. In real life, this can be a bit difficult to achieve. If one or two AUXs are running near maximum, and more loads are put on the electrical system, the electrical system will regulate itself. Unessential loads as air condition, engine room ventilation etc. will be turned off and loads as cranes and pumps will be prioritized. This mode of operation it is a bit more complicated, but do not represent any direct hazards. On the other side, such mode of operation will worsen the crew's comfort and working environment.

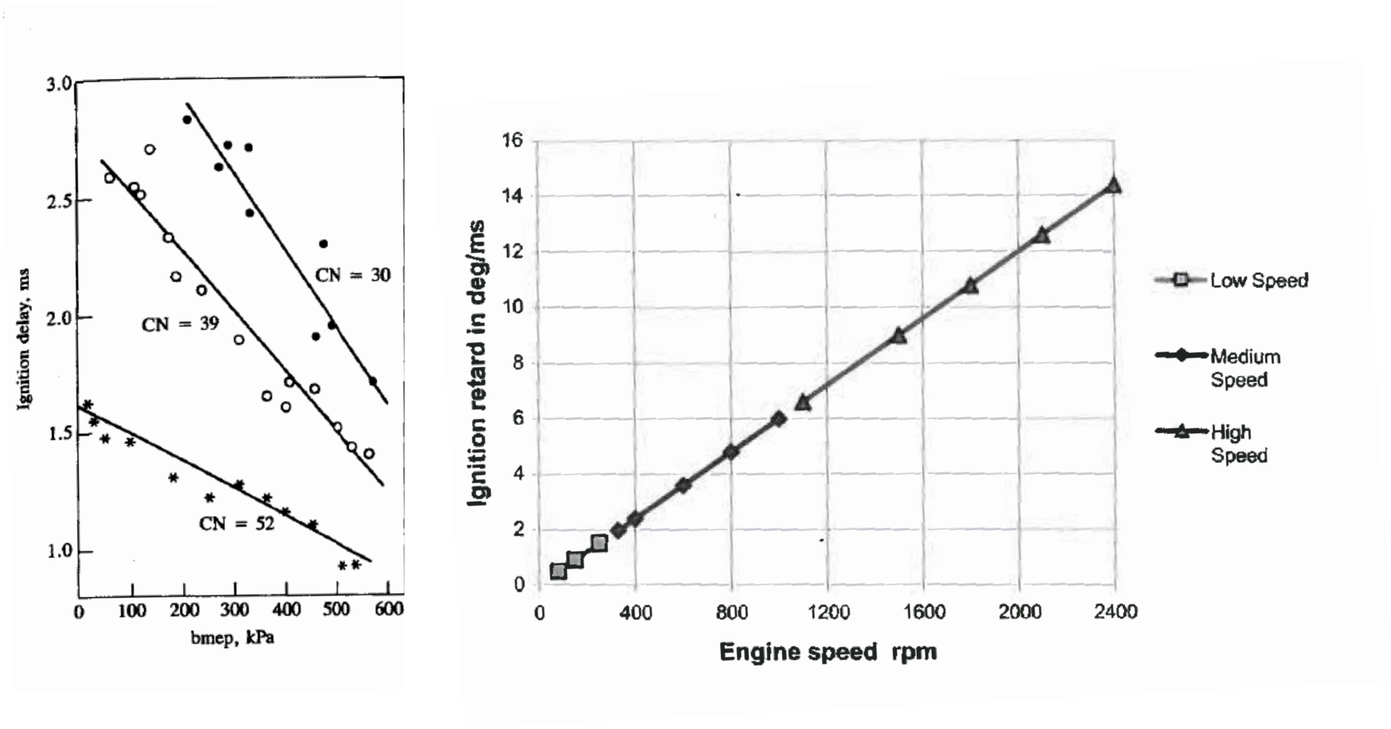


Figure 56: Ignition delay - engine load and corresponding deg/ms [21-22].

The charge air pressure can also affect ignition delay. Increased charge pressure give us higher compression pressure. This is especially relevant on low loads and for charge pressure below 1 bar overpressure [21]. Since marine medium- and low speed engines have turbo pressure around 2-3 bar (overpressure), a change in turbo pressure does not affect ignition delay any noticeable.

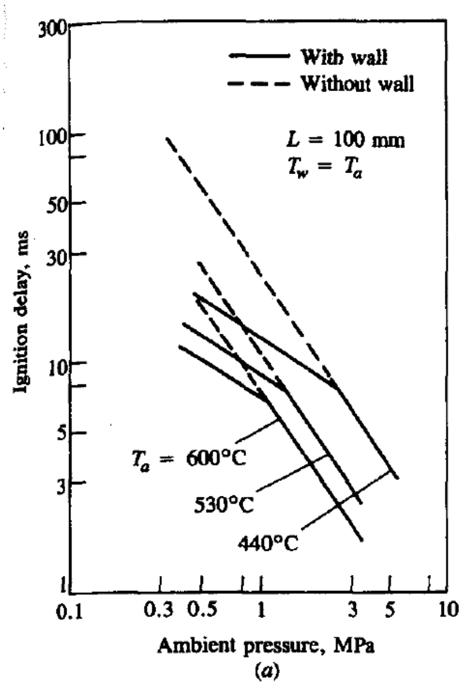


Figure 57: Charge air pressure and ignition delay.

A precaution that operators can do it to order a physical fuel test of all its fuel samples, e.g. through a fuel ignition analyzer (FIA). A physical analysis will give us the answer of how the fuel ignite. Fuels that have been tested in a regular fuel analysis can have very similar physical properties, this will result in the same calculated values on a fuel sample analysis. Through a FIA they can have completely different ignition performance.

If crew onboard suspect that a fuel got poor ignition/combustion performance, the most effective action is to increase charge air temperature, by choking cooling water to the charge air receiver.

13 Stability/compatibility

Fuel tested in a laboratory is tested for several parameters as described in chapter 5. Unfortunately, fuel stability or compatibility is not tested and is not a parameter in ISO 8217. Vessels are more and more dictated to use fuels with lower sulphur content, which are largely produced by mixing several unverified fuels. It is to be expected that that there will be more challenges with unstable marine fuels. Fuel stability and compatibility for blending are very important. Ideally, mixing of fuels shall not be done; in real life this is not so easy.

Another more complicated topic is the compatibility when mixing fuels. Vessels trading world wide are bunkering fuels from all over the world with its different characteristics. Fuel incompatibility is in many cases inherent to by-products mixed in the fuels that are delivered.

Introductorily it is important to emphasize that problems related to stability/compatibility are rare. In the same time, it is an area of concern and to be dealt with. As a rule of thumb we can say that similar fuel goes good together, as more different the blended fuels are from each other, vorsens its compatibility to each other. Fuels that are incompatible can be expressed as adding two magnetic plus-poles together.

Fuel stability is the oil's capability to stay as a uniform solution. Fuel compatibility is related to when two fuels are blended, that *they* shall stay as an uniform solution. Problems related to both compatibility and stability will be observed as a thick medium (high viscosity) or a two phase medium. In worst case it will block the fuel system and is a huge job to clean up. It can be dispersed by special chemicals which is very expensive.

It will in this chapter be discussed how HFO and MGO are stored for each other (stability) and how well they are stored together (compatibility).

When a vessel arriving a SECA area they have to switch from HSHFO to LSHFO. A vessel like this will normally carry HFO and MDO. They will carry HSHFO in the service tank and LSHFO in storage or settling tank. Prior a vessel arriving SECA area they will start filling service tank with LSHFO. Since these two fuel types are both HFO they are quite similar, probabilities for incompatibilities are therefore small.

Initiating problems related to stability/compatibility are observed as deposits (sludge) in tanks. Sludge have to be removed from the tank physically, and very expensive to deliver (2-3 times the price of HFO). Sludge cannot be used to anything and needs to be treated specially.

Some of the sludge is removed from the HFO in the separators. The separators are placed between settling- and service tank. A separator can either be configured as a purifier or a clarifier. A purifier removes sludge and water while a clarifier is for fuel with a low amount of water. If the fuel content a high amount of water they can be configured in serial. First through the purifier and then the clarifier as a second step. Normally there is only need for one separator as a purifier.

When entering an EU port, HFO will be replaced by MGO. As mentioned earlier in this thesis, MGO and HFO are very different and mixing shall be avoided. With WSMN's setup, which is normal for most vessels, **blending of these two fuels will happen in the pipes.** This makes it difficult for engineers to observe any incompatibilities, it will be observed as clogging in the fuel system. Either as a full clogging of the fuel system or a high pressure drop over components in the fuel system.

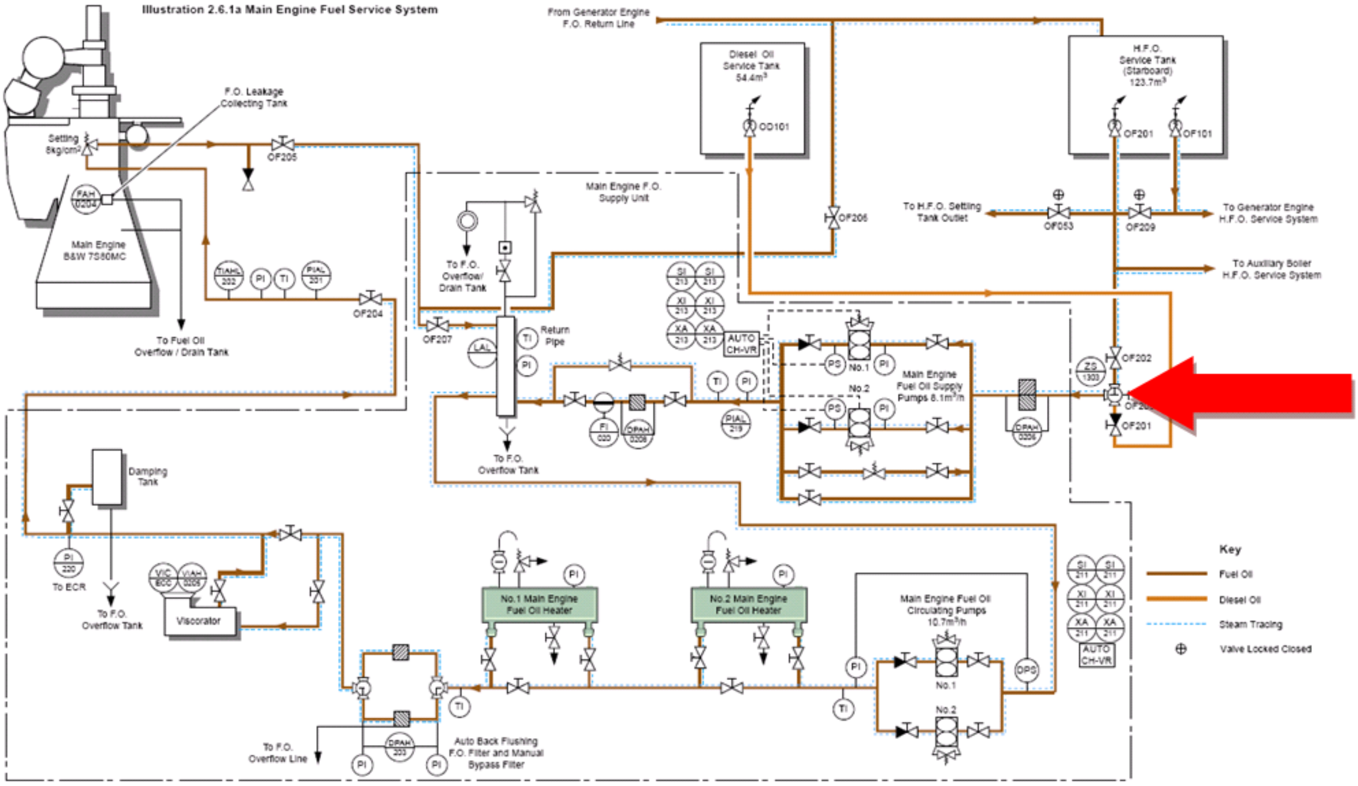


Figure 58: The point where HFO and MGO will be blended.

Fuel oil injectors are injecting a higher amount of fuel then needed for combustion. This superfluous fuel is lead to a tank (service tank). When operating on HFO, this overflow fuel is lead to HFO service tank. Under changeover we have two types of fuels in the fuel system. The stream of overflow fuel will be leaded to MGO tank after a certain time (when switching from HFO to MGO). In compatibility considerations, this time before leading overflow to MGO shall be as late as possible, when fuel in the fuel system consists of only MGO. It is better to get some MGO in the HFO than opposite.

All fuels contain sediments in different amounts. These sediments are bounded in the aromatics in the fuel and are therefore only “potential sediments”. The aromatic hydrocarbons are of a high molecular weight and contain fractions of sulphur, nitrogen, oxygen and metals as vanadium, nickel and iron.

When mixing fuels (as we have to when switching fuels) the fuel can burst. The aromatics cannot longer hold on the potential sediment to the mixture. When a fuel becomes *unstable*, the result is the same.

Most common distillate fuels are compatible with residual fuels. However, there is a possibility for complications to occur.

MGO is a clean fuel, compared to HFO. Technically it shall not be necessary to clean it further by using separator/purifier. If there is long time since last tank cleaning of MGO tank there can be presence of water and other particles in the tank, these shall be removed. This will introduce more blending of fuel since there is always some remaining fuel in the fuel system. On a general basis, fuels shall always be cleaned through a separator/purifier. If MGO tank and fuel system is clean, separators can be bypassed but this is not recommended as a permanent solution.

When blending HFO which is rich on asphaltenes (were the carbon-hydrogen ratio is *high*) with MGO which got less asphaltenes (were the carbon-hydrogen ratio is *low*), asphaltenes can fall out. HFO (poor on hydrogen) matches MGO (rich on hydrogen). The asphaltenes, that were earlier attached to HFO become mutually attracted and will fall out of the blend. These particles can be as big as 120 microns and makes the mixture thicker.

The possibility for getting an unstable mixture have also a time-variable. Fuel consumption for one AUX (MAN B&W 5L28/32H) is around 2,5 tons per day[15]. With a SFOC of 180 g/kWh this correlates to 60 % MCR load. This means that the engine will consume abound 100 litres per hour. With an assumption of fuel pipe size of 80 mm, 100 litres will give us 20 m of pipes. From capacity plan, is reasonable to assume 10 m pipe from MDO service tank to the AUXs placement.

If fuel changeover is done by switching a valve, the changeover will be done within one hour. This is not recommended, engine producers advice their engines to have a temperature gradient of 2 ^{0}C per minute. All ships shall have a proper change over procedure, specific for each ship.

WSMN is installing a diesel switch, delivered by MAN. With such solution the changeover will take a longer time that will ensure a smooth temperature differential. This is closer described in chapter 14.3.

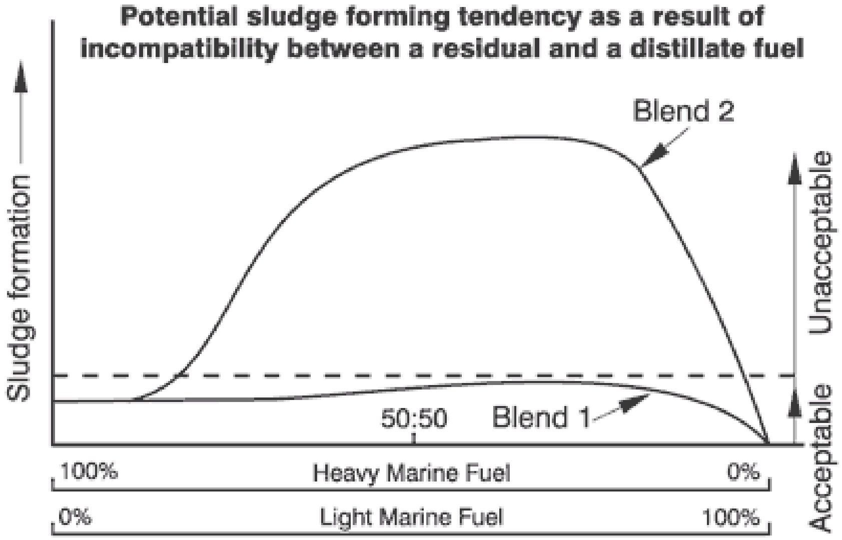


Figure 59: Potential sludge formation when blending residual and distillate fuel[40].

Figure 59 shows the sludge potential when residual and distillate fuels are blended. 50/50 ratio should be the worst occurrence, according to Kittiwake [40]. Work carried out by Shell Research shown that mixing ratio 10/90 high/low sulphur fuels is the worst case[60]. Note that in this research they used thermally cracked components which are normal to get today. DNV advices to mix maximum 10 % fuel at the same time. When installing a diesel switch, which is only a simple three way valve, the switch over ratio will occur linear. Ratio of HFO and MGO will be varying from 0 to 100 % and time frame at each percentage mixture will be as good as equal.

Different research and studies have come to different results and there is none established standard or procedures for mixing of fuels. Stability/compatibility is also new for the maritime industry and there is none well recognized standards/procedures for how mixing shall occur.

Blending of fuel shall be minimized and happen as late as possible in the fuel system, engineers shall have this topic in mind when switching fuels.

14 Preventive measures for operators

Since 1st of July 2009, ships were required to burn DMA fuel when entering Californian waters (24 nautical miles zone). The main difference in the regulations in California and EU, is that DMA is specified to be used in California, while in EU the sulphur content is the criteria. In California the fuel also have to be used on main engines. There have been several reported incidents from vessels calling Californian ports having problems maintaining rpm [44]. This resulted in vessels maintain higher rpm. For those vessels with constant propeller pitch, they are navigating at a higher speed than preferred.

According to SKULD, from the implementation date there were 15 reported casualties related to fuel switching[9]. More frequently, San Francisco Bar Pilots say that they have seen incidents every 1-3 days. Incidents resulting in situations mentioned above. Steffen Kortegaard from OW Bunker pronounced that statistics on loss of propulsion from Californian waters have skyrocketed[61]. In the period 2004 to 2008 the average statistics on loss of propulsion was 23,6 per year. In 2009 the number was 67! On an average six months period there should be 12 incidents with loss of propulsion. In the period July to December 2009 there were 22 incidents above average. If there is a correlation between implementation of California's new regulation is not confirmed but there is reason to believe that there can be a connection.

Experiences from Californian regulations and findings in this report show that the new type of fuel will introduce several more sources for failure. Existing engine/fuel-systems has to be checked and confirmed that they are suitable for safe operation on MGO. Modifications may be necessary to be carried out.

In this chapter there will be described components that have to be modified or monitored and necessary operational considerations.

14.1 Changeover procedures

When changing fuels, it shall be established procedures of how the changeover shall happen. Crew from different nationalities, speaking different languages and dialects can lead to misunderstandings and further undesirable situations. There shall therefore be a written procedure with no chance of misunderstandings.

From class, it is not a direct requirement for operational procedures. Since this is a safety issue, ISM-rules are applicable and this will be required in the safety management onboard.

A fuel change shall be noted in the engineer's log book. If there shall be any control for sulphur content in fuel used, this is a vital evidence.

Also overflow routing as described in chapter 13 shall be clearly noted in the changeover procedure. It is better to get MGO in the HFO system than opposite, HFO system is heated while MGO is not. Overflow to MGO tank shall be done as late as possible to minimize risk of filter clogging from incompatibilities.

When operating on HFO, some quantity of HFO will be remaining in the pipes due to HFO is a dirty product and can make a partial coating in the fuel pipes. MGO has a cleaning effect on these remaining constituent parts of HFO. Remaining parts of HFO can disperse and accumulate in the fuel system, a typical result is clogged filter. This is a potential reason for incidents experienced in Californian waters.

MAN Diesel have given a short guidelines on how the changeover shall be carried out[62]. It can be summarized by (for HFO to MGO):

- Reduce engine load to 25-70 % MCR.
- Stop steam tracing for HFO
- Start changeover, avoid temperature changes 2 ^{o}C per minute.

For changeover MGO to HFO the process are reversed.

Such changeover shall either be done at sea (which will be most economically) or when the vessel is safely secured at berth (which is safest). Any problems related to the changeover can affect propulsion and navigation, changeover in narrow waters shall therefore be avoided.

14.2 Cooler

From ISO 8217 the lowest DMA viscosity limit is 1,5 cSt. It is assumed that this limit will be increased when the new version of ISO 8217 will be launched. A cooler that cools the fuel oil is an easy and good solution. The cooler shall be placed right before engine inlet. Stipulated that the cooler works and keeps the MGO below 40 ⁰C, there shall not be any problems with internal leakages in fuel pumps. A cooler is available from maker, price for the unit start about EUR 28.000. A graph or table showing the relationship between viscosity and temperature of DMA should also be onboard. With a such remedy engineers have a guideline for safe use of DMA.

Cooling medium can be central cooling water onboard (fresh water), containing a typical temperature of around 36 ⁰C. If this is not enough, a chilling unit have to be used. A chiller removes the heat through vapour-compression or an absorption refrigeration cycle. A system layout is presented in figure 62.

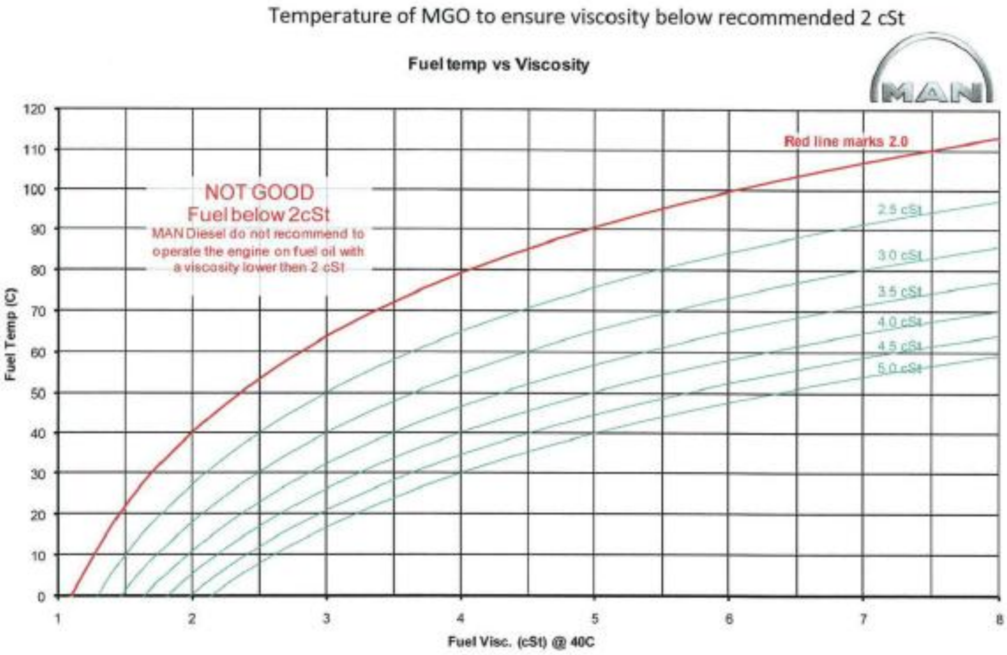


Figure 60: Viscosity and temperature for DMA [31].

Note: The horizontal axis shows the bunkered fuel viscosity in cSt at 40 ⁰C. If the temperature of the MGO is below the red curve at engine inlet, the viscosity is above 2 cSt.

The cooler/chiller introduces a new challenge, residual fuels' pour point. Residual fuel has a pour point limit at 30 ⁰C, analysis shows that fuels tested their pour point is close to the limit. A cooler/chiller should be used with caution; too heavy reduction in fuel oil's temperature can form a two-phase mixture. DMA as one phase, and partly pumpable HFO as another phase. I have not heard about occurrences of such problems, but it is a though to have in mind when operating the cooler/chiller.

14.3 Diesel switch

The changeover from HFO to MGO (and vice versa) can result in thermal shocks if this happens too quickly. Thermal shock may lead to uncontrolled clearances and further sticking/scuffing of the fuel oil valves, fuel oil plungers and suction valves.

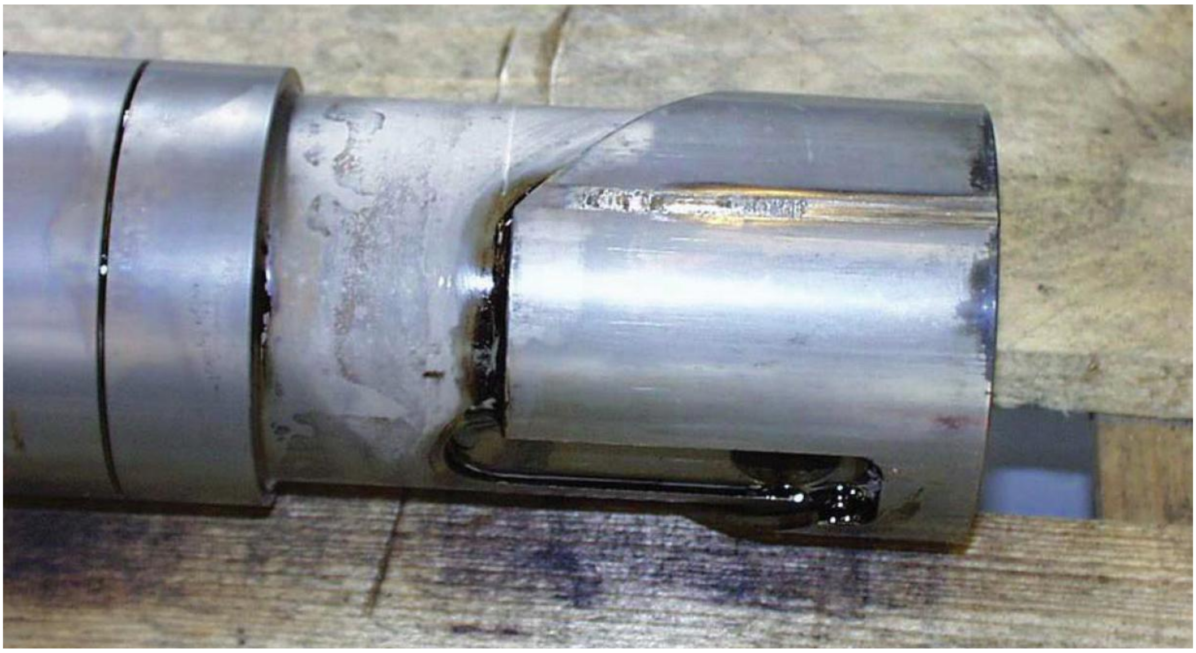


Figure 61: Fuel pump plunger sticking.[31]

Manufacturers of engines and boilers have advised a maximum temperature difference of 2 ^{0}C per minute. Preferable viscosity when HFO (380 cSt) reaches the injector is 13-17 cSt, temperature is then 134 - 124 °C. Manufacturers usually have a viscosity interval 2-20 cSt which leads to a temperature interval for HFO (380 cSt) of 120-150 °C. If HFO got a temperature of 150 ^{0}C and switching over to 40 ^{0}C MGO, the theoretically lower changeover time will be 55 minutes. This is as mentioned the minimum time it shall take for not exceeding maker's recommendations. This needs to be planned in the voyage planning so engineers don't get rushed when meeting regulated waters.

It is imaginable that managers instruct their vessels to change to MGO as late as possible so save the extra money on fuel expenses. In worst case this can lead to total blackout in close waters. Any problems related to the changeover and MGO's properties shall be dealt with in open waters or safe moored in port.

In order to minimize human related errors to the changeover, it is of safety considerations recommended to purchase a diesel-switch. This is sold by makers and is a simple unit [63]. This is a three-way valve operated by temperature sensors. The valve shall be located in the intake for fuel oil system where fuel oil quantity is chosen. The unit is very expensive, prices starts at EURO 30.000 and this is for the unit alone, man-hours etc. comes in addition. It is also an option to control the diesel-cooler with the diesel-switch. Many ship owners will choose both diesel switch and diesel cooler. With a total price of EUR 58.000 only for the units, complete price for installation will be close to EUR 100.000 including man-hours, travel etc. This is a good opportunity for MAN to make an extra income; it is also precarious that they sell products to customers based on safety related threats.

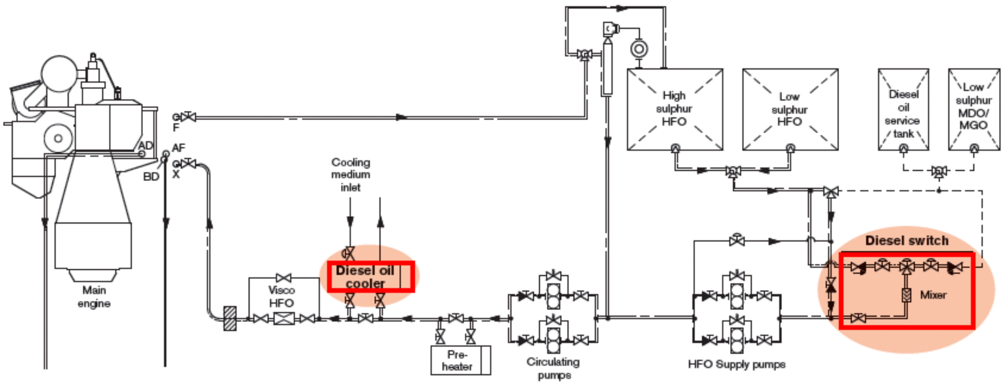


Figure 62: Location of diesel switch and cooler.

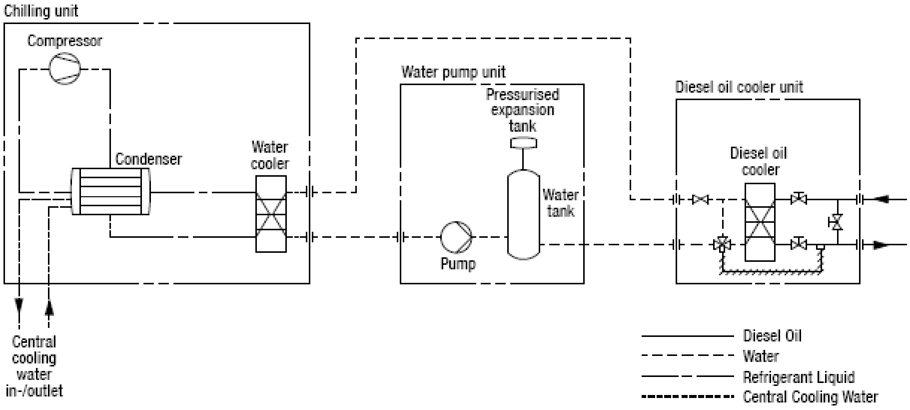


Figure 63: Diesel oil cooler and chiller[64].

Maker (MAN) advice operators to reduce engine load to 25-40 % MCR to “control the changeover”. This in many cases makes it necessary to start up one additional AUX to meet electric demand onboard. As discussed above, reduced load is not preferable when using MGO of low viscosity. Especially is it is the first time this lot are used and its properties are unknown.

14.4 Change/inspect injector plungers

Fuel oil is injected mechanically (not common rail) for AUXs on all vessels managed by WSMN. This is a piston pump, cam shaft driven and there is one injection unit per cylinder. The plunger is directed by a rocker arm that is controlled by the camshaft. This injector is exposed for wear and tear over time. When plunger is worn, we can experience internal leakages in the clearances from plunger and cylinder wall. When operating on fuels with very low viscosity, the situation is the same. Injection pressure will decrease and fuel spray will worsen. In worst case, engine load will decrease. This is most probably the situation occurred when operators experienced reduced load on the engine, this is further described in chapter 15

If injectors are old, plungers shall be changed so the internal leakage is minimized. These parts can be purchased from maker and the replacement is done by engineers onboard. It is also advisable to have spares onboard (full set).

14.5 Regularly inspect fuel hoses

Internal leakages in the fuel injection pump will result in reduced pressure in the pipes. This is also applicable for supply/booster pump. Reduced pressure increases evaporation (gassing in the fuel) and cavitation inside fuel pipe and hoses. These inside damages can lead to leakages, either as cavitation over a longer period or cavitation that will lead to strength fatigue of a pipe/hose. The same cavitation will also make pittings on other parts in the fuel system.

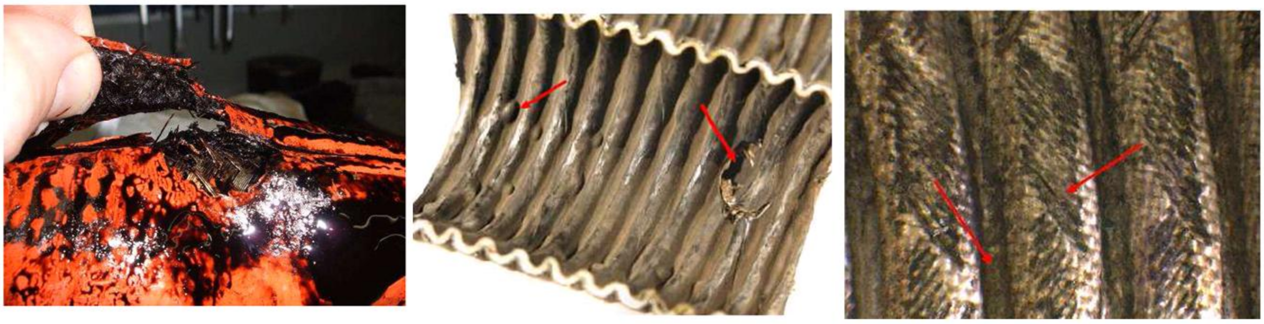


Figure 64: Damaged fuel pipes and hoses. [30]

Figure 65: Breakdown of nozzle lifting spring.

Opening spring in injection nozzle is also critical, high forces and repeating motions making it very sensitive to pittings and further cracks. Such development is not possible to observe before an accident occurs.

Typical nozzle holes' diameter is in the area 0,1 – 0,6 mm [21]. Particles released from cavitation can easily block nozzle holes. Blocking of nozzle holes can be hard to recognize, normally after noticeable reduction in performance of one cylinder unit. To find out whether nozzle holes are blocked requires extensive troubleshooting, nozzle holes it not the first item to suspect when one cylinder unit it performing poor.

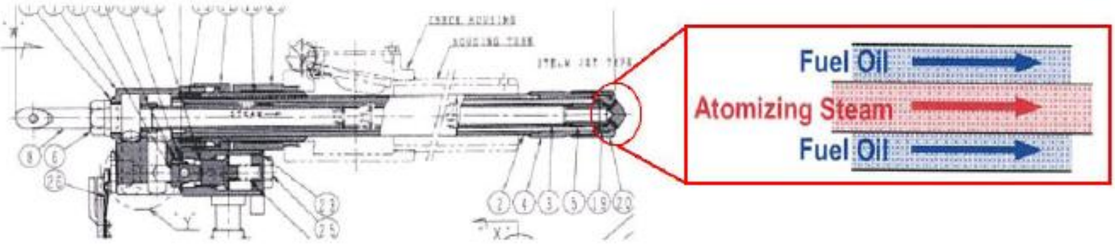
Broken nozzle lifting spring and blockage of nozzle holes is not possible to foresee but it good to have in mind when troubleshooting.

14.6 Increase charge air temperature

As described in chapter 12, ignition delay can be a problem. *If* engineers onboard experience this, or have a suspicion about it, they shall choke the cooling medium to charge air cooler. This is the only trick to improve ignition conditions if the ignition performance is suspicious.

14.7 Boiler Burners

The most important part on the burner is the atomizer. This is the unit that converts liquid fuel to small droplets. This makes the surface of the fuel larger and easier to ignite. When using HFO, HFO is mixed with high pressure steam through a nozzle in the end of the atomizer.
Switching from HFO to DMA, high pressure air is used instead of steam. This is because of the different properties concerning viscosity and heat as explained earlier. There must be installed one more nozzle designed for DMA fuel. Nozzles must then be change by crew depending on which fuel is being used. This is a plain operation and since this is a top-fired boiler it is an accessible area and don’t requires any staging.



A new pump suitable for DMA must also be installed. Mitsubishi has chosen a pump from TAIKO, this is a screw pump suited for light fuel oils and low viscosity. This new pump will give the same pressure as before and the fuel flow will be unchanged. WSMN has given maker (Mitsubishi) the modification job for the boiler. In this way maker will be responsible for the whole system. Maintenance and support can be difficult if the modifications had been done by subcontractors. The whole job will be done with representatives from maker at anchor. No need for a berth and off-hire is avoided.

14.8 Boiler’s flame detectior /flame eye

To monitor the “new” combustion, the flame eye has to be replaced by a more sensitive one. Flame eye is the same as a flame detector. If the fire stops for some reason, the flame eye should detect this and shut down the fuel supply. This is because of DMA burns different from HFO, especially on low throttle. The light from burning DMA is different from HFO and will then be different observed by the photocell (flame eye).
The control panel and its software also have to be modified. This is for controlling and implementing the new components and make sure the whole system works together. Since the heat value for DMA is slightly higher than HFO and density is different, it will be necessary to change the fuel/air ratio. This should not be an issue since this can easily be adjusted under run-in and test with manufacturers’ representative onboard.

14.9 Fuel pumps

Most pumps of these kinds are screw pumps. Engine manufacturers as MAN and Wärtsilä say their fuel pumps have a lowest operating limit of 2 cSt. Below this limit they may not deliver necessary flow and pressure around 6-8 bar. To be on the safe side, it is recommend contacting maker for advices and their experiences. These pumps may also operate properly below 2 cSt, depending on their condition. Answers from maker will normally be a limit of viscosity at a certain temperature. Temperature is not easy to maintain as the vessel is operating in all kind of weathers. Statistics shown in chapter 5.2 shows that the viscosity of DMA sold the two last years were stable around 3 cSt (measured at 40 ^{0}C). As this trend can change and the temperature in engine room can get above 60 ^{0}C in hot areas it is recommended to install a pump that can operate down to 1,5 cSt.

Boiler manufacturer Aalborg on the other side says their fuel pumps have a lower viscosity limit of 4,5 cSt. I have not found any pronounces from Mitsubishi on this topic, but they recommend installing their TAIKO pump.

From normal use on HFO, there are two fuel circulation pumps. This redundancy will not be maintained with only one low viscosity pump. Class don't have any redundancy requirements for the new pump since this is classified as a stand-by pump[65]. The same applies for cooler/chiller.

Running of fuel pumps when boiler/aux is standby shall not be done, this will increase the pressure and temperature. Further will the viscosity be even lower and the result is worse working condition for fuel pumps. It is therefore advisable to modify the control system that fuel pumps only running when necessary.

14.10 Risk assessment

Ship owners and managers are required from the ISM code (ISM Code 1.2.2.2) to do assessment of risks and potential hazards to their vessels. A new type of fuel and modifications done to engines and boilers has to be assessed. INTERTANKO has made a generic "HAZARD analysis document". This is so simple that it cannot be seen as other than a show for the gallery and a paper that can be shown on an ISM audit. How each component is affected is generalized in chapter 15.

14.11 Less significant measures

As described in my Project Thesis[13], lubrication oil does not need to be changed as operation on low sulphur fuels are only for a short time (in port stay). If an engine shall be using low sulphur fuel over a longer period, changing cylinder lubrication oil shall be considered.

When fuel is bunkered, a sample is taken and sent for analyses. Fuel received will not be used before the result is known. Test kits are not normal to have onboard. There are several solutions, from a simple set fitted in a suitcase to more advanced ones. NanoNord have made a advanced test kit[66] in cooperation with Lloyd's Register. The parameters measured is almost the same as you will get from a laboratory. The test kit is a stationary cabinet placed onboard. To buy a fuel analysis from a laboratory will be cheaper and have a higher degree of trust. There are several sources for human related failures to a test-kit. The only solution is to get an satisfactory answer is to check the fuel by a reputated fuel analysis company.

Parameters that can identify any sub standard fuel, as discussed in chapter 5, will not be detected by any test kit either.

As a rule of thumb, engine/boiler or equipment manufacturer should be consulted, many of them have in-depth knowledge on this topic. In the same time, many of them see their opportunity to sell or upgrade equipment that may not be necessary. Recommendations from class are independent as they have no intention of selling any products.

It is to be emphasize that none of the mentioned modifications are a class requirement. From IMO regulations of safe operation these findings comes in a grey area since their impact can be over some time.

15 Which fuel system components are sensitive for using MGO?

All ship management companies need to hold a DOC (Document of Compliance), meaning that the company complies with the ISM code (International Safety Management). In the ISM code is it stated:

10.3 The Company should establish procedures in its safety management system to identify equipment and technical systems the sudden operational failure of which may result in hazardous situations. The safety management system should provide for specific measures aimed at promoting the reliability of such equipment or systems. These measures should include the regular testing of stand-by arrangements and equipment or technical systems that are not in continuous use.
10.4 The inspections mentioned in 10.2 as well as the measures referred to in 10.3 should be integrated into the ship's operational maintenance routine.

From the ISM code ship managers are committed to find out which and how each equipment and technical system contributes to safety hazards. In respect of EU Directive 2005/33/EC, they have to find out which system/component that is affected by 0,1 % sulphur MGO and how to deal with these potential problems.

In this chapter it is made an overview of the different components in the fuel system. To identify new, potential problems, it is found necessary to give a short explanation of each component's "normal" failure modes. As described previously in this thesis, new operational characteristics from 0,1 % sulphur MGO are; low viscosity, poor lubricity and temperature fluctuations.

The fuel oil system for MT "Kronviken"/ MT "Solviken" are presented in Appendix C. Fuel oil system is separate and equal for both ME and AUXs. This means that ME and AUXs can run in different fuels at the same time.

For MT "Storviken"/ MT "Erviken" the fuel oil system got the same components but a different configuration. Their fuel oil system is presented in Appendix D. MT "Storviken"/ MT "Erviken" has common HFO system and separate MDO/MGO system. Since MDO/MGO tank pipes/valves are not connected to the HFO system, there is not possible to install a diesel switch unit. If a switch shall be installed, it would be one switch per AUX. Such a solution will be very expensive. WSMN has decided to not install diesel switch for Erviken/Storviken. Switching on

Erviken/Storviken will happen by turning a valve, a sudden switch. Such sudden switch will result in sudden temperature fluctuations and is not recommended, as described in chapter 14.3.

Each fuel oil system with their components for MT “Kronviken” / MT “Solviken” and MT “Erviken” / MT “Storviken” is studied and further generalized. Both types of fuel oil system layouts have the same components in the same sequence. A generalized fuel oil system layout is illustrated in figure 66.

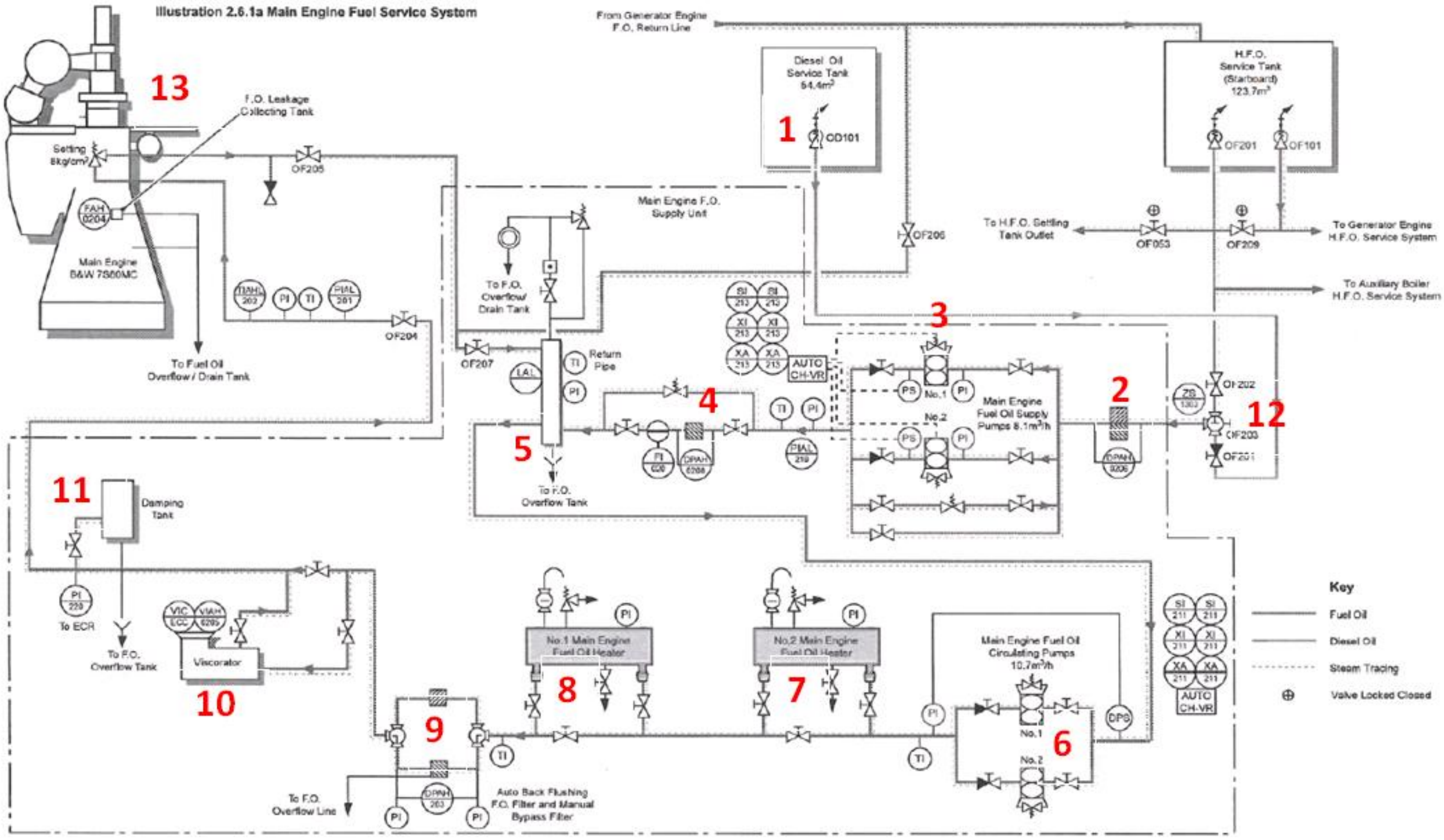
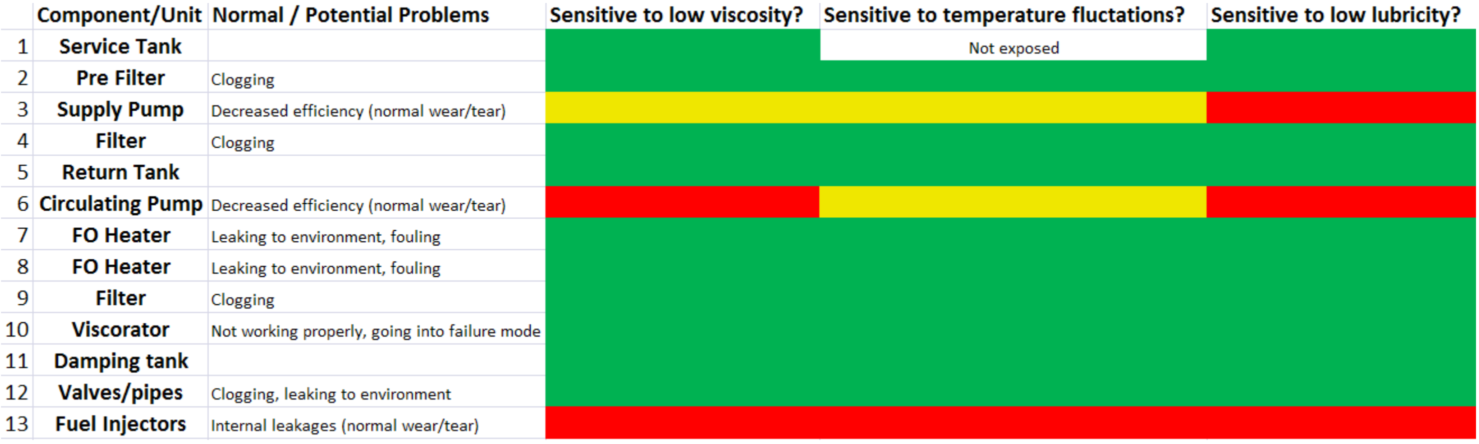


Figure 66: Generalized fuel oil system.



	Component/Unit	Normal / Potential Problems	Sensitive to low viscosity?	Sensitive to temperature fluctations?	Sensitive to low lubricity?
1	**Service Tank**		🟩	Not exposed	🟩
2	**Pre Filter**	Clogging	🟩	🟩	🟩
3	**Supply Pump**	Decreased efficiency (normal wear/tear)	🟨	🟨	🟥
4	**Filter**	Clogging	🟩	🟩	🟩
5	**Return Tank**		🟩	🟩	🟩
6	**Circulating Pump**	Decreased efficiency (normal wear/tear)	🟥	🟨	🟥
7	**FO Heater**	Leaking to environment, fouling	🟩	🟩	🟩
8	**FO Heater**	Leaking to environment, fouling	🟩	🟩	🟩
9	**Filter**	Clogging	🟩	🟩	🟩
10	**Viscorator**	Not working properly, going into failure mode	🟩	🟩	🟩
11	**Damping tank**		🟩	🟩	🟩
12	**Valves/pipes**	Clogging, leaking to environment	🟩	🟩	🟩
13	**Fuel Injectors**	Internal leakages (normal wear/tear)	🟥	🟥	🟥

Table 5: Assessment of how fuel components are affected by low sulphur MGO.

Not surprisingly, fuel injectors is the most affected component, it is negatively affected by all the new properties of 0,1 % sulphur MGO. Supply and circulating pumps is also affected, but they will only give reduced performance, fuel injectors can stick and contribute to a sudden engine stop. It is therefore advisable to have several complete injection units onboard as spares.

DNV PS has conducted a survey [67] in January 2010 on the operational impact of EU Directive 2005/33/EC. 65 shipping companies participated in the survey so the findings are pretty certain.

Their frightening findings are:

- *"Another 15% reported filter choking and fuel pump seizures when switching from normal sulphur heavy fuel oil to the much more expensive gas oil on entering the EU community ports."*

- *"Surprisingly, almost a third of the respondents did not routinely test the quality of their gas oil purchases."*

15 % experienced filter choking and injection pump seizure; this is a very high figure and is a direct safety issue. With such a situation, engine can stop and a total blackout onboard is highly possible. Only on basis on such a number, EU and its member states should slacken their demands and give a wider phase-in period. One may wonder whether it will be necessary with an accident for this to happen. There is a clear impression that several ship owners don't have knowledge about low sulphur MGO and its properties.

The fact that only two-thirds routinely check the quality of MGO purchased is direct stupidity. To get a normal fuel oil analysis done by DNV PS or FOBAS cost around USD 500 per sample. This cost in relation to costs of potential engine problems due to bad fuel should leaves all doubt.

There are some advantages in the use of low sulphur fuels. Less sulphur content results in less acid based corrosion on cast iron. Engine and exhaust components will last longer due to reduced wear. This is condensation of sulphur compound on liner surface (sulphur compounds reacts with water droplets and produces sulphur trioxide). Dew point for sulphur trioxide is not easy to establish, Shell have done research on this is 1978 and 2000 with different results[45].

The exhaust gas is also cleaner since MGO is cleaner then HFO. In relation to inert gas generation, less scrubbing/cleaning of the gas is necessary before use.

16 Environmental issues

When fuels with reduced sulphur content are burned, less sulphur is released to the environment. The negative aspects of sulphur as described in chapter 5.5 will be reduced.

Potential operational challenges related to 0,1 % sulphur MGO as described in chapter 12 may give increased NO_x emissions. NO_x emissions is regulated for new engines from IMO and their tier regulation, increased NO_x emissions due to strict regulations as EU Directive 2005/33/EC can be a step in wrong direction. The amount of NO_x emissions from ignition problems are minor in relation to the amount of sulphur saved.

In the EU region, vessels will change from MDO to MGO. Assuming that numbers of incidents with oil spills are constant, MGO instead of MDO will be spilled to the ocean. It have not been possible to find standard tests for biodegradability for MGO compared to MDO [56, 68]. In general biodegradability theory, lighter components will biodegrade easier than heavier. The introduction of MGO will in this relation have a positive effect. Consequences of a MGO spill are therefore proposed as further work.

17 Enough low sulphur fuel in the market?

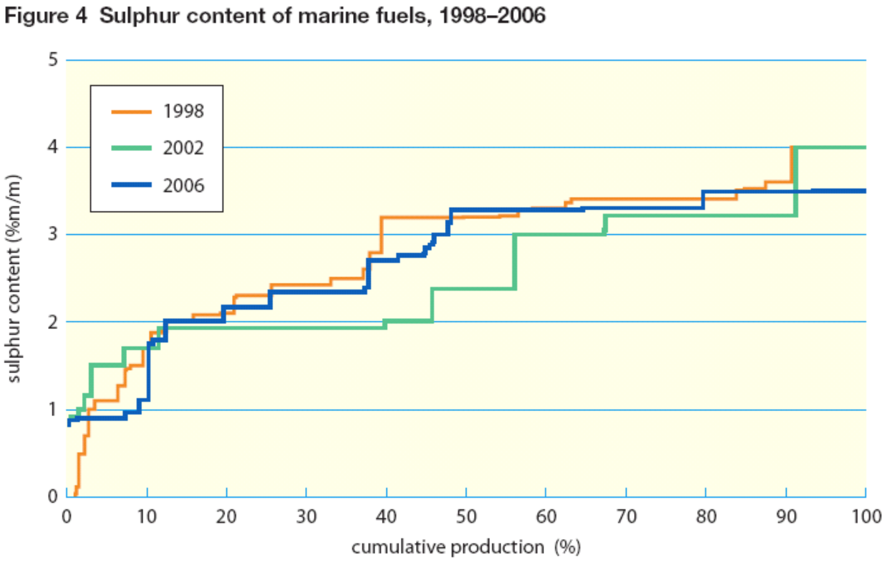


Figure 67: Sulphur content of marine fuels, 1998-2006 [69].

In fuels for automotive use, sulphur are as good as eliminated. The ongoing area is marine fuels. As the sulphur calendar shows in figure 1, there are new, strict limits coming in short time in already regulated areas. Another topic is the concern on new areas. This will definitely come in near future. Statistics from refineries shows that legislations are adopted (by commissions and further member countries) are taking effect and reduces the sulphur content in marine fuels dramatically. From 2015, vessels operating in SECA areas were dictated to use 0,1 % sulphur fuel. This means that MGO has to be used on ME.

The intention for these regulations is to decrease the global sulphur content of marine fuels. Today the global sulphur cap is 4,5 %. The plan is to reduce this figure to 3,5 % by 2012 and further 0,5 % by 2020 or 2025 (subject to a review in 2018).

Marine fuels stand for around 20 % of world's total fuel oil demand. 80 % are residual fuels while 20 % are distillates. In today's SECA rules the sulphur limit is 1,5 %, there is residual fuels available at this sulphur content. The drastic change in EU Directive 2005/33/EC is that 0,1 % sulphur fuels is only available in distillates, not in residual fuels. Vessels are decreasing its use of residual fuel, and increasing its use of distillates, making an increased demand for distillates. The share that is today sold as residual fuel has to be further refined and sold as distillates. In most cases the residual fuels are so poor on light fractions, making this process difficult. In that case, residual fuel's quality will be even inferior.

From general supply/demand theory, and arguments above valid, the price of distillates shall increase in the future. The price of fuels is strongly correlated with crude oil price. To de-couple the price development for distillates from price of crude oil is not easy.

EU Directive 2005/33/EC is only applicable when vessels is at berth, quantity distillates versus residual fuel is then low. In 2015 a similar regulation is concerning the whole SECA areas in Europe, quantity burned distillates will then increase drastically as 0,1 % sulphur fuel will be used on ME. If there shall come a noticeable increase in the price of distillates (corrected for the price change of crude oil), it shall come in 2015 when there will be consumed a larger quantity of distillates.

The fact that demand for residual fuel is decreasing, forcing refineries have to make an adjustment. Highly possible, new cracking methods will be developed to utilize the residual part of crude.

18 Lessons to be learned

EU Directive 2005/33/EC is one of many environmental regulations, there will for sure be introduced many more in years to come. Ship owners and manager should have a proactive approach and understand each regulation thoroughly.

The first obvious change in EU Directive 2005/33/EC is the sulphur content. The fact that this resulted in very low viscosity and poor lubricity are topics that came the last year. Marine experience on lubricity is limited and experience so far is that (too low) viscosity is more critical than lubricity. However, this is a topic that is still not clarified.

When introducing new regulations, the changes to the exposed components (machinery/boilers) should have been deeply investigated and findings highlighted for all affected parties.

Today, every ship owner stands alone and has to find a solution that will suit its vessels.

19 Conclusion

There have in this thesis been highlighted the main challenges and proposed solutions regarding EU Directive 2005/33/EC. MGO is new for the industry and experiences are now gathered. In order for WSMN to provide top quality ship management services, they shall have knowledge about 0,1 % sulphur MGO and their vessels shall be undergo necessary modifications.

The main difference between MGO is HFO is low viscosity. To increase the viscosity, a diesel cooler shall be installed. To be on the safe side, and as a redundancy to the diesel cooler, new injection units shall be kept on board.

Changeover operation from HFO to MGO and vice versa shall be as automatically as possible. For this reason a diesel switch shall be installed. Ship specific changeover procedures shall also be established. There shall be two types of changeover procedures; one including the diesel switch and one with manual operation of valves, in case the diesel switch is not working.

Burner's burner/atomizer and flame eye shall be modified for MGO use.

A normal fuel sample analysis shall be "upgraded" with a C/H ratio. This will give us vital information and compensate for the poor information from ISO 8217 about a fuel's ignition/combustion properties.

In all measures mentioned above, manufacturers shall be contacted and solutions to be approved by them.

19.1 Suggestions for further work

After assessing 0,1 % MGO and EU Directive 2005/33/EC there are some key topics that needs to be further assessed, they are as follows:

- An oil spill of MGO versus MDO: Vessels trading in EU will exchange MDO with MGO. A potential grounding, and further oil spill will be interesting to investigate. Degradability studies of 0,1 % sulphur MGO have, after my knowledge, not been done.
- Carbon/Hydrogen ratio: A FIA-test is too expensive to do on all fuels but is the most accurate test. C/H ratio is the parameter that correlates best to FIA results, which is the most accurate parameter when it comes to ignition/combustion performance. Further assessment of C/H ratio of a fuel and establish limits can give vital information at low cost.
- A fuel's lubricity properties: Low viscosity and poor lubricity are causing the same problems. A separation of these parameters involves a deeper insight in a fuel's lubricity properties. I do believe much vital information can be gathered from the automotive industry.
- Best practice in industry: Do surveys on each engine, how each engine type and manufacturer is affected by 0,1 % sulphur fuel, and why. There are sub-suppliers that make the injection system for engine manufacturer. Is there any best practice in the industry when it comes to injection system? Any manufacturer that delivers injection system that can handle low viscosities good?

These bullets are most linked up to ship owners and operators. Questions raised above can be assessed as a cooperation project by ship owners.

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21 Appendix

21.1 Appendix A - MGO bunkering receipt and analysis

21.2 Appendix B - Example of 380 cSt fuel oil analysis

21.3 Appendix C - Fuel oil system for Kronviken – Solviken

21.4 Appendix D - Fuel oil system for Erviken - Stroviken