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GUIDELINE FOR THE OPERATION OF MARINE ENGINES ON LOW SULPHUR DIESEL

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The International Council on Combustion Engines

Conseil International des Machines a Combustion

Contents

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1 Executive summary

This document has been prepared to advise the crew, users, vessel owners, charterers, crew, fuel and lubricant suppliers, equipment manufacturers, and classification societies about the fuel sulphur reduction options and implications, and especially the introduction of 0.10% m/m sulphur distillate in the ECA's from 1 January 2015. There are also general sections to provide information on legislation, economic implications, refining and supply considerations and operating vessels on lower sulphur fuel.

IMO MARPOL Annex VI provides the legislative framework for fuel sulphur reductions and the associated timing. The relevant parts of this legislation are in the document and the implications of the changes are analysed.

Manufacturing, supply and fuel economic considerations are analysed and discussed. There is little doubt that the move from residual to distillate will increase costs considerably. An alternative is to install scrubbers or other aftertreatment devices to reduce the sulphur emission to a level which is in compliance with legislation. There is a large amount of information available on scrubber aftertreatment technology and as this is changing continuously it is not covered in detail in this document.

There are a number of operational issues which must be considered to ensure efficient and safe vessel operation on the low sulphur distillate and when changes and changeover of fuel are made. Vessel crews need to familiarise themselves with this information to ensure that smooth transitions between fuels are made. There are also a number of engine operational procedures which need to be followed in order to ensure that short and long term operation on distillate fuel does not lead to wear or malfunctioning of fuel system and engine components.

The impact of renewable liquid fuels is covered and some recommendations to facilitate operation on these fuels, if chosen, are given. As the scope of this document is limited to liquid fuels, there is no detailed information provided for operation on LNG or other gaseous fuels.

2 Introduction and scope

The purpose of this publication is to provide a reference for the transition to lower sulphur marine fuels in the Emission Control Areas (ECA's), compliance options and fuel sulphur reduction in general. The document specifically addresses issues around the reduction of fuel sulphur to 0,10% m/m maximum from 1 January 2015 in the ECAs. Tier III NOx legislation is beyond the scope of this document as it is scheduled for introduction after 2016 and is not a fuel related issue. Whenever "ECA" is used in this document, it refers to an ECA established to limit SOx and particulate matter emissions in accordance with regulation 14 of MARPOL Annex VI. LNG and other gaseous fuels are beyond the scope of this document.

Ship transportation is considered the most energy efficient mode of transport producing the lowest CO_2 emissions on a mass and distance basis. Nevertheless, SO_2 emissions generated by the merchant fleet represent a significant contribution to the global emissions.[1] The sulphur content of marine fuels is determined by local legislation and regulated on a worldwide basis through the International Maritime Organization (IMO) [2] MARPOL Annex VI which is in turn implemented by national legislation of the signatory Parties

The world is moving to lower emissions based largely on environmental and health considerations. Sulphur has a relatively short atmospheric lifetime, 1 to 2.5 days for SO_2 and 4 to 6 days for sulphate.[1] This implies that the highest concentrations and heaviest depositions of sulphur are found close to the sources. Sulphur emissions from ships have an impact both in remote oceanic areas and near the coastline where there is a high density of ship lanes. Emissions of SOx (the bulk of which is SO_2 but SO_3 and other species also occur) are a major contributor to acid deposition which has demonstrated harmful effects to the natural environment as well as building structures. Sulphur together with primary emissions of fine particulates can also harm human health.[1]

This transition brings about economic, technical and environmental implications which need to be understood. Broadly speaking, lowering fuel sulphur limits has the potential to reduce fuel choice as well as alter the structure of refined product markets. It may lead to rising fuel prices. Manufacturing a greater proportion of lower sulphur fuels will tend increase CO_2 emissions due to increased refinery energy use. [3]

A number of options are in place or under development to reduce the emissions of ships. The marine industry will be one of the key areas of environmental focus for the next decade. This is expected to place a significant challenge on the supply of low sulphur fuels.[4] Engine builders and owners may need to optimize their engines to operate on low sulphur fuels. Exhaust gas after treatment devices such as scrubbers are an alternative to the use of low sulphur fuels as they remove the sulphur products of combustion prior to discharge of the exhaust gas to the atmosphere thus allowing the continued operation on high sulphur fuels.

The primary objective of this document is to provide a reference for ship owners, charterers, operators and crew.

A number of maximum, minimum and nominal values are given in this document. These are typically within normal ranges experienced in the marketplace and within general Original Equipment Manufacturer (OEM) requirements. OEM requirements are often engine specific and can change over time. Accordingly it is important for operators to check and adhere to the relevant OEM requirements where these are available.

3 Legislation

In the late 1980's the International Maritime Organisation (IMO) started work on the reduction of air pollution from ships. However it was only with the ratification of MARPOL Annex VI, and its entry into force on May 19, 2005, that there was a direct impact on the shipping industry. Since that time the emissions from shipping have played a major part in the development of the marine industry, with IMO setting ever tighter limits. The European Union has added supplementary requirements to those imposed by IMO and the state of California has set its own specific requirements. These legislative requirements are set out in the following sections:

3.1 IMO MARPOL Annex VI

The MARPOL Annex VI legislation regarding sulphur emissions can be summarised into two regulations. Specific details on NOx and other emission requirements are outside the scope of this document

3.1.1 Regulation 4 covers equivalents; where a vessel is fitted with apparatus (i.e. exhaust gas scrubbing system, see section 6), or other strategies are used to ensure that the compliance method is at least as effective in terms of emissions reductions as those defined in 3.1.2 below.

3.1.2 Regulation 14 covers sulphur oxides and particulate matter. It should be noted that this regulation applies to the fuel as used by all vessels in operation after the introduction date and not just new vessels. The regulation defines the sulphur content of the fuel where compliance is to be achieved on the basis of the fuel as loaded. There are different sulphur limits applicable inside and outside ECA's, these being areas where IMO has agreed that a higher level of protection is required.

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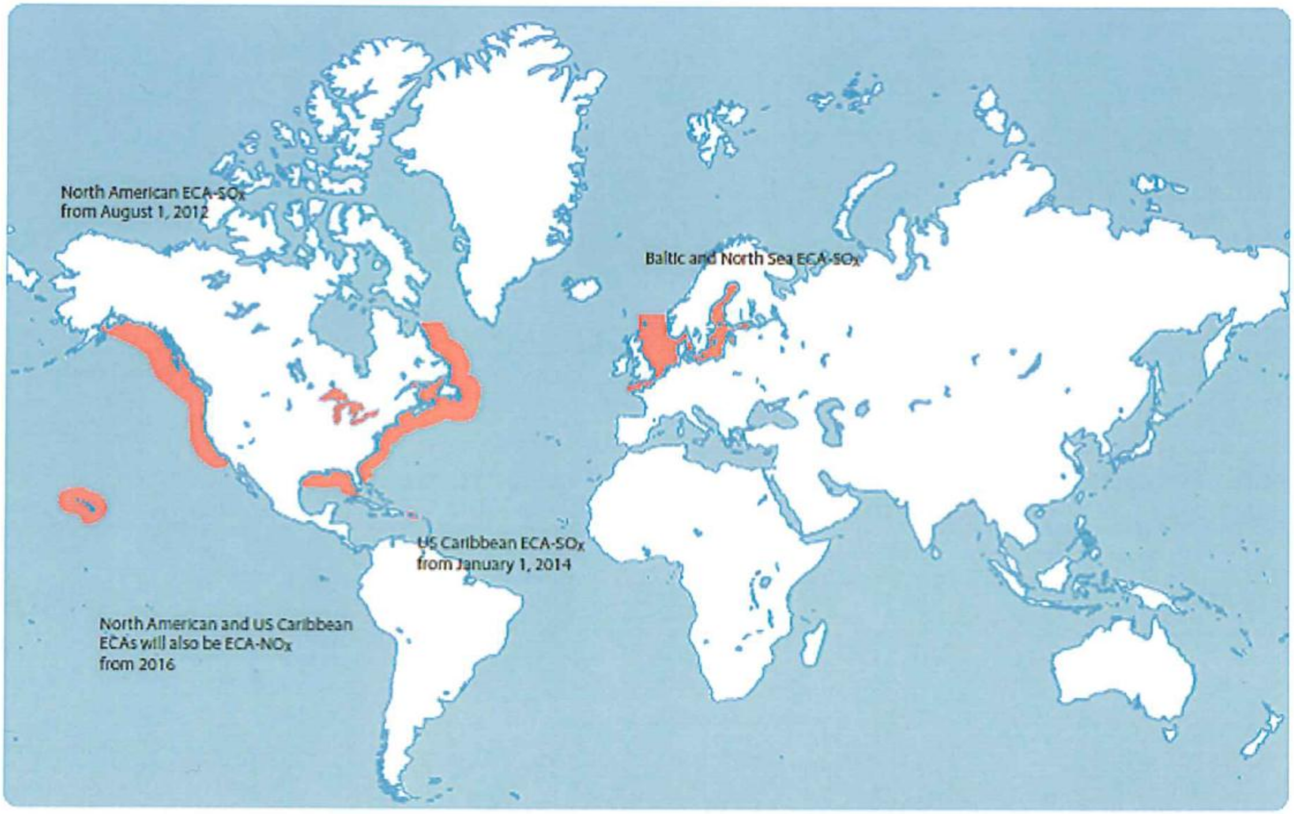

Figure 1: Emission Control Areas
Source: Lloyd's Register

The IMO legislation has set the following future requirements for sulphur emissions for vessels not equipped with an approved alternative means of compliance such as an exhaust gas after treatment system.

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The IMO maximum sulphur requirements are shown graphically and in tables below:

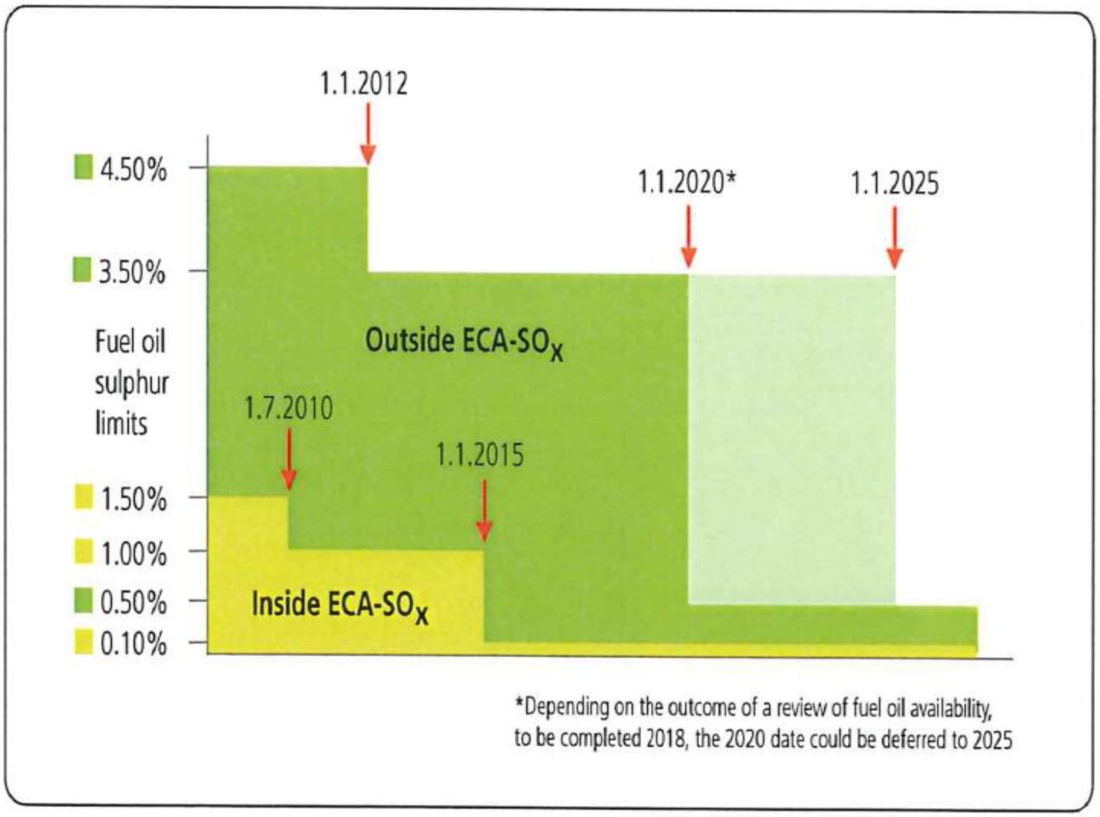

Figure 2: MARPOL Annex VI – Fuel sulphur requirements
Source: Lloyd's Register

Sulphur limits outside Emission Control Areas

Implementation date	Remarks
1/1/2012	reduced from 4,50 % m/m to 3,50 % m/m
1/1/2020(2025)	reduces from 3,50 % m/m to 0,50 % m/m The date is subject to a feasibility review to be completed by 2018. The review will determine whether sufficient low sulphur fuel will be available by 1 January 2020. If the review finds that insufficient fuel will be available, then the compliance date will be deferred until 1 January 2025.

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Emission Control Areas

Implementation date	Remarks
1/8/2012	North American ECA implementation date
1/1/2014	US Caribbean Sea ECA implementation date (Puerto Rico and USA Virgin Islands)
1/1/2015	ECA Sulphur limit reduces from 1,00 % m/m to 0,10 % m/m

Table 1: Global marine fuel sulphur limits

3.2 European Union regulation

The European Union originally developed Directive 1999/32/EC [5], which was subsequently amended by Directive 2005/33/EC [6], to implement the IMO MARPOL Annex VI regulations into EU legislation. However this legislation also contained certain additional requirements. Of significant note are:

- In EU areas of territorial seas, exclusive economic zones and pollution control zones, excluding ECA's. Passenger ships going to or from any EU port, including ferries or cruise vessels on scheduled services, the fuel sulphur is limited to a maximum of 1.5% m/m.
- From the 1st January 2010 ships at berth at an EU port must use fuel with a maximum sulphur content of 0.1 % m/m except those which, according to published timetables, are due to be at berth for less than 2 hours.

The 2012 review of the EU legislation [7] incorporates the latest MARPOL Annex VI regulations and contains the following additional requirements:

- In EU waters outside ECAs, the current 3,50% m/m fuel sulphur limit will change to 0.5% m/m from 1 January 2020 irrespective of any delay agreed by IMO in relation to the corresponding MARPOL Annex VI requirement – see 3.1 above. Until that time the existing 1,50% m/m limit for scheduled service passenger ships remains in place. The 0,10% m/m sulphur limit will be retained in respect of fuels used by ships while at berth.
- Fuel with more than 3,50 % m/m sulphur will only be allowed for sale and use by ships equipped with an approved closed loop (ie no discharge of wash water overboard) exhaust gas cleaning system.

The European Parliament Directive 2009/30/EC [8] limited the sulphur content of fuels used in inland waterway vessels to a maximum of 0.0010% m/m (10 mg/kg) from 1st January 2011.

3.3 USA, California and North America regulation

The California Air Resource Board (ARB) have defined a region, extending up to 24 nautical miles from the California shoreline or from the shoreline of the Channel Islands off California's coastline, in which only distillate fuels of grade specific maximum sulphur contents are permitted to be used. These maximum sulphur contents are given in the table below:-

Date	MGO (DMA, DMZ)	MDO (DMB)
1 July 2009	1.5 % by weight	0.5 % by weight
1 Aug 2012	1.0 % by weight	0.5 % by weight
1 Jan 2014 (was 2012)	0.1 % by weight	0.1 % by weight

Table 2: California fuel type and sulphur regulations

Under ARB regulations scrubbing technology specifically is not allowed except on an experimental research basis. However the ARB regulation does contain a clause where the ARB regulations will be superseded by IMO legislation in 2015 when the ECA fuel sulphur limit drops to 0,10% m/m and so matches their requirement.

4 Fuel manufacturing, supply, demand and energy considerations

4.1 Fuel manufacturing

The concentration of sulphur in marine fuel is dependent upon the blending that has been undertaken to prepare the fuel and the naturally occurring sulphur content of the crude oil processed by the refinery. Although the trend is gradual, the world's remaining known crude reserves are on average increasing in sulphur content. It should be noted that in general high sulphur crudes command a lower price than low sulphur crudes.

The requirement for a 0,10% m/m sulphur maximum in the ECA's from 1 January 2015 means that it is almost impossible to blend any residue into the distillate fuel and still meet the 0.10% m/m sulphur requirement. Effectively only distillate grades (DMA, DMB and DMZ) that meet the ECA sulphur requirements will be available. In order to reduce tankage costs and complexity, bunker suppliers may in the future, as they do even now, provide only the current automotive diesel quality which typically only contains 10mg/kg (0.0010% m/m) sulphur. This is already the case in some countries where ECA's have not been declared or enforced yet. Operators will have to be careful when ordering fuel to ensure that it meets the requirements of the ISO 8217:2012 [9] specification, and in particular the FAME content restriction and required anti-wear properties of minimum lubricity and minimum viscosity as well as ensuring that the minimum flash point (see section 5.1) for marine fuels requirement is met.

4.2 Refinery options

The main objective of refiners is to convert crude oils into more valuable products such as distillate and chemicals which attract the highest unit prices. The first option for refiners to meet low sulphur targets is to use low-sulphur crudes. This is particularly pertinent in the initial stages of the sulphur-reduction process and puts upward pressure on prices for low sulphur crudes. [3]

Typically it is most economical for the refiner to process residues to lower viscosity and lower sulphur distillate fuels. Such distillate fuels also have a broader market and are therefore typically a more attractive choice than low sulphur residual fuel.

As the market has gradually moved towards more distillates and less residual fuels, while the average crude oil barrel on offer was slowly becoming heavier, the refining industry has adapted by installing conversion capacity i.e. plants that can convert residues into distillates. Such plants are in fact very similar to those required to desulphurise residues, the difference being more in the degree of severity applied than in the process principles used. [2] [10]
Residue desulphurisation is technically feasible and is currently used in limited installations to convert high sulphur residues to meet the maximum sulphur requirements. The process is relatively expensive and has for example been implemented where there is long term commitment to purchase the de-sulphurised residue through an agreed pricing mechanism. It requires heavy processing, essentially high pressure and high temperature hydro-treatment and the use of expensive catalysts.

There is also an overall CO_2 implication. Sulphur reduction relies on three key factors: temperature, pressure and hydrogen - all of which require energy. The more substantial the reduction in sulphur content, the more energy is expended in its removal. At some point, the environmental trade-off between the production of low-sulphur fuel, leading to lower SOx emissions, and the resulting higher CO_2 emissions becomes unclear. [3]

4.3 Supply and demand

It is beyond the scope of this document to analyse supply and demand implications of the introduction of 0,10% m/m max sulphur fuel into the ECA's. Estimates vary on what the increase in the market will be. However, it is anticipated that a further 40-45 million tons [11] of distillate diesel will be required each year in the ECA's to meet the 0.10% m/m sulphur limit. The global middle distillate demand is about 1.6 billion tons per year [12], thus the incremental marine requirement represents an increase of about 2.5% in total demand. This should not produce significant supply and demand issues in an expanding market.

4.4 Energy density and fuel consumption

Marine fuels are typically sold, and fuel consumption are calculated on a mass basis. Marine fuel specific energy on a mass basis is variable within a range of about 5%. Typical values and the range of values are as follows:

	Typical net specific energy	Low net specific energy	High net specific energy
	MJ/kg	MJ/kg	MJ/kg
Residual fuel	40.5	39.6	42.1
Distillate	42.6	42.2	43.1

Table 3: Marine fuel specific energy long term market averages.

Source: DNV

There are regional variations in net specific energy value, as indicated in the diagram below:

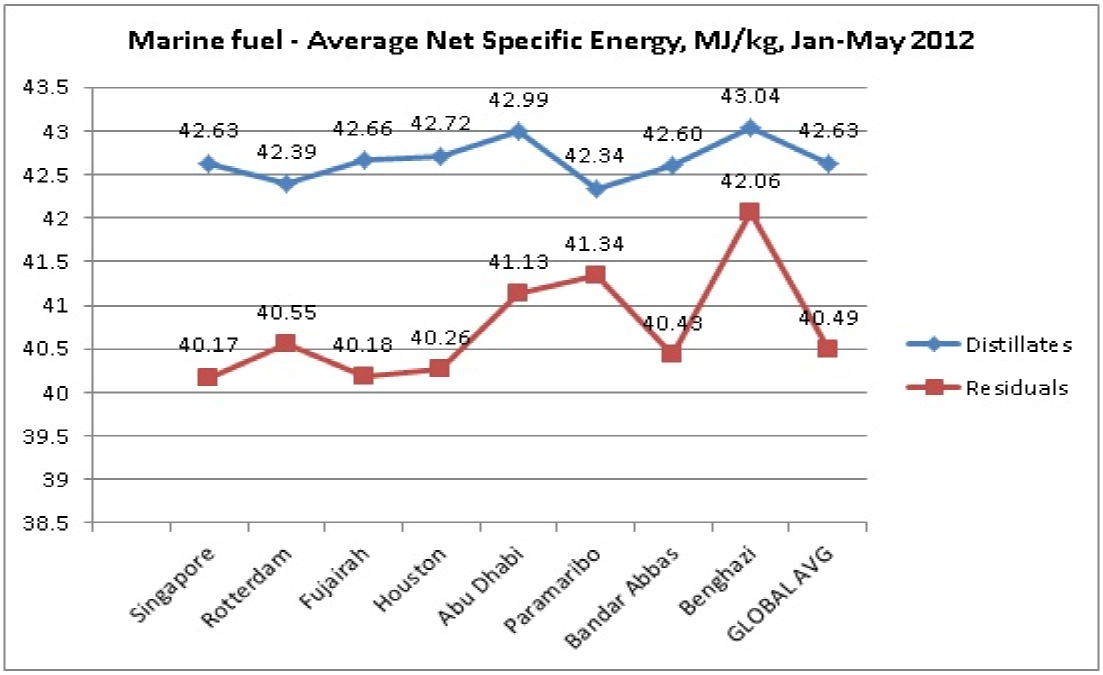

Figure 3: Distillate and residual net specific energy value by location.
Source: DNV

There should be a fuel consumption benefit of about 5% in specific fuel consumption (measured in g/kWh) over the whole load range when operating on low sulphur distillate relative to residual fuel. The fuel consumption benefit is due to the higher net specific energy value on a mass basis of distillate relative to residual fuel. The physical reason for the benefit is that distillate has higher hydrogen to carbon ratio than residual fuel, and as hydrogen has a much higher net specific energy value than carbon on a mass basis, the resulting overall net specific energy value is higher. The lower sulphur and ash content of distillate fuel also contributes to the higher net specific energy value.

This fuel consumption benefit goes some way to compensate for the significantly higher cost of distillate fuel relative to residual fuel. In most cases, distillate will only be used in the ECA's, which typically may represent only a short operating period for most vessels trading internationally.

5 Ship Systems

5.1 Engine operation on low sulphur distillate fuel: general

Although most marine medium speed and slow speed engines are designed for residual fuel operation, they are also capable of operation on distillate diesel fuel. Nevertheless, some specifics have to be considered.

The most important issues to consider when running on low sulphur distillate fuel are:

- Viscosity of the fuel – at engine inlet
- Lubricating oil choice
- Lubricity of the fuel
- Change-over procedures to and from residual fuel

A precondition for safe operation on distillate fuel is of course the compliance with the fuel specification of the engine manufacturer.

In case of low sulphur marine distillate the specification will in most cases be identical to the current ISO 8217[9] specification grade DMA or DMZ.

In 2010 a new edition of the ISO 8217[13] specification entered into force that included three very important changes compared to the former edition [17] (the changes in the 2012 edition are only in respect of one of the test method references and an effectively editorial correction):

- Wider application of minimum viscosity limits and the addition of lubricity and oxidation stability requirements for all distillate grades.
- The minimum viscosity was increased from 1.50 mm²/s (cSt) at 40°C to 2.000 mm²/s (cSt) at 40°C for DMA and DMB grades.
- A new grade, DMZ, was introduced which is identical to DMA except for a higher minimum viscosity of 3.000 mm²/s (cSt) at 40°C

Fuel pumps are designed for a minimum viscosity and fuel anti wear performance. When the viscosity of the fuel in the pump is too low, hydrodynamic lubrication of the pump can be inadequate, causing wear and scuffing.

A decrease in fuel viscosity may cause an increase in fuel leakage between the pump plunger and barrel. The leakage can lead to hot start and low fuel setting start difficulties, especially in worn fuel pumps. It is advisable to make distillate hot start checks at regular intervals so that the limits of operating conditions for a particular engine are determined. Low viscosity fuels can also lead to the engine not delivering the full designed power output as the design amount of fuel is not delivered by the pump.

This has led most 2- and 4-stroke engine builders to request a minimum viscosity of the fuel before the fuel injection pump of about 2.0 mm²/s (cSt).

This minimum viscosity defines a maximum fuel temperature. For fuels according to the ISO 8217:2012 [9] standard with a minimum viscosity of 2.000 mm²/s (cSt) at 40°C, cooling or chilling may be required to maintain the minimum viscosity before the fuel injection pump.

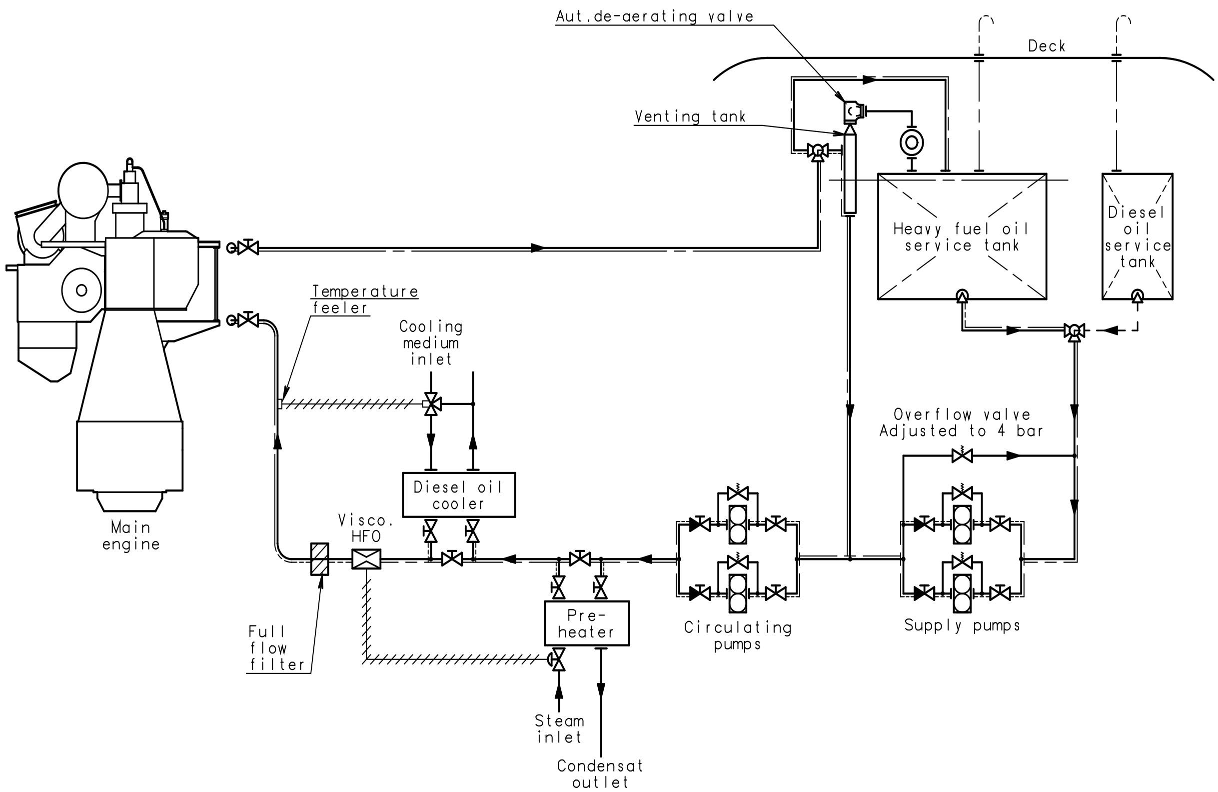

Figure 4: The location of a fuel cooler in the fuel service system

In addition a lubricity criterion was adopted from automotive diesel engine experience, where a variety of fuel pumps and fuel injection systems were damaged by low sulphur distillates with very poor lubricity, which impacts boundary lubrication.

The sulphur limits in marine applications, max. 0.10% m/m (1000 mg/kg) since 2010 in ports EU ports and from 1 January 2015 onwards in the ECAs, are significantly higher compared to automotive applications which are typically in the range of 0.0010-0.0015% m/m maximum (10-15 mg/kg). Therefore it cannot be excluded that an automotive type fuel with a much lower sulphur content having poor lubricity could be supplied in some geographical areas to marine users. It is important that marine distillate fuels of the DMA and DMZ[9] grades meet the given lubricity requirement. As is the case with automotive fuels, lubricity characteristics can be restored using lubricity improving additives.

5.1.1 Operation of four-stroke medium speed engines on low sulphur distillate

Engines burning residual fuel typically show deposits on the inlet valves. These deposits consist of soot and fuel ash and act as a lubricant when the valve closes, which is done with an additional rotational movement.

When burning distillate fuel inlet valve seat deposits are significantly less than during residual fuel operation, as distillate produces fewer combustion deposits. To add additional lubricant to the valve seats during operation, some engine types are equipped with a valve seat lubrication system. By injecting a small amount of lube oil into the charge air, a small ash and coke layer is produced on the valve seat which prevents excessive wear.

Most residual fuel operated engines are equipped with water cooled injection nozzles. This reduces the temperature at the nozzle tip avoiding coking of the fuel which would cause deposits, sometimes called trumpets, on the nozzles. Distillate fuel has a much lower fuel pump and injection temperature compared to residual fuel. Therefore additional cooling with water, might cause over cooling with the risk that the nozzle temperature falls below the dew point of the sulphuric acid in the combustion gas, causing corrosion of the nozzle. Consequently nozzle cooling water has to be switched off during distillate operation.

Fuel leakage from the pump into the lubricant is low during residual fuel operation. The amount of fuel leakage increases with a decrease in viscosity and can be significant during distillate fuel operation leading to accelerated lubricant degradation. To avoid leakage of distillate fuel into the oil some engines are equipped with sealing oil (lubricating oil sealing) at the fuel pump, that has to be used during operation on distillate fuel. Due to potential incompatibility between lubricating oil and some residual fuels the sealing oil should, if possible, be switched-off while operating on residual fuel. This incompatibility can cause deposits in the fuel pump resulting in fuel pump sticking.

Liner lacquering is a rare phenomenon generally only observed with operation on low sulphur distillate fuel. These deposits form a very smooth surface on the liner with the effect that adhesion of the oil film to the surface is compromised. A significant increase in lubricating oil consumption (factor 2-4) can be a result of this lacquer. This phenomenon is mainly known from applications with a load pattern running intermittently on full load followed by idling (e. g. fishing vessels). However, engine design and aromatic fuels with a large proportion of heavy components can also promote lacquer formation.

Operation on low sulphur distillate while still using the lubricant for HFO with a BN of 30 to 55 is not critical for a limited period of time (typically 1000 hours but refer to OEM recommendations). For long term operation on low sulphur distillate a lubricant with a suitably lower base number is recommended.

When the engine will be operated on distillate fuel for over 1000 hours before reverting back to residual fuel later again, a low BN version (20 or 30, in accordance with OEM recommendations) of a “residual fuel lubricant” should be used while operating on distillate fuel. Specific OEM requirements need to be considered when making the decision to switch to a different lubricant BN.

Lubricants designed for engines operating continuously on distillate fuel typically have a BN in the range of 10 to 16 mgKOH/g. Operation on residual fuel is not permitted with such a lubricant. Mixing of a “distillate diesel engine lubricant” with a “residual fuel type lubricating oil” is also not allowed as compatibility problems must be expected.

Fuel (Permanent operation)	**Lubricant**	**BN**
Residual	Residual fuel type	30-55
Distillate	Distillate type*	15

Fuel (Intermittent operation)	**Lubricant for distillate operation**	**BN**
Residual and <1000 hours** on Distillate	Residual fuel type	30-55
Residual and >1000 hours** on Distillate	Residual fuel type*	20-30

*Do not mix Residual with Distillate type lubricants
** Continuous operation

Experience with operating medium-speed engines on low sulphur distillate (permanently and temporarily) is widely available. Several applications have required such a fuel use pattern in the past (e. g. power plants in environmentally sensitive areas, offshore vessels, military applications, dredgers operating in inshore areas). These applications have demonstrated that operation on low sulphur distillate is satisfactory, as long as the above mentioned recommendations are followed.

5.1.2 Operation of two-stroke low speed engines on low sulphur distillate fuel

Most modern two-stroke engines are designed and optimised for operation on high sulphur residual fuel oil. The high Base Number (BN or TBN) cylinder lubricating oil is designed and optimised for sustained engine operation on high sulphur residual fuel oil. When switching from high sulphur residual fuel oil to low sulphur (in lubricant terms <1.50% m/m sulphur) or very low sulphur (<0.10% m/m sulphur) fuel some precautionary measures need to be taken.

During combustion the sulphur in the fuel is released forming SO_2 and some of this forms SO_3. This reacts with the water from the scavenging air and water formed during the combustion process to form sulphuric acid:

$$S + O_2 \rightarrow SO_2$$
$$SO_2 + 1/2O_2 \rightarrow SO_3$$
$$SO_3 + H_2O \leftarrow \rightarrow H_2SO_4$$

The sulphuric acid is neutralised by alkaline additives containing, for example, $CaCO_3$ by the following simplified reaction:

$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2O + CO_2$

If the sulphuric acid is not neutralized, corrosion of iron occurs according to the following reaction:

$Fe + H_2SO_4 \rightarrow FeSO_4 + H_2$

Sulphuric acid corrosion is the primary cause of corrosive wear experienced in the cylinder liners and on all types of piston rings.

The cylinder lubricating oil is designed and optimised to neutralise the acid formed. The BN is a measure of the cylinder lubricating oil's capacity to neutralise acid. The higher the BN, the more acid can be neutralised. [14]

When operating on low and very low sulphur fuel, very little sulphuric acid is formed, and hence the alkaline components in the lubricating oil are not neutralised and thus may form compounds that can potentially harm the engine. Under some operating conditions, and for some engine types, the alkaline components form deposits on the piston crown land that can disrupt the oil film between the piston rings and the cylinder liner, and hence the risk of metal-to-metal contact, seizures and scuffing increases. Deposits can also form behind the piston rings and this can cause excessive ring and liner wear as the rings are no longer free to move.

Consequently, new cylinder oils with a lower alkalinity or BN have been developed for operation on low and very low sulphur contents. Operating the engine with an unmatched cylinder oil BN and fuel sulphur content could increase the risk of either scuffing or excessive corrosive wear. [14] It should be noted that engine design and operating parameters can also affect the cylinder oil alkalinity requirement.

As there is currently very limited experience with prolonged operation on very low sulphur fuels the following approach is recommended: [14]

- Low BN cylinder oils should be chosen for low and very low sulphur fuels, and high BN oils for high sulphur fuels.
- The period for which the engine can be run on low sulphur fuel and high BN cylinder oil is very dependent on engine type and mode of operation. It is not expected to result in any unsatisfactory conditions in the course of a few days.
- Evaluate the engine's actual cylinder condition after the first operating period on low sulphur fuel, and act accordingly. If excessive piston crown deposits are seen to be forming, operate at low lubricating oil feed rate or change to a low BN cylinder oil.

In all cases the engine manufacturer's recommendations need to be followed.

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5.2 Changeover between residual and distillate fuel

5.2.1 Introduction

When a vessel enters or leaves an ECA it will typically be required to change fuel unless an approved equivalent is employed (e.g. abatement technology). From 2015 onwards, vessels prior to entry of an ECA must change over from residual fuel with a maximum sulphur content of 3.50% m/m, to distillate fuel with a maximum sulphur content of 0.10% m/m. Conversely, after exiting an ECA it will generally be desirable to change back to residual fuel from distillate in order to reduce fuel costs unless a return into the ECA is imminent. Most operators have experience of changing over between residual and distillate fuels and vice versa. These requirements dictate that changeover must take place during sailing, whilst approaching or leaving the ECA boundary.

Automatic fuel changeover systems are available; however the process can be carried out manually. It is mandated that detailed procedures are put in place and duly documented onboard, and that the crew is familiar with the operation. Insufficient knowledge of the required actions may result in component damage or engine shutdown. For detailed advice on changeover procedures always consult the specific equipment manufacturer's recommendations.

There are a number of technical considerations and challenges associated with fuel changeover. These include:

- Temperature gradient
- Changes in viscosity
- Incompatibility

5.2.2 Temperature gradient

In order to ensure fuel injection equipment keeps functioning correctly, it is recommended that a maximum fuel changeover temperature gradient is not exceeded. Generally engine manufacturers recommend a gradient of no more than 2ºC per minute [14] [15]. Rapid changes in fuel temperature will increase the likelihood of pump malfunction and seizures. For the reasons stated above it is clear that from initiation to completion fuel changeover can take considerable time, in some cases upwards of 60 minutes for the fuel temperature change alone. Many engine manufacturers recommend actions that can provide further protection, whilst possibly reducing the time required. For example; when changing over between HFO and distillate or MDO or vice versa, engine load can be reduced, which helps slow the rate of temperature change.

5.2.3 Changes in viscosity

Typically the optimum operational viscosity of a fuel at the engine fuel pump is within the range of 10-20 mm^2/s (cSt), but always ensure that the OEM requirements for the particular engine are met. In order to achieve this viscosity with residual fuels it may be necessary to heat it to in excess of 100ºC. However distillate fuels have significantly lower viscosities than residual fuels, typically in the range of 2.0 to 11.0 mm^2/s (cSt) at 40ºC and as such must not be heated and may in practice instead have to be cooled or chilled. Most equipment manufacturers recommend a minimum fuel viscosity at the fuel pump inlet of 2.0 mm^2/s (cSt). Too low viscosity fuel may lead to excessive leakage within the fuel pumps and problems when operating at high load. Starting difficulties may be experienced especially at low engine power settings when fuel demand is very low and this is reduced due to excessive internal pump leakage.. Insufficient viscosity may also lead to fuel pump seizure and premature wear due to a reduced hydrodynamic lubricating oil film. As well as engine mounted pumps, the operation of fuel handling system pumps should also be considered.

Distillate fuels should be sourced with sufficient viscosity to achieve the equipment manufacturer's minimum requirements. Fuel coolers or chillers can be used if necessary which assist in preventing the viscosity of the fuel becoming too low. Additionally early switching off of pipework steam and trace heating systems will assist in reducing the fuel temperature when the changeover is made.

Conversely when changing back to residual fuel from distillate it must be ensured that the temperature of the fuel is high enough to achieve the required viscosity at the fuel pump inlet. Trace and steam heating in pipework can be switched on to assist this process, but heating of distillate must be avoided.

5.2.4 Incompatibility

As described above the changeover procedure takes quite some time, during which there will be a mix of the two very different fuels. The risk of incompatibility between residual fuel and low sulphur distillates is considered higher than that typically associated with mixing of different types of residual fuel [15]. Introducing distillate may cause the asphaltenes in the residual fuel to precipitate as heavy sludge, with filter clogging as a possible result which, in extreme cases, will cause fuel starvation in the engine leading to engine shutdown. Another associated issue can be injection pump sticking due to deposits between the plunger and barrel.

Compatibility tests may be carried out either on board during bunkering, or via an independent laboratory.

Asphaltene dispersant / stabiliser fuel additives may reduce the risk of fuel incompatibility. See CIMAC Guide No 25 “Recommendations Concerning the Design of Heavy Fuel Treatment Plants for diesel Engines”, section 7.1.1 (page 43) for more details regarding fuel additives.

5.2.5 General considerations

To avoid compounding compatibility problems it is recommended not to return residue and distillate mixtures back to the distillate or MDO service tank.

When a two-stroke engine is to be operated with low sulphur fuel for a prolonged period of time, many engine manufacturers recommend that the cylinder oil should be switched from a high BN type to a 40BN or a lower value. Cylinder oil feed rates should also be considered and engine manufacturer recommendations must be followed. [16] The operation of two stroke engines on

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high BN cylinder oil at high feed rates while using low sulphur distillate fuel can lead to rapid piston crown deposit accumulation resulting in severe scuffing.

5.3 Fuel quality, alternative fuels, care and handling

5.3.1 Fuel quality considerations

The ISO 8217[9] Marine Fuel Standard provides the overall requirements for all marine fuel grades. However, as far as sulphur is concerned, the limits are provided by the relevant statutory requirements.

The 2010 revision of the ISO 8217 [13] Marine Fuel Standard took into account the main issues associated with the use of low sulphur distillate by:

- amending existing parameters;
- including a series of new test parameters to look specifically at the aspects of quality that can be affected by the reduction of sulphur content.

As far as these amendments are concerned the main change is with respect to the minimum viscosity limits. For a DMA grade fuel the minimum viscosity limit has been increased to 2.000 mm^2/s (cSt) from 1.50 mm^2/s as given in ISO 8217:2005 [17]) whilst a new grade, DMZ, was created which is identical to the DMA grade except for the 3.000 mm^2/s (cSt) minimum viscosity limit. Additionally, a minimum viscosity limit of 2.000 mm^2/s (cSt) was introduced for the DMB grade.

The ISO 8217:2010 [13] standard also introduced lubricity (ISO 12156-1 Diesel fuel - Assessment of lubricity using the high-frequency reciprocating rig (HFRR) - Part 1: Test method) as quality parameter for all distillate fuels with sulphur content below 500mg/kg (0.050 % m/m). However, as the test is only applicable to clear and bright samples, it may not be possible to test samples of some DMB grade fuels although in such cases it would be expected that the trace residual component resulting in that discolouration would impart the required lubricity.

Furthermore, an oxidative stability (ISO 12205:1995 Petroleum products -- Determination of the oxidation stability of middle-distillate fuels) requirement was also introduced for the distillate grades This requirement was included in order to address the reduced oxidative stability of fuels due to the increase in refinery processing and also to cover the possible inclusion of bio-derived material. However, as with the lubricity test, the oxidation stability test is only applicable to clear and bright samples and therefore again it may not be possible to test some samples of some DMB grade fuels. .

With regard to the possible inclusion of bio-derived material, the 2010 revision of the ISO 8217 [13] Marine Fuel Standard introduced the requirement that:

“fuels shall be free from bio-derived materials other than '*de minimis*' levels of Fatty Acid Methyl Ester (FAME) (FAME shall be in accordance with the requirements of EN 14214 or ASTM D6751). In the context of this international standard, '*de minimis*' means an amount that does not render the fuel unacceptable for use in marine applications. The blending of FAME shall not be allowed."

However, following the adoption of the EU Directive 2009/30/EC [8], in April 2009, relating to Marine Diesel Fuels to be used for inland waterways and recreational craft when not at sea has a significant bearing on the aspect of bio-derived material in fuels.

This EU Directive required that the sulphur content of fuels for use in non road mobile machinery and by inland waterway vessels from 1 January 2011 to be no greater than 10 mg/kg (0.001% m/m), but also permitted the use of distillate type fuel derived from sustainable plant resources by allowing a FAME content of up to 7%.

This being the case, ship owners / operators must be aware that there is the possibility that this kind of fuel may be provided in areas where low sulphur marine fuel supplies are limited. In such cases it should be established with the supplier as to the actual (or at least the maximum locally allowed) FAME content before ordering.

5.3.2 Renewable fuels

Vegetable oils and fats can be converted into fuel suitable for use in diesel engines and have the benefit of being sulphur free. Low and medium speed engines can operate on neat vegetable oils and animal fats provided that adequate preheating and filtration is applied. There are some engines currently operating satisfactorily on such fuels. Automotive diesel requires such neat oils and fats to be processed in order to reduce the viscosity and improve the cold flow properties. The process normally adopted is trans esterification. The resultant fuel is known as FAME as referred to above in relation to the 2010 revision of the ISO 8217[13] standard. Due to these processing requirements the cost FAME is significantly higher than crude oil derived distillate and hence will tend to be limited to that required by local legislation such as the EU Directive 2009/30/EC [8].

Renewable fuels are not considered to be serious alternatives to crude oil derived marine fuels due to the high cost and limited availability.

Furthermore there are serious concerns about the long term storage stability and oxidation resistance of some renewable fuels. This can lead to severe filter blocking issues and could become a safety and operational issue for ships at sea. FAME is a nutrient for micro-organisms which can multiply especially in the presence of free water in or under the fuel. This can lead to the formation of sludge-like matter which readily blocks both coarse and fine filters. It is thus crucial to ensure that tank bottoms are dry and that there is no free water in any distillate fuels and in particular those containing FAME components. However, it also needs to be understood that, where FAME is present, water tends to be dispersed in suspended droplets throughout the fuel in total, thus presenting a much greater risk of microbial activity on tank walls and in effect the whole tank area rather than being confined to tank bottoms.

Hydrotreated vegetable oils are also available but normally only in small quantities. These fuels have properties very similar to crude oil derived distillates with virtually zero sulphur, good oxidative stability, zero aromatics and excellent ignition properties. They are thus considered to be useful fuel components for blending into the distillate pool.

5.3.3 Gas to liquid fuels

Gas to liquid fuel manufacturing processes can produce liquid distillate type fuels which are suitable for use in marine engines. These fuels can have very desirable properties such as very low sulphur, low aromatic content and high stability. However, care must be taken to ensure adequate viscosity and lubricity to ensure that no wear takes place in fuel pumps and the fuel systems. These fuels typically have a highly paraffinic composition and are thus not suitable for blending with residues as the resultant blend is likely to be unstable especially if a relatively large amount of diesel is added to the residual fuel.

However, due to the relatively high production costs of such premium fuels these are unlikely to be used in marine applications.

5.3.4 Gaseous fuels

LNG and other gaseous fuels are now considered to be potential sources of low sulphur fuel for marine applications. A number of LNG tankers, ferries, coastal ships and land based engines are operating on LNG or gaseous fuel. These often operate in dual fuel mode with marine liquid fuels. In many cases these engines use diesel as the pilot injection fuel when operating in LNG mode. Whilst the technology exists or is being developed to use LNG and other gaseous fuels in more marine engines, such fuels are outside the scope of this document which is confined to liquid marine fuels.

6 Abatement technologies

Please see the EGCSA website: http://www.egcsa.com/

7 Abbreviations & Acronyms

IMO	International Maritime Organization
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
EGCSA	Exhaust Gas Cleaning System Association
ECA	Emission Control Area
LNG	Liquefied Natural Gas
NOx	Nitrogen Oxides
SOx	Sulphur Oxides
EU	European Union
ARB	Air Resources Board
DMA	Grade of Marine Distillate Fuel
DMZ	Grade of Marine Distillate Fuel

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DMB	Grade of Marine Distillate Fuel
cSt	Centistokes
BN or TBN	Base Number or Total Base Number
OEM	Original Equipment Manufacturer
HFRR	High Frequency Reciprocating Rig
FAME	Fatty Acid Methyl Ester

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