

A Guide to Fuel, Lubricant, and Engine Concerns Relative to the IMO 2020 Fuel Oil Sulfur Reduction Mandate

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Maritime Administration, US Department of Transportation

**A GUIDE TO FUEL, LUBRICANT, AND ENGINE CONCERNS RELATIVE TO THE
IMO 2020 FUEL OIL SULFUR REDUCTION MANDATE**

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FOREWORD

The US Maritime Administration (MARAD) is an agency within the US Department of Transportation tasked with promoting waterborne transportation, including port and vessel operations and environmental safety. MARAD also provides crucial information in the form of primers and reports to ship owners and operators. These publications focus on the potential impacts of upcoming regulatory or other changes to marine vessel operation. Under the guidance of MARAD, Oak Ridge National Laboratory has been tasked to develop a primer that can be shared with vessel owners and operators with emphasis on the impacts of the 2020 sulfur regulations on engines, fuels, lubricants, and all related systems. The impacts of past and future fuel-related regulations and other information pertinent to the short-term future of shipping are also included.

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ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

BN	base number (a measure of the acid-neutralizing base component of lubrication oil)
CIMAC	International Council on Combustion Engines
CLO	cylinder lubrication oil
cSt	centistoke = mm^2/s (a measure of fluid viscosity)
ECA	environmental control area
EU	European Union
FONAR	fuel oil non-availability report
gas oil	a broad term for distilled petroleum streams or products in the diesel-to-vacuum-gas-oil range
HCO	heavy cycle oil (also called slurry oil, which is the “bottom” product from a fluidized catalytic cracker unit)
HFO	heavy fuel oil (usually composed of residual oil blended with lighter components to be near $380 \text{ mm}^2/\text{s}$ at 50°C)
IACS	International Association of Classification Societies
IMO	International Maritime Organization
ISO	International Organization for Standardization
knot	one nautical mile per hour (equal to 1.852 kilometers per hour or 1.151 miles per hour)
LC(G)O	light cycle gas oil
MARAD	United States Maritime Administration
MDO	marine diesel oil (middle distillate with a small proportion of HFO)
MGO	marine gas oil (distillate blend fuel similar to number 2 heating oil)
MIC	microbially induced corrosion
mm^2/s	unit of fluid viscosity equal to a centiStoke (cSt)
OEM	original equipment manufacturer
OGV	ocean-going vessel
ORNL	Oak Ridge National Laboratory
SAE	SAE International (a transportation professional society, formerly Society of Automotive Engineers)
SRB	sulfate-reducing bacteria
ULSFO	ultra-low sulfur fuel oil (0.10 wt.% sulfur or less by mass)
VLSFO	very low sulfur fuel oil (0.50 wt.% sulfur or less by mass)

EXECUTIVE SUMMARY

BACKGROUND

The significant change to the 2020 International Maritime Organization global marine fuels sulfur rule poses many challenges to the marine shipping industry. Beginning January 1, 2020, there will be a very large shift from high-sulfur residual-based heavy fuel oils (HFO), which are blended mainly for viscosity, to new fuels blended to contain 0.50 wt.% sulfur, also known as very low sulfur fuel oil (VLSFO). Increases in distillate production and desulfurization of refinery streams are anticipated as part of meeting marine fuel demand. This brings some uncertainty concerning compliance of the fuel supply and much uncertainty concerning fuel composition. Furthermore, the change in fuel properties will drive significant changes for lubricants, equipment, operating procedures, and shipping economics. The consensus is that the initial use of 0.50 wt.% sulfur marine fuel oils will increase operating costs since this fuel will be more expensive than high-sulfur HFO. The existing onboard fueling infrastructure and operational protocols are expected to be suitable for use with most of the 0.50 wt.% sulfur fuels that will be available, but more careful operation and quality control will be needed to ensure trouble-free operation. These practices will take the forms of proper sampling; frequent and more diligent cleaning; and tighter control of temperatures (viscosities) during fuel handling, switchover, and blended operations. Compliance needs to be followed to minimize the potential for any problems. If recommended practices are not followed, buildup of piston deposits or erosion by catalyst fines could cause excessive wear and damage to engines. Also, fuel incompatibility due to asphaltene precipitation could lead to system plugging and poor engine operation.

FUEL COMPATIBILITY

VLSFO blends are expected to be derived from a broad range of refinery streams and to vary broadly in properties as suppliers try to meet the 0.50 wt.% specification. Stability and compatibility concerns are paramount, at least in the near future. For instance, some VLSFO blends could be mainly paraffinic, increasing the risk of asphaltene precipitation during fuel-mixing operations, including switchover. Also, some paraffinic fuels have an affinity to precipitate solids in cold conditions, and more attention to this problem will be required in some regions. Catalyst fines are expected to be present in many VLSFO blends, and therefore cleaning these fuels properly will be critical. Recommendations to avoid compatibility problems during switchover and blending center primarily on (1) obtaining fuel that meets proper specifications and receiving accurate fuel analyses, (2) installing additional tanks (or dividing tanks) and fuel transfer systems to minimize fuel mixing and contamination, (3) diligent cleaning of fuel system hardware, and (4) maintaining and following proper protocols for purifiers to remove catalyst fines. Frequent cleaning and following of operational guidelines are necessary to maintain compatibility.

In many cases, changes will be made in ship equipment and operating procedures because of the switch to VLSFO. Because blends of VLSFO are expected to vary widely in viscosity, there will be a need for compatible pumps, better temperature control, centrifugal purifiers, and other equipment. Engines and boilers might need to be carefully evaluated for compatibility and safe operation with the new fuels. These considerations point to the need for many ships to undergo capital upgrades at a time of increasing fuel costs and financial uncertainty.

CATALYST FINES

An increased presence of catalyst fines in VLSFO is anticipated for some fuel suppliers or in some regions. Heavy-cycle fuel oil from a catalytic cracker has low sulfur content and is expected to be blended into low-sulfur fuel oils. Fuel purifiers will need to be operated properly and settling tanks to be drained of bottom contaminants at proper intervals to effectively remove catalyst fines. Rough weather and high

seas can entrain tank sediment, and special attention to purification will be needed under these conditions. Fuel filters may also need more frequent cleaning and maintenance.

FUEL HANDLING AND PROCESSING

The HFO handling and processing systems onboard ships may require some modifications beyond the need for additional fuel storage tanks to separate different fuel chemistries. This could include the addition of a chiller, which might be needed to increase the viscosity for some lowest viscosity fuels. Since VLSFO may contain catalyst fines, the fuel cleaning system will need to be effective for a wide spectrum of fuel viscosities. Water will need to be removed and surfaces cleaned to minimize the risk associated with microbially induced corrosion (MIC) with more paraffinic fuels. The use of biocide fuel additives and inspections might become more frequent as a result.

Fuel switchover from distillate to HFO or VLSFO when exiting an emission control area will require careful operation to mitigate potential compatibility issues. To minimize risks, it is recommended that a small mixing tank be employed to assess compatibility when conducting a switchover operation. When switching from distillate to a high-viscosity fuel, it is important to keep the rate of temperature increase low to protect fuel system components. Switching from heavy fuel to a distillate fuel (such as marine diesel oil or marine gas oil) might require controlled slow cooldown. In both instances, leak checks and operation of the fuel pumps will need to be monitored to ensure smooth operation.

CORROSION AND WEAR

With most ships featuring crosshead engines switching to VLSFO, a shift away from rapid cold corrosion risk is expected. However, the potential for MIC may be increased for fuels with high paraffin content. MIC can be mitigated by maintaining cleanliness, removing standing water, and biocide treatments.

Another area of concern with VLSFO use is the greater risk of deposit-related problems from both excessive base in cylinder lubrication oil (CLO) or a lack of detergency. New operating procedures concerning cylinder lubrication may be required, and new developments in CLO formulation are forthcoming. It may be beneficial to have more varieties of CLO available onboard. Hard deposit formation on the piston or rings can negatively affect the lubricating film by causing bore polishing and interfering with rings and the CLO film on the cylinder liner. One approach being considered to mitigate this effect is to intermittently use a lower base number CLO to prevent hard deposits and to allow slight beneficial corrosion of the liner surface to open the graphite lamella structure, which provides oil pockets to maintain a good oil film.

SUMMARY STATEMENT

The economics of shipping will be changed and challenged by the switch from HFO to VLSFO. This transition will not be seamless, and problems are likely to be encountered due to different fuel chemistries and improper lubricant selection or management. Fueling protocols may need to be recalibrated to ensure that problems are prevented or mitigated. Capital investments to make ships perform better with VLSFO will be made by some but resisted by many because of challenging economics. The most successful ship operators will be those who undertake high diligence and understand the potential problems and solutions.

1. INTRODUCTION

In 2020 the shipping industry will be faced with a significant challenge associated with the International Maritime Organization (IMO) sulfur limit rule changing abruptly from 3.5 wt. % to 0.50 wt. %. This rule applies to the open ocean globally, not just for certain coastal zones. Ships carrying fuel with sulfur in excess of the 0.50% limit without the use of an emissions reduction system (scrubber system) will be in violation of the rule. However, there is a grace period ending March 1, 2020, whereby high-sulfur heavy fuel oil (HFO) that is being carried (but not burned), must be de-bunkered. Estimates for the number of ships equipped with scrubbers by 2020 vary, but most estimates are near 2,500–3,800 (Fuels Institute, 2019). With roughly 30,000 ships operating mainly on HFO in the past (Kass et al., 2018), it is certain that there will be a relatively small demand for high-sulfur fuel and a high demand for compliant fuels. This new rule will bring changes to fuels, lubricants, equipment, operating procedures, and shipping economics.

1.1 PURPOSE

The chief purpose of this document is to give guidance to owners and operators of marine cargo vessels concerning challenges and changes needed because of the year 2020 0.50% sulfur fuel limit. Fuel oil meeting this specification is known as very low sulfur fuel oil (VLSFO). A primer on marine fuels and lubricants and their relationship to engine performance and fuel systems will help owner/operators understand the physical and chemical property changes expected with newer fuels and lubricants and how this can affect ship operation and equipment requirements. In addition to engine performance, the systems used to process and handle fuels and lubricants onboard cargo vessels are complex and need to be closely monitored. The response of these systems to different fuel and lubricant formulations are discussed. In many cases, various capital upgrades may be the best option to cope with the changes. In addition, the changing risks associated with current engine technologies and the changing nature of fuels and lubricants in the near term are discussed in this report.

Highly related to the global 2020 sulfur rule are the recent 0.10% sulfur limits required for environmental control areas (ECAs) and other regional or local requirements that pertain to ship and engine emissions. Because of the requirement to switch from 0.50% to 0.10% sulfur in ECAs and other special emissions regulated zones, there has been much experience with switching between HFO and new low-sulfur fuels in recent years. Insight and lessons learned from this recent experience are included here. Furthermore, worldwide availability, quality, and price of 0.50% sulfur fuel is uncertain and it is expected that widely varying fuel compositions will satisfy the demand for low-sulfur fuels. Significant changes to high-sulfur fuel (for use with scrubbers) availability, composition, and price are also expected.

The use of higher cost VLSFO will change the economics of shipping. It is anticipated that some shipping sectors will institute slower ship speeds to save on fuel cost despite slow steaming already being widely used. General information concerning this important topic and other methods of fuel use reduction or increased efficiency is included.

1.2 BACKGROUND

1.2.1 Recent Trends in Shipping

1.2.1.1 Slow Steaming

The early 2000s saw a period of rapid economic growth and increased trade, ship building, and orders for new ships. To optimize profit, many cargo ships traveled near full design speeds. About 2007, the economics of shipping changed drastically with fluctuating oil prices and a worldwide economic downturn. Considering that the fuel cost component of shipping is generally more than half of the operating costs, methods to use less fuel became very important to shippers (Schmuttermair, 2010).

Slow steaming was developed in large part by Maersk beginning in 2007 (Halff, 2017; Sanguri, 2012; Jorgensen, 2011) as a response to reduced world trade, which created an oversupply of merchant cargo ships. The reduced income from lower shipping rates provided an economic impetus to reduce fuel costs by evaluating reducing ship speeds. This reduced speed operation was termed “slow steaming.” Maersk implemented slow steaming on selected vessels, essentially performing lower-load/lower-speed research experiments (Sanguri 2012). A speed range of 24 knots (full speed) to 12 knots was examined. Maersk determined that the many problems associated with low-load operation were tolerable or solvable and that significant cost savings could be realized (Sanguri, 2012; Jorgensen, 2011).

Slow steaming became standard because of the competitive advantage it gave considering the general oversupply of ships and the prevailing freight rates. Slowing the ship speed reduces the engine power needed and therefore its fuel consumption. The reduction in fuel consumption is so pronounced that shipping costs are reduced significantly even though travel time between ports increases. A typical container ship may have shifted its speed from 24 knots to 18–21 knots or even 15 knots or less; the later speed range is considered super-slow steaming (Maloni, 2013). Note that both ocean going vessel (OGV) design speeds and what would be considered slow or super-slow steaming may vary widely. With the shift to slow steaming, more ships were put into use and most shipping entities survived the serious economic difficulties. However, slow steaming also brought forth numerous challenges (Harrold, 2013).

1.2.1.2 Engine Design Changes

The advent of slow steaming also introduced the need for engine design changes. Engines operating at lower power have different lubrication and corrosion protection requirements than those operating at higher power. Many ship powertrains were reengineered to enable and optimize sustained lower load operation. More efficient, longer stroke engines penetrated the market, increasing fuel savings. These engines are designed for high efficiency at partial loads and operate at lower cylinder liner temperatures. One drawback was that the lower cylinder surface temperature promoted sulfuric acid condensation and what is known as cold corrosion. Changes were made to cylinder lubricant oil formulations to counter the increased acid condensation causing cold corrosion.

IMPORTANCE OF MARINE SHIPPING

More than 90% of all worldwide goods are transported via large marine cargo vessels, powered mainly by heavy fuel oil and large two-stroke crosshead engines. Global marine fuel consumption is estimated to be near 330 million metric tons (or about 87 billion gallons) per year (Kass et al., 2018). These facts highlight the continuing importance of marine shipping to the health of world economies and the importance of recognizing and improving its environmental impact.

1.2.1.3 Environmental Control Areas

A number of designated ECAs have been approved by the IMO. These ECAs include the North Sea, English Channel, Baltic Sea, coasts and inland waters of the United States and Canada, and the US Caribbean Sea (as seen in Figure 1.1). Sulfur emissions are limited in these areas by restricting fuel to 0.10% sulfur or by use of exhaust gas cleaning to achieve sulfur emissions equivalent to that if a low-sulfur fuel were being used. Some ECAs have NO_x emission restrictions as well. Additional environmental areas were created for the coasts and ports of California, the European Union (EU), and China. California was first to designate a low-sulfur fuel control area, currently enforced to require 0.10% sulfur distillate fuel. The EU regulations require low-sulfur fuel use while ships are in port. China has several designated areas where the maximum fuel sulfur level is currently 0.50%. These types of emissions regulations are likely to continue to expand and to become more restrictive.

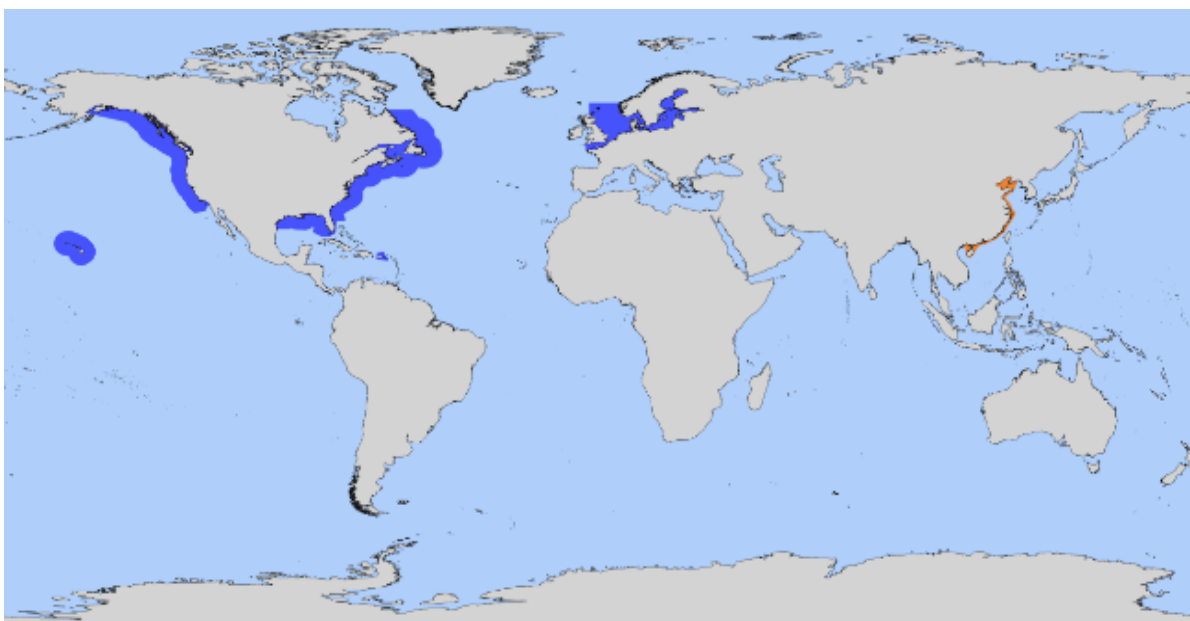


Figure 1.1. Major areas near the North American, European, and Chinese coastlines where use of lower sulfur fuel is required (Blue = 0.10% sulfur, Orange = 0.50% sulfur). Figure courtesy of MAN Energy Solutions, 2019a.

As of this writing (2019), most ships operate outside of ECAs using high-sulfur fuels and then switch to a fuel compliant with the appropriate sulfur limit when entering an ECA. Fuel switching from HFO to a low-sulfur distillate has significant risks and can cause equipment failure and loss of ship propulsion. These risks have forced the shipping community to develop the ability to properly switch from a high-viscosity fuel (typically HFO) to a low-viscosity distillate fuel during transit. Switching between these types of fuels requires careful adjustment of fuel temperature as a means of controlling its viscosity within a range appropriate to the onboard equipment. High-viscosity fuels typically require the fuel to be heated, while distillate fuels can require cooling to increase their viscosity. This experience will be helpful in some ways to address the widespread shift to VLSFO use and the anticipated wide variety of fuel properties (including viscosity) to be encountered.

1.2.2 Changes Anticipated from Use of 0.50 wt.% Sulfur Fuel

1.2.2.1 Changes in Fuel Supply and Refining

The worldwide shift from high- to low-sulfur fuel is expected to require more than 3 million barrels of fuel per day (>170 million Mt/year) shifted to low-sulfur fuel production (S&P Global Platts, 2017; S&P Global Platts, 2019a; Tolson, 2019). Providing this volume of fuel will pose a challenge for refiners, blenders, and fuel suppliers globally. In the past, fuel produced for the 3.5% sulfur limit was often blended targeting a 380 mm²/s viscosity specification (at 50°C), but this goal will be replaced with blending to achieve the 0.50% sulfur fuel specification.

Many differing blend streams will be used to meet the new sulfur specification; therefore, fuel properties might vary widely. The stability for blended fuels is anticipated to become more of a concern in the near term. Switching over from one fuel to another represents a heightened risk of incompatibility, especially if the two fuel chemistries are markedly different. Mixing fuels during bunkering may also carry a very high risk, and more effort to avoid mixing is expected. For example, some blends of VLSFO are likely to be paraffinic in nature and others could contain significant asphaltenes, which could precipitate when the fuels are mixed. Testing of fuels for compatibility might need to be improved for the wide variety of VLSFO compositions expected. Furthermore, catalyst fines are expected to be present in many VLSFO blends, and they must be removed before injection. Because of the changes refiners and blenders will be required to make, the nature of high-sulfur HFO for ships with scrubbers is also anticipated to change significantly, at least in some regions.

Refineries with a greater degree of complexity will have the most flexibility in responding to the need for new marine fuels. Many North American refineries will likely be able to increase the output of low-sulfur blending streams for marine fuel. European refiners currently produce a significant amount of residual fuel and will have to devise ways to supply compliant fuels. What is known as sweet (low-sulfur) crude oil will become more valuable, and sour (high-sulfur) crudes will be adversely affected, at least in the short term. It is likely the oil business worldwide will be prepared for changes and will compete for market share of the marine fuels, reducing the risk of high-level disruption in the market.

1.2.2.2 Changes to Operations and Equipment

Property and chemistry changes in new fuels will require more diligence during handling. Preventing damage to fuel systems (pumps, purifiers, injectors) and engines will be a key concern, and fuel system equipment changes will be needed for many ships. An increase in separate fuel tanks and piping systems may be a wise alteration to minimize fuel mixing. Added flexibility to the entire fuel system will help ship operators cope with the variety of new fuels that will be available. Upgrades to fuel temperature control systems may be needed because of the viscosity range of VLSFO. Also, some VLSFO may be highly paraffinic in some regions and because of having a higher temperature pour point and cloud point will need to be handled diligently in cold conditions. Onboard boilers and engines used for electrical power production may need fuel system modifications to handle lower viscosity fuels and other varying properties. New procedures for protection, safety, and proper operation may be required.

1.2.2.3 Changes to Lubricants

The 2020 changes in fuel sulfur and composition for both low- and high-sulfur fuels (for ships with scrubbers) will also increase the importance of well-matched lubricant formulations and feed rates, particularly for crosshead engine cylinder lubrication oil (CLO). In general, the previous risk of rapid cold corrosion when burning high-sulfur fuels will be greatly reduced for use of VLSFO, but the risk of forming deposits and bore polishing may worsen. CLOs with widely varying base numbers (BNs) will be

marketed, and additives (dispersants, detergents, etc.) will likely change as well to match lubricants to particular engine and fuel combinations. Many ships will likely need to carry multiple lubricants with differing BN and additives onboard. Some lubricant changes may also be needed for 4-stroke distillate engines as the fuel choices change.

1.2.2.4 Need for Fuel Efficiency

With the changes in fuels, the low-sulfur fuel price will be well above the price of high-sulfur HFO. It is possible that even slower steaming will become widespread with speeds of 10–13 knots (S&P Global Platts, 2019b) being employed in some sectors. There are also many upgrades and modifications possible for certain ships to improve fuel economy. These involve the engine and propulsion system and may be in conjunction with slow steaming. Other changes can be made to reduce drag and improve propeller efficiency and flow. These improvements will require capital costs and ship downtime.

Shippers may give more consideration to alternative fuels, particularly if cost-effective paths are found and route/supply compatibility is achievable. Alternative fuels such as methanol and liquified natural gas may also help meet future CO₂/greenhouse gas reduction rules as will speed reduction and efficiency improvement.

2. MARINE FUELS PROPERTIES AND CHEMISTRY

Marine fuel classes, along with their properties and chemistries, are described in International Organization for Standardization (ISO) 8217: Petroleum Products-Fuels (Class F)-Specifications of Marine Fuels (ISO 8217, 2017). The specifications listed in this standard are broad, and the standard is currently under revision. Additional details for individual fuel categories are provided in standard ISO 8216-1. Fuels are categorized as a residual fuel if they contain any unprocessed residuals. Distillate fuels are produced entirely from refinery streams that have received further processing after distillation.

2.1 RESIDUAL FUELS

ISO categories for residual fuels begin with the letters ISO-F-RM to indicate an ISO-defined fuel category (ISO-F), with the letters R and M denoting a residual fuel for marine use. The last letter (A, B, D, E, G, or K) denotes a particular category. The last letter is followed by a number (for example 380) that indicates the kinematic viscosity of the fuel at 50°C. An example category is ISO-F-RMG380, which is a typical category for a traditional HFO. ISO standards also allow the fuel categories to be abbreviated (i.e., RMG380 in place of ISO-F-RMG380).

Residual fuel categories RMA10, RMB30, and RMD80 have lower levels of carbon residue, lower pour points, lower ash content, and lower metal content than RMG and RMK fuels. Category RME180 has lower carbon residue, ash, and metal content but is otherwise similar to category RMG180. Table 2.1 shows the ISO 8217 specifications for residual fuels (this table should not be used in place of consulting the current ISO standard for the latest important information and details).

RMA fuels contain substantial amounts of residual and enough distillate products blended in to reduce the viscosity to the specified level for a given category. The lower the viscosity, the more distillate is needed in the fuel blend. The residual fraction of these fuels typically contains high levels of aromatic compounds, including asphaltenes. The distillate portion of these fuels is typically paraffinic, which serves to reduce the density and improve ignition.

WHAT ARE DISTILLATES AND RESIDUALS?

Distillates and residuals refer to the products of a distillation process. Distillation uses heat to separate components of a mixture according to their boiling point. The distillate is the product that leaves the mixture as a gas (i.e., the distillate is distilled from the source material). The residual is the liquid product that remains after distillation has occurred. In this case, the residual is a “heavier” petroleum blend than the distillate, meaning that it includes molecules with higher molecular weights and boiling points. Viscosity and density are also typically higher for residuals than for distillates.

Table 2.1. Marine residual fuel categories. (Petroleum Products–Fuels (Class F) – Specifications of Marine Fuels. ©ISO. This material is reproduced from ISO 8217:2017, with permission of the American National Standards Institute (ANSI) on behalf of the International Organization for Standardization. All rights reserved.

Characteristic		Unit	Limit	Catefory ISO-F-										Test Method Reference	
				RMA	RMB	RMD	RME	RMG				RMK			
				10	30	80	180	180	380	500	700	380	500		700
Kinematic Viscosity at 50 °C		mm ² /s	max.	10.00	30.00	80.00	180.0	180.0	380.0	500.0	700.0	380.0	500.0	700.0	ISO 3104
Density at 15 °C		kg/m ³	max.	920.0	960.0	975.0	991.0	991.0				1010.0			ISO 3675 or ISO 12185
CCAI		-	max.	850	860	860	860	870				870			
Sulfur ^A		mass %	max.	Statutory requirements										ISO 8754 or ISO 14596 or ASTM D4294	
Flash Point		°C	min.	60.0										ISO 2719	
Hydrogen sulfide		mg/kg	max.	2.00										IP 570	
Acid number ^B		mg KOH/kg	max.	2.5										ASTM D664	
Total sediment (aged)		mass %	max.	0.10										ISO 10307-2	
Carbon residue: micro method		mass %	max.	2.5	10.00	14.00	15.00	18.00				20.00			ISO 10370
Pour point (upper) ^C	winter	°C	max.	0	0	30	30	30				30			ISO 3016
	summer	°C	max.	6	6										ISO 3016
Water		vol %	max.	0.30	0.50	0.50	0.50	0.50				0.50			ISO 3733
Ash		mg/kg	max.	0.040	0.070	0.070	0.070	0.100				0.150			ISO 6245
Vanadium		mg/kg	max.	50	150	150	150	350				450			IP 501, IP 470, or ISO 14597
Sodium		mg/kg	max.	50	100	100	50	100				100			IP 501, IP 470
Aluminum plus silicon		mg/kg	max.	25	40	40	50	60				60			IP 501, IP 470 or ISO 10478
Used Lubricating Oils: calcium and zinc or calcium and phosphorus		mg/kg	-	calcium > 30 and zinc > 15 or calcium >30 and phosphorus > 15										IP 501 or IP 470, IP 500	

A The purchaser shall define the maximum sulfur content in accordance with relevant statutory limitations.

B Refer to Annex E in the standard, ISO 8217:2017(E).

C Purchaser should confirm that this pour point is suitable for the intended area of operation.

2.2 DISTILLATE FUELS

ISO 8217 also defines categories and specifications for distillate fuels. Although residual fuels do contain distillates to reduce the viscosity of the fuel blend, distillate fuels differ in that they do not contain any residuals. Rather, distillate fuels are entirely composed of distillate and other processed petroleum streams.

Distillate fuel categories include DMX, DMA, DMZ, and DMB; their specifications are shown in Table 2.2 (This table should not be used in place of consulting the current ISO standard for the latest important information and details.). These categories are often also known as marine gas oil (MGO). As with categories for residual fuels, the most significant difference among the distillate fuel categories is the specification for kinematic viscosity. Additional specifications were added for distillate fuels, including oxidation stability, carbon residue, cloud point, appearance, and lubricity.

Fuels in categories DMA and DMZ (sometimes called MGO) are blended using light cycle gas oil LC(G)O. LC(G)O and heavy cycle oil (HCO) are a blend of streams produced by additional processing of

residuals from vacuum distillation (Vermeire, 2012). The additional processing can include thermal cracking, hydrodesulphurization, and/or catalytic cracking. These processes are used to convert some of the residuals into lighter hydrocarbon streams and to remove sulfur. LC(G)O can contain about 60% aromatics and can increase the density of the fuel blend above the level achievable using gas oil from an atmospheric distillation process.

Category DMB is also referred to as marine diesel oil (MDO). It has a lower cetane number than other distillate fuel categories and thus can contain greater blend levels of LC(G)O than is possible with other categories. DMB has the highest viscosity, density, and pour point specifications of the four distillate categories.

WHAT ARE ASPHALTENES?

Asphaltenes are complex aromatic polymers that are suspended in crude oil. Asphaltenes commonly include nitrogen and sulfur within the polymeric structure and have attached paraffinic side chains. The side chains contribute to the stability of asphaltene suspensions in crude oil and refinery streams. Without these side chains, asphaltenes tend to agglomerate and often become so large that they can no longer be held in suspension. Agglomeration of asphaltenes is a common cause of sludge formation and filter plugging.

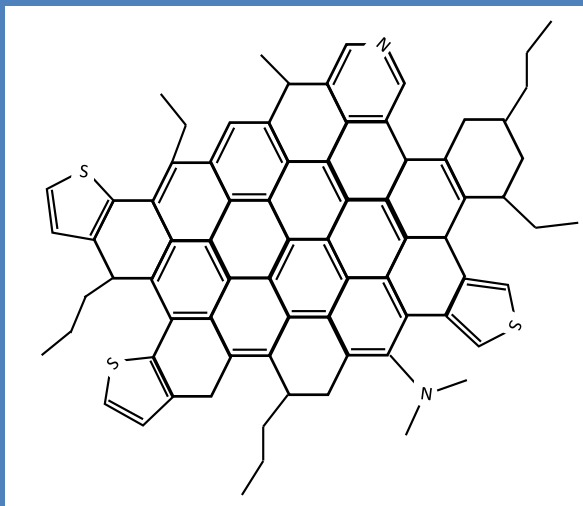


Table 2.2. ISO Specifications for distillate fuel categories. ©ISO. This material is reproduced from ISO 8217:2017, with permission of the American National Standards Institute (ANSI) on behalf of the International Organization for Standardization. All rights reserved.

Characteristic	Unit	Limit	Category ISO-F-				Test Method Reference
			DMX	DMA ^A	DMZ ^A	DMB ^A	
Kinematic Viscosity at 40 °C	mm ² /s	max.	5.50	6.00	6.00	11.0	ISO 3104
	mm ² /s	min.	1.40	2.00	3.00	2.0	
Density at 15 °C	kg/m ³	max.	-	890.0	890.0	900.0	ISO 3675 or ISO 12185
Cetane Index	-	min.	45	40	40	35	ISO 4264
Sulfur ^B	mass %	max.	1.00	1.00	1.00	1.50	ISO 8754 or ISO 14596, ASTM D4294
Flash Point	°C	min.	43.0	60.0	60.0	60.0	ISO 2719
Hydrogen sulfide	mg/kg	max.	2.00				IP 570
Acid number	mg KOH/kg	max.	0.5				ASTM D664
Total sediment by hot filtration	mass %	max.	-	-	-	0.10 ^C	see 7.4 ISO 10307-1
Oxidation Stability	g/m3	max.	25	25	25	25 ^D	ISO 12205
Carbon residue: micro method on the 10% volume distillation residue	mass %	max.	0.30	0.30	0.30	-	ISO 10370
Carbon residue: micro method	mass %	max.	-	-	-	0.30	ISO 10370
Cloud Point ^E	winter quality	°C	max.	-16	report	report	-
	summer quality	°C	max.	-16	-	-	-
Cold Filter Plugging Point ^E	winter quality	°C		-	report	report	-
	summer quality	°C	max.	-	-	-	ISO 3015
Pour point (upper) ^E	winter quality	°C	max.	-	-6	-6	0
	summer quality	°C	max.	-	0	0	6
Appearance	-	-	Clear and Bright ^F				^C
Water	vol %	max.	-	-	-	0.30 ^C	ISO 3733
Ash	mg/kg	max.	0.010				ISO 6245
Lubricity, corrected wear scar diameter (WSD) at 60 °C ^H	µm	max.	520 ^G				ISO 12156-1

A ISO 8217:2017(E) established corresponding fuel grades DFA, DFZ and DFB with identical specifications, but allowed to have FAME content up to 7% by volume.

B The purchaser shall define the maximum sulfur content in accordance with relevant statutory limitations.

C If the sample is not clear and bright, the total sediment by hot filtration and water tests shall be required

D If the sample is not clear and bright, the test cannot be undertaken and hence the oxidation stability limit cannot be established

E The pour point does not guarantee operability in all climates. The purchaser should confirm that the pour point, cloud point, and cold filter plugging point are suitable to the ship's design and the intended voyage.

F If the sample is dyed and not transparent, then the water limit and test method shall apply.

G This requirement is applicable to fuels with a sulfur content below 500 mg/kg (0.050 mass %).

2.3 DIFFERENCES IN CHEMISTRY BETWEEN DISTILLATE AND RESIDUAL FUELS

The specifications for marine fuel grades discussed in previous sections capture differences in physical properties among the distillate and residual fuel grades but do not discuss potential differences in the chemical makeup of these fuels. Sources around the world produce highly variant crude oil chemistries. Relying on a single source of crude oil can simplify refining operations, particularly if the crude oil is “light”; that is, its chemistry is dominated by relatively small hydrocarbon molecules. Refineries that must take crude oils from many sources typically are much more complex in design to accommodate the varying chemistries of the crude oil. The sulfur level is a key defining characteristic since it negatively impacts both processing and end quality. Crude is defined as “sweet” if its sulfur content is below 0.5 wt.%, higher concentrations are classified as “sour”. Reduction of sulfur content to meet upcoming IMO regulations will require substantial use of hydrotreating at refineries.

Aggressive hydrotreating of heavy residuals such as those used for residual fuel blends has historically not been economical because it requires a greater amount of heat and hydrogen input than does hydrotreating of lighter molecules. Such aggressive hydrotreatment often completely saturates aromatic molecules with hydrogen, converting them to naphthenes. Some refineries may include these streams in marine fuels if they can do so economically. Refineries that are optimized around heavy, sour crudes are more likely to use this approach, particularly if there is excess capacity. These streams are likely to exhibit increased paraffin content (and higher pour point) because of the aggressive hydrotreating needed.

In cases where the input crude oil is sufficiently low in sulfur, marine distillate fuels may be produced using streams from a visbreaker (or thermal cracker) that have not undergone hydrotreatment. Streams such as these are likely to remain aromatic in nature and continue to contain asphaltenes. Although the stability of these streams at the refinery is assured as a matter of refinery operations, fuels blended using these streams might carry an increased risk of asphaltene instability when blended with other streams and fuels after they leave the refinery. This risk of instability is a result of the removal of side chains from the asphaltenes during thermal cracking. Since the thermal cracker is not a catalytic process, it does not introduce catalyst fines in downstream products such as marine fuels (Gary and Handwerk, 2001).

Product streams from hydrodesulfurization and catalytic cracker units will also likely be used to blend marine fuels. The operating strategy of the hydrodesulfurization unit determines whether these streams will have increased paraffin content. If the hydrodesulfurization unit is operated at mild conditions, the HCO from the catalytic cracker that is used to blend marine fuels will remain substantially aromatic in nature. At more severe conditions, the hydrodesulfurization unit can hydrogenate aromatic rings resulting

AROMATICS, PARAFFINS, NAPHTHENES, AND OLEFINS

Aromatics, paraffins, naphthenes, and olefins are classifications that describe the molecular structure of hydrocarbons. Aromatic compounds all exhibit a ring structure with conjugated carbon—carbon double bonds—the simplest of which is the benzene molecule. Paraffins (also called alkanes) have a backbone of carbon atoms joined by single bonds. The remaining bonds for each carbon are filled by hydrogen atoms. The carbon atoms in a paraffin can be arranged linearly or can be branched. Naphthenes (also called cycloparaffins) are a special case of alkanes that are ring structured but with carbon-carbon single bonds in the rings instead of the conjugated double bonds characteristics of an aromatic. Olefins (or alkenes) are paraffins that have at least one carbon-carbon double bond in the molecule (Gary and Handwerk, 2001).

in a HCO that has increased paraffin content. In either case, the HCO from the catalytic cracker will contain catalyst fines. Asphaltenes may also still be present in the HCO and would also carry increased risk of instability when blended with other fuels after leaving the refinery.

If the product streams from the visbreaker and catalytic cracker are not low enough in sulfur, refineries might have to add other petroleum streams with lower sulfur levels to reduce the sulfur content of the overall fuel blend. These streams are likely to be lighter petroleum streams and may be more paraffinic in nature. Further information on refinery technologies and their relationship to crude oil sources and petroleum products is available from the International Council on Clean Transportation (Mathpro, 2011).

3. MARINE FUEL OIL: CHOICE, HANDLING, AND CONDITIONING

Marine fuel selection and use is dependent on many factors including ship type, routes, and even weather conditions. This variability requires multiple fuels that can have large differences in properties. Careful planning and detailed knowledge of the ship's fuel requirements and storage, cleaning, and flow systems are needed, and the capabilities of the existing equipment should be well understood. There are a great number of standards and procedures that must be followed. The fuel choices relate not only to the main propulsion system but also to the auxiliary engines and boilers. Regulations require detailed fuel recordkeeping and testing to comply with authorities. The existing ECAs, other restricted environmental zones, and the new IMO 2020 sulfur rule create a high level of uncertainty and complexity to the fueling and powering of large OGVs.

MIXER BEWARE!

To meet IMO sulfur regulations, VLSFO formulations will be offered that are blended from a wide variety of refinery streams, greatly increasing the spread and uncertainty of fuel properties and increasing the risk of incompatibility when fuels are mixed.

3.1 EXPECTED OPERATIONAL IMPACTS FROM THE 2020 IMO SULFUR RULE

Aside from mixing and switchover risks, VLSFOs will have various properties that require adjustments to the onboard fuel handling and cleaning systems. To operate well, attention should be given to fuel viscosity, pour point, cloud point, the need to control temperatures/viscosities, centrifugal purifier systems, pumps, and controls.

Because China has required 0.50% maximum sulfur fuel use within their territorial waters in recent years, such fuels have been used and analyzed, and the data shows a wide variety of properties (Jacobsen, 2019). Catalytic cracker HCO, also known as slurry oil, has a low sulfur content, and HCO has been and will continue to be blended into low-sulfur compliant fuels. This means compliant fuels will likely often contain catalyst fines. Data shows that although catalyst fines are sometimes found in 0.10% sulfur fuel, they are more commonly present in 0.50% sulfur fuels (Jacobsen, 2019). High-sulfur HFOs have commonly contained catalyst fines, and it is not known whether the frequency and amount of catalyst fines in such fuels will change significantly because of HCO streams being used for blending low-sulfur fuels.

3.1.1 Concerns with switching to 0.50 wt.% sulfur fuels

Some concerns with changing over to compliant fuels are highlighted here (Jacobsen, 2019); further concerns are discussed in more detail elsewhere.

- Tanks and fuel systems must be cleaned of high-sulfur fuel, sludge, etc., to avoid contamination of compliant fuel. Fuels may be blended to contain almost exactly 0.50% sulfur, leaving no margin for any increase in sulfur once onboard.
- The need for more separate tanks and fuel transfer systems should be addressed to deal with the wide variety of compliant fuels that should not be mixed.
- Many new fuels will have lower viscosity than HFO. Some pumps, seals, and other equipment designed for HFO may not be suitable for the new fuels, particularly because of low viscosity. Additional maintenance and new equipment may be required.

- Some VLSFO may have unusual properties based on past experience. For example, some paraffinic fuels may have relatively high pour point temperatures.
- Centrifugal purifier systems may need to be set up (or replaced) for the new fuels, which are expected to frequently contain catalyst fines.
- New fuels may have a “cleaning” effect on the tanks and fuel systems, dissolving and/or re-entraining sediments and deposits left by previous fuels. This may release previously settled-out catalyst fines, sulfur, and sludge into the new fuel.
- Having correct temperature/viscosity control for the variety of fuels being used will be necessary. Heating, cooling, and chilling capabilities may need revision.
- Safe and acceptable compliant fuels might not be readily available, forcing shipping companies to file and defend compliant fuel oil non-availability report (FONAR) claims.
- High VLSFO prices will affect shipping costs.

3.1.2 Ship Preparation and Operational Changes for 2020 and Beyond

Some ships may benefit from minor to extensive revisions to their fuel systems to allow flexible and proper operation with the variable fuel properties that are expected and therefore reduce risk. Engineering studies and modifications may be warranted, with proper approvals from relevant authorities or classification societies.

An excellent, detailed resource for this topic is the International Association of Classification Societies (IACS) document Rec 151: “Recommendation for petroleum fuel treatment systems for marine diesel engines” (IACS 2017). Some generalized highlights concerning ship preparation follow.

- Institute procedures and modifications to segregate different types of fuels from different sources. This may involve changes to tanks, piping, and pumps. Minimize the need for fuel mixing during fuel switchover or minimize the mixing volume when mixing is required.
- Have procedures for fuel compatibility testing, and perform the tests as needed.
- Address any fuel-handling mechanical constraints, ensuring that minimum/maximum characteristics of fuel oil as identified in fuel standards such as ISO 8217 can be safely handled onboard the ship. Also verify machinery performance using fuel oil with the variety of expected characteristics for 2020 (particularly if there is no prior experience) and make necessary changes.
- Include pumps, gaskets, seals, and machinery components in testing of low-viscosity fuels and be sure the current temperature control systems—including cooling—are appropriate.

CATALYST FINES

Catalytic cracking and hydrocracking are refinery processes that use a catalyst to encourage chemical reactions in the process stream. The catalysts are ceramic particles, similar to sand. Refineries separate and re-use catalyst particles from the product streams as they emerge from the catalytic process, but no separator is 100% effective. Thus, some of these particles remain in the petroleum stream and become contaminants in marine fuels. These particles are known as catalyst fines.

- Increase the storage capacity of distillate fuel oil to cover periods when other compliant fuels are unavailable or price prohibitive. Be sure fuel heating can be prevented or controlled. Additional cooling may be needed because of excess distillate returned from the engine picking up heat, which can lead to vapor lock or viscosity that is too low.
- Be sure all engines and boilers can be operated correctly and safely on the expected light fuels.

3.1.3 Unavailability of Compliant Fuel

It is possible that a ship will not be able to bunker a safe, compliant fuel and will need to file an IACS FONAR. The US Coast Guard will be charged with inspecting for US compliance, so it is advised to be aware of the latest rules concerning FONAR situations and file accordingly. Note that the FONAR declares noncompliance and documents justifications for the noncompliance. FONARs may be investigated to determine whether the situation was unavoidable. The threshold for avoiding noncompliance penalties may be high, and noncompliant bunkers may be required to be de-bunkered at significant expense. Although initial uncertainty about FONARs and enforcement is quite high, experience should reduce uncertainty in the future.

3.2 CHOOSING FUELS

Although fuel costs often drive fuel selection, a significant onboard fuel problem caused by poor selection can be quite costly. Whenever possible use trustworthy fuel suppliers and understand the characteristics of the fuel as much as possible before bunkering. Fuel should be specified to meet the ISO 8217:2017 standard (or latest revision) when ordering 0.50% sulfur fuel. Proper planning well into the future and use of contracts are advantageous.

Large oil companies/refiners and large suppliers may increasingly be entering the 0.50% sulfur (VLSFO) market because this fuel will sell at a price well above the crude oil price (Tolson, 2019), providing a reliable profit margin. This market may exceed 150 million metric tons per year. More highly reputable companies entering the market may increase the transparency concerning the fuel composition and mixing risks and may improve quality.

It is important to consider what range of fuel properties will be compatible with current ship equipment, onboard fuels, shipping routes (ECAs and other zonal requirements), and other situations and needs. If mixing fuel is unavoidable, an onboard heavily paraffinic fuel would preferably be matched with similar fuel; likewise, an aromatic fuel would be best matched with another aromatic fuel. This approach requires that reliable fuel composition information is available. Asphaltene precipitation is a major risk when fuels are mixed onboard.

BUNKERING IS INHERENTLY RISKY

Bunkering is a process with considerable risk and should be done according to a detailed plan with organization and vigilance. Mistakes, such as spills, can result in crew member injuries, pollution, fines, and even the arrest of the responsible parties.

There are many safety protocols to be followed for bunkering. Petroleum fuels can contain hydrogen sulfide, a poisonous gas that irritates skin, the mouth, and lungs. Hydrocarbon vapors are toxic and anesthetic and can cause death when inhaled (mainly in enclosed spaces). Such fuels also pose a risk of fire and even explosions from flammable vapors (BIMCO and IBIA, 2018).

3.3 BUNKERING

Bunkering is the term for the ship receiving fuel into the large fuel storage tanks or bunkers. Bunkering should be considered a process with considerable risk and should be done according to a detailed plan with organization and vigilance (Ford, 2012; Woodyard, 2009). All regulations, including those for documentation and recordkeeping, must be followed properly. Bunkering is somewhat routine, which could lead personnel to become complacent about the risks involved. It is of great importance to develop and follow detailed checklists, procedures, and processes that are specific to individual ships. Some best practices are explored in the next several sections. Beyond good practice, a very detailed ship-specific bunkering plan is always required.

Before bunkering low-sulfur fuel, ship tanks and piping should have been cleaned or flushed to remove all high-sulfur fuels, water, catalyst fines, and sludge to prevent contamination of new fuels. It takes very little high-sulfur contamination to change a compliant fuel to one that exceeds the sulfur limit.

3.3.1 Planning and Monitoring Bunkering

A prebunkering checklist should be available and be strictly followed (ignoring a checklist item often contributes to a bunkering incident). A listing of recommended actions includes the following:

1. An updated bunker piping diagram that has been approved by the ship officers should be available. Ports may have very specific bunkering regulations covering bunkering plans and practices (Washington State, 2018). Suggested prebunkering and monitoring checklist items can be found many places, but detailed suggestions are offered by Ford (2012).
2. The amount of fuel onboard should be known, and a plan for measuring fuel levels (soundings) should be ready.
3. A communication plan between the fuel providers and the ship personnel is needed (radio or otherwise). This communication should be frequently tested because signals can be blocked in some areas. Clear signals are needed for stopping flow, for an emergency stop (or loss of communication or any discovered problem), and for slowing fuel flow to allow more time to check proper progress. Hand signals are still sometimes used. It is good practice to have an emergency stop button available to the ship's officers (Ford, 2012).
4. A Shipboard Oil Pollution Emergency Plan with proper equipment and supplies should be in place at the start of bunkering. Equipment (pumps, shovels, oil booms), various absorbent products, dispersants, and containers, etc., should be made ready and in place. Also, various plugs to stop oil from entering drains and openings should be in place (Ford, 2012).
5. Ship moorings should be inspected, and ship movement should be monitored, particularly if receiving fuel from a barge. Excessive ship movement could result in a damaged or severed hose, which is an immediate and serious problem. Inspection of the delivery hose before fuel transfer should be included; reputable suppliers should be able to provide certification of the hose upon request.
6. Safe bunker fill levels (often 90%) and current capacities must be understood and levels monitored frequently. Personnel should have planned methods to recover from a miscalculation of capacity, false reading, or other problems. Diligence to prevent overfills is essential, considering the very high "cost" of even a minor spill. Using methods for soundings (a measure of depth of fuel in the tank) or ullages (a measure of the tank headspace above the fuel surface) can cross check other measurements or calculations and provide confirmation of remaining tank capacity.

7. The tank to be filled and the related piping and valves should be identified, tagged, and rechecked before starting the bunkering process. The pumping rate should be very low when first bunkering, which will allow checking for problems such as leaks or incorrect valve positions with less risk of a major accident. Pressures and flows must be monitored throughout the bunkering process to enable rapid response to a problem should one develop. Pumping should slow down once again as bunkering nears completion to avoid overfilling. Once bunkering is complete, levels and quantities should be checked, necessary valves closed, and disconnections made properly (Ford, 2012).

3.3.2 Fuel Oil Analysis

A reputable laboratory should analyze each batch of fuel and provide a fuel oil analysis as soon as possible after bunkering. Test laboratories will normally send an alert of any unusual or potentially damaging fuel characteristics. The analysis will confirm whether the fuel meets purchase specifications and will document contaminant levels, water content, etc. These results will be needed in case of a dispute with the bunker supplier and can assist engineers in devising the best strategy for use of the fuel (Ford, 2012). There is concern that current compatibility tests might be inadequate for the breadth of fuel formulations expected in 2020 and beyond; however, new fuel mixing compatibility tests are being developed and explored and may become available.

3.3.3 Bunkering Malpractice

Although most fuel purchases are completed under honest and fair circumstances, mistakes do occur and malpractices are sometimes reported (Ford, 2012). Being suspicious may be helpful under some circumstances. A few generalized malpractice examples follow.

- When moving fuel from one tank to another, basic trickery is sometimes used to change measurements indicating that more fuel has transferred to a ship than has actually been acquired by the ship.
- Introduction of air into the fuel upstream of the flowmeter is a known method of malpractice. The fuel density should be checked to confirm it is indeed an expected density. A Coriolis-type flowmeter can be used to accurately measure mass flow independent of temperature and pressure.
- There has been reported use of a small bleed line after the flowmeter that returns to the suction side of a transfer pump, effectively circulating some fuel through the flowmeter twice. Inspection of “extra” lines should reveal such malpractice.
- Suppliers may misrepresent fuel specifications and quality.
- Causes of fuel oil spills may not be reported.

It is worthwhile to consider causes of spills during bunking. A good discussion and documented examples of spills can be found in UK P&I Club and Brookes Bell (2018). There are several common causes of bunker spills, and often a combination of these causes are factors in bunkering incidents. A list of common causes/factors follow.

- Incorrect setting of pipeline system valves, causing either overpressure or flow of fuel oil to an unintended location. Valve malfunction can occur, which is often related to poor maintenance or insufficient valve testing.

- Insufficient or incorrect monitoring of tank levels during bunkering. All tanks should be checked, not just those expected to receive fuel.
- Excessive fuel flow rate or pressure, which stresses the system or even exceeds design pressures or capacities of hoses, lines, or other system components. High flow rates can also cause crew members to hurry monitoring and measurements and can force fast decisions that may cause mistakes.
- Air pockets that form for certain tank structures and ventilation pipework, especially if the fuel pumping rate is high. The trapped air can release before the tank is full, causing an unexpected discharge of liquid or mist through the ventilation system.
- Failures of transfer pipelines and hoses or connection points. This can be attributed to poor maintenance, insufficient pressure testing, excessive pressure, or not closing off inappropriate manifold connections (which become over-pressurized or were not prepared for pressurized fuel).
- Faulty high-level alarms (which can normally “save things” when a mistake is made).
- Pump and leakage issues not seen with HFO but occur when bunkering new, lower viscosity fuels.

Human factors are also involved in bunkering spills and problems, some of which follow. These factors contribute to personnel failing to follow documented procedures and good practices.

- Using a generic bunking plan without making it specific and clear for the bunkering operation about to take place. Many tanks, valves, and piping may be involved, and all valve positioning must be correct for each transfer.
- Complacent behavior such as lack of attention to details and ignoring the risks involved because of the routine nature of bunkering operations.
- Fatigue from excessive workloads and multitasking. Bunkering can occur at inconvenient times and coincide with other important operations such as cargo movement, maintenance, dealing with authorities, audits, surveys, etc. Personnel may be doing multiple jobs at once.
- Inexperienced or poorly trained personnel being unfamiliar with equipment or procedures.
- Breakdown in communications or poor planning interfering with the ability to respond quickly and correctly when needed.

More bunkering information on best practices and case studies of spills can be found in many references, including BIMCO & IBIA (2018), Ford (2012), ABS (2018), UK P&I Club and Brookes Bell (2018), and Washington State (2018).

3.4 FUEL PROCESSING

This section includes a brief overview of typical fuel processing protocols for ships capable of using heavy and intermediate fuels such as VLSFO. These fuels have an inherent risk associated with entrained water, catalyst fines, sludge, other solids, and otherwise removable contamination. Virtually everything that applies to HFO handling also applies to VLSFO; however, additional considerations and complexities are expected because of the anticipated wider variation in the fuel properties of VLSFOs. An excellent overview of fuel handling and processing (cleaning) is found in the International Council on Combustion Engines (CIMAC) Recommendation No. 25 (CIMAC, 2006) and *Pounder’s Marine Diesel*

Engines and Gas Turbines (Woodyard, 2009). The latest engine manufacturer and equipment supplier bulletins should always take precedence and be heeded as appropriate. All such ships should have detailed schematics of the fuel delivery and process system, from the bunker tanks to the engines and boiler fuel injection systems. In between, there is much essential fuel-handling related equipment (CIMAC, 2006). A detailed fuel oil management plan and very detailed procedures must be in place and be well understood by pertinent personnel.

After bunkering, the first movement of fuel is to a settling tank (Figure 3.1). A positive displacement pump with strainers and a pressure relief valve for pump protection is typical for extracting fuel from the bunker. The valving and piping systems could be both flexible and complex because of multiple bunkers, settling tanks, service tanks, and the ability to direct fuel to other storage tanks (bunkers) and to pump fuel off-ship (de-bunkering) to other storage (barge, etc.) via the bunkering manifold (Ford, 2012).

For the fuel system to function properly, the fuel viscosity must be controlled at every step in the process by controlling the temperature of the fuel. Adding heat reduces viscosity, thereby improving fluid flow, while the opposite is true when heat is reduced. Excessively low viscosity can damage fuel system equipment, cause leaks, and cause poor combustion or even main engine stalling (for example because of vapor lock). Temperature and viscosity are also very important to the auxiliary engines and boilers. Boiler explosions are possible from use of overheated or incorrect fuels.

Generally, a system of heaters and coolers (coolers often use sea water) are used in the tanks and throughout the fuel system. In cases where lower temperatures are needed than can be provided using sea water, chiller systems can also be used. HFO bunkers must be heated so that the fuel will flow through the system. The variety of formulations expected for VLSFOs suggests that, for some cases, cooling may be needed in locations that had previously required only heating.

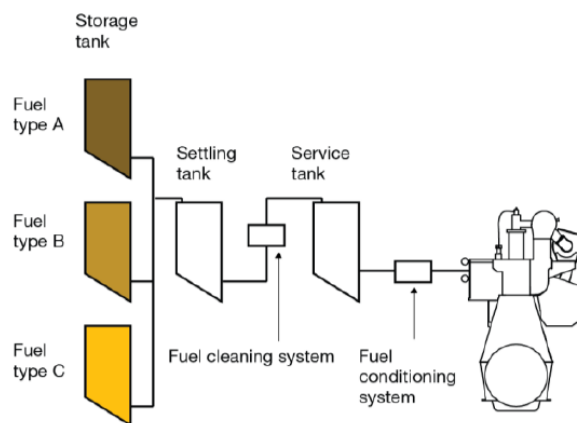


Figure 3.1. Highly simplified minimal fuel system. Figure courtesy of MAN Energy Solutions, 2019a.

3.4.1 Settling Tanks

Stored fuel oil is moved from the bunker storage to a settling tank, as shown in Figure 3.1, which provides an important settling function for suspended water and solids. Fuel is heated to a proper temperature (below the flashpoint) to aid in the settling process. Settling tanks have sloped bottoms to collect water, sludge, catalyst fines, etc., in the lowest section. Once the desired temperature is reached, heating is usually stopped to limit thermally induced currents, which oppose the settling process. Occasional reheating might be needed because of heat loss. Deaerating also occurs in the settling tank (Ford, 2012). The high fluidity of low-viscosity fuels will reduce or eliminate the need for heating.

Settling tanks have bottom drains, and the bottoms (containing water, sludge, and catalyst fines) should be removed to a sludge tank on a regular basis. Rough weather and high seas will stir up sediment in tanks (and perhaps piping), which could contain high concentrations of catalyst fines (MAN, Nov 2017; Rolsted, 2013). Consequently, operation in these conditions could necessitate performing the draining operation more often to minimize re-entrainment of contaminants.

3.4.2 Fuel Cleaning System

From the settling tank, fuel is routed to centrifugal separator devices, also known as purifiers and clarifiers (Woodyard, 2009), which are used to remove water, sludge, and catalyst fines that were not removed by the settling process. The centrifugal fuel cleaning step is very important to prevent excessive catalyst fines, sludge, and water from continuing to the service tank. Poor operation of the fuel cleaning system can result in very costly engine problems.

The term purifier refers to a centrifugal device that separates two liquids – water and fuel in this case – and can remove sludge and solids. A clarifier is a similar centrifugal device that removes solids and sludges but does not have a continuous flow path for liquid separation (however water is removed with the sludge and solids).

The separators need to be operated properly and have a regular maintenance plan as specified by the manufacturer. Fuel sampling every few months can be used to check centrifuge efficiency as a normal part of operation when no problems are suspected. If high catalyst fines levels become problematic, the fuel might require additional or specialized cleaning. Additional testing and monitoring should be done to ensure fuel quality and proper cleaning system performance. It is generally optimal to keep fuel flow as low as possible through the separators (slightly higher than the total fuel consumption rate) at the appropriate temperature. For HFO this temperature is often stated to be ~98°C; however, it could be lower for less viscous fuels. It is often more beneficial to run two separators in parallel than in series because of the efficiency gain for lower flow rates (CIMAC, 2006; Woodyard, 2009). Some highly automated systems are available, but others need to be examined and adjusted and the discharge valves (which release sludge and solids) correctly used. The appropriate equipment manuals and bulletins should be followed to maximize fuel cleaning.

A homogenizer or emulsifier is an optional device that creates a water-fuel emulsion with what should be the small amount of water remaining in the fuel after it passes through the purifier and clarifier. The homogenizer should always be installed after the service tank and before the 10 µm particle filter. This positioning allows maximum opportunity for removal of water, sludge, and catalyst fines from the fuel.

3.4.3 Service Tanks

After the separators, the fuel is transferred to the service tanks. These should have sloped bottoms and drains to collect and remove any remaining sediment and water. Again, high seas could re-entrain catalyst fines, sludge, and water and send it on to the engines, so draining the tank bottoms to the sludge tank is important. Also, the design should include overflow piping that takes the fuel from a point near the tank bottom and directs it back to the settling tank. This will pull fuel that is “less clean” from the service tank to the settling tank. If excessive contamination has reached the service tank, a special method to “reclean” the fuel oil in the service tank may need to be devised.

3.4.4 System from the Service Tank to the Engine

After the leaving the service tank, fuel must be filtered, further pressurized, and set to the correct viscosity and temperature for optimal cylinder injection. This generally involves a self-cleaning filter followed by a

mixing and heating system (or cooling if needed). A flowmeter and a viscometer are in place just before injection. This final section of fuel handling equipment is to ensure that clean fuel at the correct temperature, viscosity, and quantity is injected for proper combustion, engine operation, and engine health (Winterthur Gas & Diesel, 2016).

A 10 μm filter should be the final filtering step before the fuel is sent to the engine. If this filter needs to be backflushed or cleaned more often than normal, it is likely an indication of a problem with insufficient fuel cleaning. Filter backflushing oil should be routed to the sludge tank and not be reintroduced to the fuel system.

3.5 FUEL SWITCHING

As discussed in the introduction, because the emergence of ECAs required many ships to switch fuels before entering such environmental zones, there is much recent experience that is relevant with this practice. This step has been identified as one of the most critical operations impacted by the IMO 2020 sulfur cap because of the high variability of VLSFO formulations. In many cases, VLSFOs may lower the temperature control difficulties of fuel switching for ECAs because of the smaller difference between the 0.50% and 0.10% sulfur fuel viscosities. The risks are expected to increase, however, due to fuel incompatibility issues particularly when changing between aromatic fuels with asphaltenes and paraffinic fuels, the properties of which are often not well known. This will be true for all fuel switching: switching between different VLSFOs and switching between ultra-low sulfur fuel oil (ULSFO) (for ECAs) and VLSFOs. Ships may carry a wider variety of fuels and may need a more complicated fuel system to minimize risks from fuel comingling and incompatibility. Figure 3.2 shows a fuel system configuration that is more complicated than the simple system in Figure 3.1. The high level of complexity of an onboard fuel treatment system is described well by CIMAC Recommendation No. 25 (CIMAC, 2006).

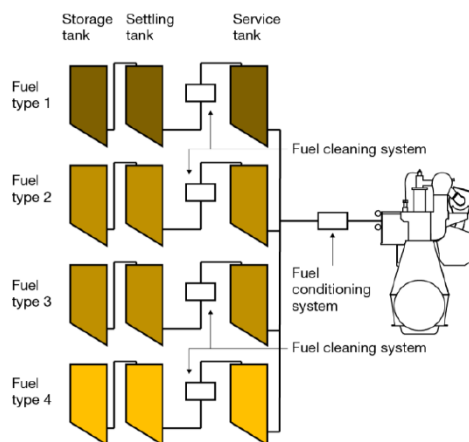


Figure 3.2. More versatile but complex fuel system for segregating fuels and to minimize mixing. Figure courtesy of MAN Energy Solutions, 2019a.

3.5.1 Fuel Switching Procedure, Risk, and Loss of Propulsion

Considerable risk can be associated with switching fuels for entering ECAs or other environmental zones. Using a light distillate fuel such as MGO in equipment (engines, boilers, fuel systems) designed for heavier fuels has risks and can be dangerous. Upgrading or replacing equipment and controls may be necessary to comply with regulations, pass inspections, and operate a ship safely and properly. An excellent treatment of this topic is found in the American Bureau of Shipping *Marine Fuel Oil Advisory 2018* (ABS, 2018), particularly Appendixes 1 and 2.

The experiences due to the California Air Resources Board regulations, which came into effect in July 2009, are good examples of fuel switching issues. Fuel switching was a new requirement, with the mandate being that ships must use low-sulfur MGO or MDO (the sulfur level varied with the year and was eventually lowered to the current 0.10% level). Loss-of-propulsion incidents within California State waters roughly tripled under mandated low-sulfur MGO/MDO fuel use (Cowan, 2015).

Many loss-of-propulsion and equipment failures are possible during fuel switching. The IMO requires all vessels to have a fuel changeover plan that is ship specific (MARPOL Annex 6 compliant). This detailed changeover plan, including emergency procedures, should always be followed. The following discussion provides general information about changeover procedures.

Switching fuels can involve two fuels with vastly differing properties. A common example follows. HFO is highly viscous and requires heating to 120°C–140°C or greater for proper flow and combustion. Switching to an ECA-compliant fuel such as an MDO or MGO may require cooling (rather than heating) to attain the proper viscosity. The HFO may first be brought to a somewhat lower temperature for the changeover to MDO/MGO. The MDO/MGO should be introduced slowly, keeping the temperature rate of change to 2°C per minute (commonly cited maximum rate of change; Jacobsen, 2019) or below in the fuel system and keeping the mixed fuels within the correct viscosity range. When mixing fuels together, the best practice is to slowly change the proportions of each fuel in the service tank while the volume of mixed fuel is low. Some fuel systems will have a relatively small mixing tank designed for fuel switching, which helps to minimize the amount of mixed fuels. Fuels should not be mixed in storage or settling tanks. The process should be carefully monitored and can take several hours to complete. At completion, only the new fuel is going through the fuel system at the correct temperature and viscosity. It is also important to clear all applicable fuel lines and pumps of the noncompliant fuel to pass ECA inspection. The switch back to HFO (i.e., from a low- to high-viscosity fuel) is similar, with some of the same risks as well as some additional ones, such as temperature control. For example, pump plungers heat faster than the barrel as fuel temperature is ramped up. This causes the plunger to expand in size relative to the barrel, thereby reducing the clearance between the plunger and barrel. A loss of proper clearance raises the risk of pump damage.

Careful temperature control is very important because of thermal contraction and expansion in the fuel system and to properly control the fuel mix viscosity. Loss of power can result from vaporization of overheated fuel. Fuel rate settings may need to be altered during changeover to ensure the correct amount of fuel injection. Fuel pressure and viscosity must be maintained to prevent excessive leakage through seals, inadequate pumping pressure, pump failure, and other equipment failures. Increased maintenance of seals, flanges, etc., may be required for frequent fuel changeover events. Because fuel viscosity and effective lubricity are directly related, low viscosity can cause lubricity problems.

3.5.2 Engine Fuel Viscosity Specifications

Slow-speed crosshead engines typically have an injection pump minimum fuel viscosity specification of 2 mm²/s (cSt); some engines require 10–20 mm²/s at the engine inlet. For medium-speed diesel engines (operating between ~400 to 1400 rpm), the minimum pump viscosity often ranges from 1.8 to 3.0 mm²/s, while for high-speed diesel engines (>1400 rpm) the range can be from 1.4 to 1.5 mm²/s (ABS, 2010; Winterthur Gas & Diesel, 2016; Jacobsen, 2019). Keeping light fuels in the right temperature range to satisfy the viscosity criteria for the specific engine in use is very important. There are several ways fuel can be heated above the specified operating temperatures to impart improper viscosity and lubricity values. These include warm weather operation, fuel changeovers, and fuel recirculation from the engine fuel system back to the mixing tank.

3.5.3 Low-Viscosity and Lubricity Effects on Pumps and Seals

Pumps designed to use HFO have internal clearances that are appropriate for the viscosity range typical of HFO. Use of fuels outside this range can cause pump failure from excessive wear. This is especially true if the fuel film thickness is too low to provide the necessary lubrication between the pump plunger and casing. Low viscosities can also cause fuel to leak past pump rotors, causing decreased fuel flow rate, which leads to a loss in engine power.

Rapid temperature changes or gradients that may occur during fuel switching can also cause changes in the clearances between pump components. The result is scuffing, sticking, excessive wear, and pump failure. It is imperative that the specific pump specifications are considered and that fuel changeover be managed in a way that keeps the fuel within specifications for all pumps. Pump replacements or additional equipment may be needed in some cases to facilitate fuel changeover strategies. For example, an MGO with a viscosity of 1.5 mm²/s at 40°C may require a chiller system to achieve a target viscosity of 2.0 mm²/s (ABS, 2010; ABS, 2018). Alternative approaches to controlling fuel viscosity and lubricity include the use of specialized fuel additives.

When using light fuels in systems originally designed for heavy fuel, the gaskets, flanges, seals, and other fittings may require more frequent maintenance because of viscosity differences. Leakages and seepages require immediate cleanup to prevent potentially dangerous situations, including fires. All trouble spots must be carefully monitored.

Fuel changeover can also affect multiple engine and boiler systems on a ship. The suitability of each component of the fuel and combustion system of all engines and boilers for the possible range of fuels must be well known, and problems must be addressed to allow for problem-free fuel changeover.

3.5.4 Asphaltene Precipitation, Sludge Entrainment, and Wax Crystallization

A possible consequence of fuel mixing during a fuel changeover is the formation and/or release of asphaltene agglomerates. These agglomerates can clog strainers, filters, separators, and purifiers; cause sticking of fuel injection pumps; and cause other fuel flow restrictions. Generally, the greatest risk for agglomerate formation occurs when a more paraffinic fuel mixes with a heavy aromatic-based fuel (which may be described as asphaltenic). Introducing the lighter fuel can additionally have a cleaning effect on the fuel system, releasing sludge or other substances into the fuel stream that may clog filters. A severe incident of asphaltene precipitation can be difficult to remedy and could result in a serious loss of power situation. In cases of excessive asphaltene sludge, it might be possible to run the fuel through the centrifugal purifiers at low flow rates and discharge the sludge more frequently (ExxonMobil, 2019). This may require a reduction in vessel speed (or a shutdown) to reduce fuel needs. It is wise to have a plan in place to cope with such a situation.

Fuels with high pour-point temperatures and low-to-medium viscosities and densities are likely to be highly paraffinic and therefore risky to mix with other dissimilar fuels. When both density and viscosity are high, the fuel is probably highly aromatic (Jacobsen, 2019).

Highly paraffinic fuels can also cause problems with clogged filters when the fuel reaches a low temperature (below the pour point) and precipitates waxy solids. This risk is often related to shipping in cold climates or cold weather. Therefore, it is important to know the fuel's cloud point temperature to avoid situations of wax formation. Effective heating of the fuel system will alleviate this issue; however, it can be difficult, if not impossible, to provide enough thermal energy to uniformly heat the large volumes of fuel usually maintained onboard.

4. MICROBIAL CONTAMINATION

4.1 BACKGROUND

Microbially induced corrosion (MIC) is the degradation of metals (such as steels and aluminum and copper alloys) resulting from the microbial production of organic acids or hydrogen sulfide (if the conditions are anaerobic). MIC is one of the most pervasive and damaging means of metal degradation in the United States. Microbial contamination in onboard fuel and lubricant systems is a relatively common phenomenon; however, the mechanisms promoting rapid propagation are not well understood (Enning and Garrelfs, 2014; Stuart, 1995; Li and Ning, 2019). Although common in marine shipping, the main areas of concern are with distillate fuels and lubricants. HFOs (or residual fuels) are not as affected by microbial contamination. Microbes, whether bacteria, yeasts, or molds, are ubiquitous in shipyards and onboard marine vessels (Woodyard, 2009, Ch. 4). They are present in the water, fuel, and the atmosphere. Fuel- and lube-borne microbes exist primarily in a dormant state. They typically become a problem only when they experience a high growth rate that results in the formation of a large dense colony known as a biofilm, which is visible as a mat or slime. These biofilms can produce damage by either clogging filters and lines or by producing corrosive acids that rapidly degrade metal structures. Clogging can further damage the engine by interrupting, or starving, the fuel delivery to the injector and negatively impacting the combustion process. Injector fouling is a key concern.

Microbes are typically classified as either aerobic (requiring air/oxygen to propagate) or anaerobic (propagate in environments that do not contain air). One of the most corrosive types is anaerobic sulfate reducing bacteria (SRB), which converts the sulfate in seawater into a highly corrosive sulfide. Note that the sulfur borne in the fuel is not part of this process. To propagate rapidly, microbes require both nutrients and water. On ships, the fuel (or lubricant) is usually the nutrient source. Note that the presence or formation of a separate aqueous phase (water) is necessary to provide a pathway towards microbe growth. The potential of this water phase to promote microbe growth depends on several factors, including fuel solubility and toxicity; dissolved oxygen, sulfur, nitrates, and other nutrients; and the presence (or not) of microbes able to degrade the fuel structure. Propagation occurs at the fuel-water interface.

Lubricants are also susceptible to microbe propagation. However, the operating temperatures are normally too high to allow for microbe growth. Problems in the lubricating system can occur when the engine is shut down for an extended period of time. Proper housekeeping is the best approach to preventing and mitigating microbe propagation. Especially important is regular decontamination using commercial biocides and minimizing water accumulation in the tanks and lines.

4.2 MICROBES AND FUEL

Hydrocarbon fuels, especially diesel, are essentially sterile when first produced from the fractionation process in the refinery. However, they eventually become contaminated with microbes, which originate from the air, water, and soil during storage and transport. Although microbial contamination can survive in these fuels, they normally do not grow (or propagate) unless there is a water layer separate from the fuel. This separate water is an absolute necessity for microbe propagation. The other requirement is a source of nutrients, which can include hydrocarbons, carbon dioxide, nitrates, oxygen, phosphorous, and sulfates. The fuel chemical structures provide the necessary hydrocarbons, while the other nutrients normally exist as contaminants in the fuel.

The types of microbes that can propagate in hydrocarbon fuels are considerably diverse. About 30 types of bacteria, 80 types of fungi, and 12 or more types of yeast have been identified as being capable of degrading hydrocarbons found in transportation fuels. Microbes use low molecular weight alkanes (or

aliphatic hydrocarbons) for growth. In contrast, aromatics are not normally used by microbes and are therefore not considered biodegradable. Therefore, the aromatic content of fuels can serve to inhibit microbial growth.

The quantity of water necessary to propagate microbes is extremely small. Microbes can propagate in water layers only a hundred microns deep, which is nearly undetectable. Biocides and rapid turnover of fuel are the primary means of controlling MIC, as it is extremely difficult (and costly) to remove moisture in fuel systems. The susceptibility of the candidate fuels to promote MIC is based on their hydrocarbon chain length, level of aromatics, dissolved oxygen, and solubility in water.

Distillate fuels are susceptible to microbe attack, whether it be aerobic or anaerobic based. Especially notable are the alkanes, which are readily processed by microbes. It is the high levels of aromatics in gasoline that prevent microbe fouling in gasoline systems. Molecular branching of the fuel molecules generally increases the resistance to microbial attack (Stuart, 1995). In many instances, the conditions for microbe propagation are self-perpetuating and growth can be extremely rapid.

4.3 SULFUR-REDUCING BACTERIA CONVERSION OF SULFATE TO HYDROGEN SULFIDE

Note that fouling occurs with both aerobic and anaerobic microbe propagation. Films form with both types and lead to the previously mentioned issues with plugging onboard ships. However, corrosion is primarily associated with anaerobic conditions, particularly the corrosion induced by anaerobic SRB. This is of concern because of SRB prevalence, rapid growth, and induced corrosion. Note that aerobic conditions do not necessarily preclude SRB propagation. The consumption of oxygen in aerobic biofilm growth may create the anaerobic conditions necessary for SRB propagation.

The actual mechanisms driving SRB-induced corrosion are not entirely understood. In the most basic sense, microbes require an electron donor and an electron receptor to provide the energy required for metabolization. The electron donor is the hydrocarbon fuel, and the electron receptor is sulfate (which is present in seawater). A schematic of the corrosion process is shown in Figure 4.1 (Li and Ning, 2019). Sulfate is reduced to H₂S by the following reaction:



Then the H₂S will react with iron according to



However, the actual intermediate steps to form FeS are complex, and more than one series of reactions may be involved. Note that during the formation of a single FeS molecule, three additional Fe ions are dissolved and lost from the anodic site. The corrosion rate accompanying SRB is around 70 times faster than what would occur in sterile conditions (Li and Ning, 2019).

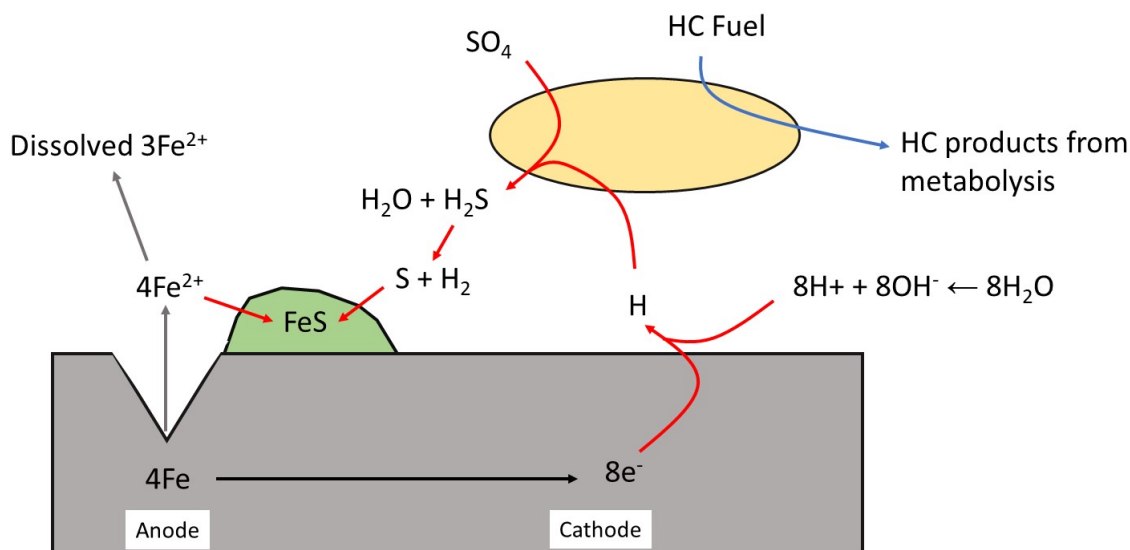


Figure 4.1. The process of SRB corrosion of iron.

SRB can also corrode iron by taking electrons from the metal surface to reduce sulfate. However, this process is much slower than when a nutrient source (fuel) is present.

4.4 IMPACT OF 2020 SULFUR CAP

For lubricants no additional impact on microbial contamination is anticipated. However, the 2020 sulfur cap is expected to increase the amounts of distillates in VLSFO. Currently, HFO or residual fuel systems do not have serious issues with bio-fouling, since asphaltenes and other aromatic components effectively inhibit microbe growth. That will change as many VLSFO blends are expected to be more paraffinic. Higher alkane content in the fuel will increase the opportunity for microbe propagation and highly paraffinic fuels will likely have the most issues with microbial fouling. The end result will likely be enhanced maintenance and frequent use of biocides with problematic VLSFO blends to mitigate biofouling.

5. LUBRICATION

5.1 INTRODUCTION

Two primary types of engines are used in marine propulsion. Four-stroke diesel engines are used to power small-to-medium-range vessels via connections to the propeller and to provide electrical power. The other primary engine type is the large 2-stroke crosshead engine used to power large ocean-going vessels. These slow-speed engines are directly coupled to the propeller, and the propeller is always rotating when the engines are operating. The lubrication requirements for each engine type are significantly different.

Lubricants that are designed for engine use must be able to withstand the extreme combustion environment and, at the same time, provide a lubricating film between sliding surfaces. Almost all motor oils are complex blends of base oils and chemical additives. Base oils are derived from crude oil and provide the necessary viscosity and temperature stability. Additives are used to either improve the base oil properties or provide added performance features. For marine engines operating on residual fuels, important additives include detergents, dispersants, and anticorrosion additives. Detergents and dispersants are designed to keep the engine surfaces clean, especially the piston, rings, and cylinder wall regions. Detergents are especially purposed for mitigating carbon (and other) deposits and to prevent buildup on the piston surface, rings, and grooves. Dispersants help to maintain particles (such as carbon soot) in suspension, where in certain cases they can effectively be removed via filtration and separation (Woodyard, 2009). The lubricant system has two main purposes. First, it provides a lubricant film to reduce friction among moving parts. Second, the oil flow through the engine is the primary means of removing heat from pistons, bearings, and shafts. Failing to properly lubricate an engine will result in engine failure.

There are key differences in lubrication system design for the large 2-stroke crosshead engines (used to power large cargo vessels) compared with the smaller 4-stroke marine engines. The 4-stroke marine diesel engines are versions of standard diesel engines that have been modified to run on residual fuels. Most of the modification centers on fuel delivery; the lubrication pathway of the standard diesel engine is usually retained without modification. These engines are known as trunk piston engines. Typical of diesel engines in general, a single connecting rod attaches directly to bearings on the crank and piston.

For 4-stroke trunk piston engines, a single lubricating oil is used to reduce friction and wear and to remove heat. Any location where there are metal surfaces moving against each other needs to be lubricated. Otherwise, galling or excessive heat buildup will occur, which will lead to failure. For trunk piston engines, the oil film reduces metal-metal contact mainly via hydrodynamic lubrication, meaning there is complete separation of the moving surfaces by the fluid film. Examples include engine main bearings and connecting rod bearings. Key factors affecting lubricant performance are viscosity, viscosity index, and shear rate. For trunk piston engines, the lubricant also provides a lubricating film on the piston rings and cylinder liner to reduce cylinder wear and lower piston friction.

The more complex crosshead concept differs from trunk piston engines in that the lower connecting rod is attached to the crank and to the crosshead assembly. The crosshead mechanism is a constrained vertical guide for the combustion piston and piston rod. This design ensures that the crosshead assembly experiences the bulk of the side forces. The combustion piston is effectively shielded from the large side forces that would cause rapid wear on the cylinder liner. The crosshead assembly is rigidly connected to the combustion piston by the piston rod, and together they can be considered a single complex piston. Another key feature of the crosshead engine is the diaphragm seal that the piston rod passes through and which separates the cylinder lubricant and combustion products from the crankcase lubrication oil. The diaphragm seal assembly (commonly referred to as the stuffing box) separates the combustion chamber from the crankshaft region and necessitates the use of two separate lubricant systems; one lubricates the combustion chamber, and the other lubricates the crankcase (entire lower portion of the engine).

For crosshead engines, the system oil, or crankcase oil, (the terms for oil lubricating the lower portion of the engine) lubricates the crankshaft, connecting rod, and crosshead but not the cylinder liner and piston rings. A separate lubricating oil system known as the CLO system is employed, which is devoted solely to lubricating the cylinder liner, piston, and rings. Note that CLO is also referred to as marine diesel cylinder lubricant. It is a once-through system such that excess CLO is drained away and not reused and fresh CLO is constantly supplied. These two separate lubrication systems are independent and unique to crosshead engines.

5.2 SULFURIC ACID FORMATION AND THE ROLE OF BASE NUMBER FOR MARINE LUBRICANTS

Sulfuric acid is formed during the combustion of sulfur-bearing fuel with excess air. Most of the fuel-borne sulfur is converted to gaseous SO_2 or absorbed into particulate. A smaller fraction is converted to SO_3 . The SO_2 will also react with oxygen (usually in the exhaust) to form additional SO_3 , but this process is considered too slow to be significant (Kass et al., 2005). Sulfuric acid (H_2SO_4) is formed when the SO_3 reacts with water according to the reaction



The water may be present as humidity in the intake air or formed during the combustion event. Of these two sources, humidity is considered to be the most important contributor to sulfuric acid production in 2-stroke crosshead engines. Under traditional operation, the temperatures inside the combustion chamber (especially the cylinder liner) were too high to allow for condensation of the sulfuric acid. However, with the advent of slow steaming and ultra-slow steaming and use of longer stroke engine designs, the combustion temperatures are reduced to a point that cylinder surface temperatures often drop below the dewpoint of sulfuric acid. The actual temperature depends on the combustion processes and internal pressures; but for diesel engines, this dewpoint is around 150°C . The acidity has been shown to increase linearly with fuel sulfur content (Brice, Carney, and Brown, 2019). Lowering the sulfur content of marine

BASE NUMBER

Base number (BN) is a measure of the acid-neutralizing capability of a lubrication oil. The BN of an oil is specifically defined as the acid-neutralizing capability that is equivalent to the milligrams of potassium hydroxide per gram of oil (mg KOH/g). For example, an oil with a BN of 50, has the acid-neutralizing capability of 50 mg KOH per gram of oil. Cylinder oils actually have base additives that are chemicals other than KOH. The higher the BN, the more acid the lubricant can neutralize.

fuels will reduce the amount of sulfuric acid produced in the cylinder. However, fuels containing only 500 ppm fuel sulfur have shown pronounced corrosion via sulfuric acid condensation (Kass et al., 2005).

BN (base number) is defined as the acid neutralizing equivalent number of milligrams of potassium hydroxide (mg KOH/g) added to each gram of pH neutral oil (cylinder or system). The actual base additive can vary and is usually not KOH. These acid-neutralizing detergents are usually Group-II metals (such as calcium, barium, and magnesium) organo-metallic colloid complexes (Wu, Papadopoulos, and Campbell, 2000; Chevron, 2013), which are soluble in the oil. Common examples are calcium sulfonate and calcium phenate. The term “overbased detergents” is used when these complexes contain an excess of the base component. These detergents help neutralize the acid solution by raising the pH to a more neutral level. Ideally, this neutralization will occur in the lubricant film before the acid has a chance to condense and contact the surfaces. The BN of the lubricant refers to the degree of alkalinity of the lubricant. The higher the BN, the higher the alkalinity. More on BN, cold corrosion, and engine damage is given in Section 6.1.

Another lubricant additive that influences deposits and corrosion mitigation is the dispersant. The dispersant serves to clean the combustion chamber walls by holding soot in suspension. Dispersants are also effective at assisting the acid-neutralizing ability of the detergents (Wu, Papadopoulos, and Campbell, 2000). The choice of detergent and additional additives such as dispersants can alter the speed of neutralization as well as the deposit handling and thermal properties of the lubricant.

Many factors must be considered when choosing an appropriate cylinder lubricant. Because fuel sulfur content is the most important factor, existing original equipment manufacturer (OEM) recommendations are based on fuel sulfur level to mitigate corrosion induced by sulfuric acid formed during combustion. A lower BN lubricant is recommended when operating on low-sulfur fuel because too much base results in the formation of hard abrasive deposits containing calcium carbonate or other inorganics. These deposits will accumulate in the piston crown lands and damage the cylinder liner (see Section 6.2). A careful balance must be achieved to mitigate sulfuric acid corrosion while preventing hard deposit buildup. In addition to the lubricant BN, the feed rate of the cylinder lubricant must also be adjusted properly to mitigate corrosion and optimize lubricant performance.

When operating on HFO with sulfur content up to 3.5 wt.%, the use of high-BN cylinder lubricants (70 BN and above) have been found to be the most effective in controlling corrosive wear. Cylinder lubricants with 40 BN are preferred when operating on 0.5 to 1.5 wt.% sulfur fuel. Within ECAs, where 0.10 wt.% fuel sulfur is mandated, the usual BN range for cylinder lubricants is 15–25 BN (Brice, Carney, and Brown, 2019).

5.3 LUBRICATION SYSTEM FOR 2-STROKE CROSSHEAD ENGINES

As discussed previously, crosshead engines have two separate lubrication systems. The system oil (or crankcase oil) lubricates the main bearings, cams, and crosshead assembly, and a separate system provides lubrication for the combustion chamber piston rings. Because the system oil for crosshead engines is not contaminated with combustion products and fuel via blowby, it does not need to be formulated for significant acid neutralization (high BN) or contain significant levels of dispersants. This lubricating oil is recirculated through the engine during operation. Lubrication of the piston rings is achieved using a separate lubrication system, known as the CLO system. CLO is injected directly into the combustion chamber (often timed to inject between the piston rings as the piston moves up and down) to provide lubricity between the piston rings and cylinder liner and for acid neutralization. It is partially burned and exhausted, and the remainder is scraped down below the piston where it accumulates in the scavenge space. The used CLO is drained away and stored as waste oil; it is not reused.

5.3.1 Main System Oil

The system oil lubrication system is supplied by one of two pumps, one of which will be operating while the other is on standby. This allows continuous oil flow even when a pump fails or is being serviced. As shown in Figure 5.1, the main lubricating oil system lubricates everything in the engine except the piston rings.

System oil formulations typically are SAE International (SAE) 30 weight, have a BN between 5 to 12, and contain enough detergents to keep the piston cooling gallery free from carbon deposits. These oils also contain rust and oxidation inhibitors and are formulated to enable water removal (avoid water emulsification) in case of water contamination. There is also a separate oil circuit that circulates the system oil through a centrifugal purifier to remove water, sludge, carbon particles, and other solids. This system is essential to maintaining lubrication oil quality. The viscosity of the oil, when in service, slowly increases with time if there is leakage of waste cylinder oil through the piston rod stuffing box and into the crankcase. This causes both the viscosity and BN to increase in the system oil. This contamination with the higher BN CLO may harm the oil's water-separating characteristics and can lead to bearing lacquering and other problems.

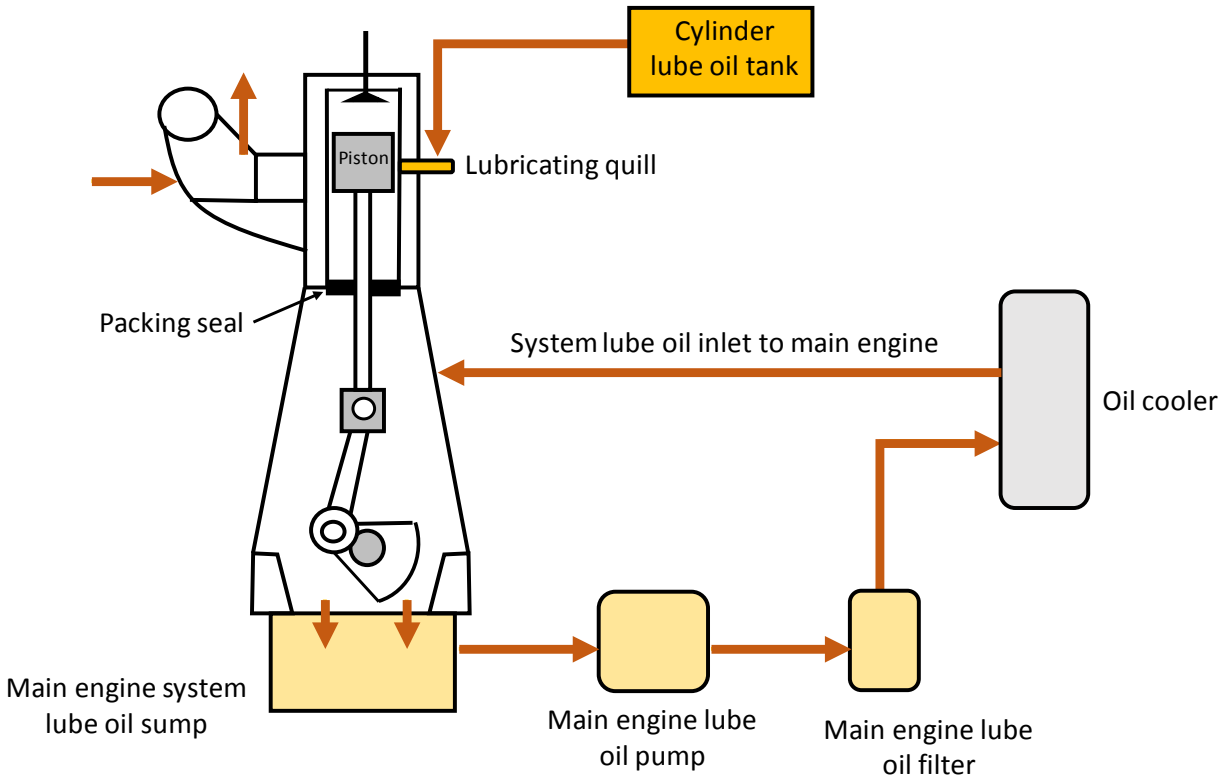


Figure 5.1. Lubrication circulation pathway in 2-stroke crosshead engine.

5.3.2 Impact of Low-Sulfur Fuel Operation on System Oil Lubrication

Because the system oil is separated from the combustion portion of the engine, it is not expected that there will be dramatic changes to system oil formulations. Low-sulfur fuel operation requires less BN in the cylinder lubricant, so leakage into the system lubrication will have less effect on BN. No changes to the system oil system equipment should be needed for use of VLSFO.

5.3.3 Cylinder Lubricating Oil

The diversity of engine designs, operating conditions, and worldwide bunker fuel qualities has led to a wide variety of cylinder oils. Typical variation in engine conditions on an individual ship can often require multiple CLOs because no single type is ideal for the challenges encountered. Cylinder lubricants in 2-stroke engines have multiple functions; they are designed not only to achieve good lubrication and internal cleanliness but also to neutralize sulfuric acid formed in the combustion chamber. A proper oil film is desired on the cylinder wall, and deposits need to be minimized. The cleanliness level should always ensure the cylinder rings can move freely. Virtually all CLOs are SAE 50 weight; however, major marine OEMs require a minimum kinematic viscosity of 18.5 cSt at 100°C, which is higher than the minimum for SAE 50 classification according to the SAE J300 standard.

Ideally, the total amount of base introduced into the engine should correlate to the level of acid formation, which is directly dependent on the sulfur level in the fuel oil (but also depend on the specific engine characteristics and operating conditions). If the oil feed rate or BN is too low, then cold corrosion will occur (see Section 6.1). However, if the feed rate or BN is too high, the excessive alkalinity of the cylinder oil can manifest as hard deposits on the piston top land and other places. These deposits can cause bore polishing, interfere with ring function, and cause scuffing and other problems (see Section 6.2) (Jacobsen, 2016). The cylinder oil BN and feed rate are often prescribed by the engine builder to maintain lubrication and cleanliness. Very generalized BN recommendations for fuel sulfur content follow (Brice, Carney, and Brown, 2019):

- For residual fuel containing >1.5% sulfur, 70 BN or higher is recommended.
- For fuel containing 0.50%–1.5% sulfur, 40 BN is recommended.
- For fuel containing 0.10% sulfur (distillate operation in ECAs), the recommended BN is between 15 and 25.

In addition to the important role of CLOs in reducing corrosion by containing over-based detergents, other additives are also essential to proper CLO function. The choice of detergents and dispersants affects the speed of acid neutralization, formation of deposits, and the thermal properties of the lubricant.

To assess the acid neutralizing performance of the CLO, it is common practice to measure the residual BN of the scrape-down oil during operation. OEM recommendations advise that the residual of the scrape-down oil should be above 15 BN to maintain satisfactory corrosion protection (Brice, Carney, and Brown, 2019). The latest applicable engine bulletins and information should always be followed.

5.3.4 Cylinder Lubrication for High-Sulfur HFO

Because residual bunker fuels contain high sulfur levels, the BN of the cylinder lubricant used with them is high, typically 70 or greater. BNs of 100, and higher, have been used when continuously operating on bunker fuel containing near or above 3.5% sulfur. In the past, when using high-sulfur residual fuel, the liner temperature was generally kept above the sulfuric acid dew point to prevent condensation of sulfuric acid. Slow steaming (and efficiency improvements) and more efficient engine designs have generally lowered liner temperatures such that sulfuric acid condensation has to be dealt with. Higher BN CLOs and proper CLO feed rates are necessary to neutralize the sulfuric acid formed during combustion of high-sulfur fuels. The high level of detergency normally present in high-BN CLOs will generally control piston deposits.

5.3.5 Low-Sulfur Fuel Operation Impact on Cylinder Lubrication

The large changeover to VLSFO to meet the 2020 requirement for 0.50% fuel sulfur will also change the CLO requirements, which is a topic of uncertainty and concern. Problems and successes with the use of CLOs with VLSFO will be carefully watched beyond 2020, and attention should be given to the latest engine OEM bulletins concerning CLO. In the past, the use of high-BN CLO with high-sulfur residual fuel usually meant excellent detergency was available for piston and cylinder cleanliness. Lower BN CLOs applicable to VLSFO might have inadequate detergency, which can lead to fuel-based deposits. However, use of higher BN CLOs can cause deposits from the noncombustibles in the additives.

Again, a key issue for low-sulfur fuels has sometimes been hard deposit formation on the top lands of the piston and other places that form when the BN of the CLO is excessive. A piston cleaning ring (when present) helps to minimize these deposits. The formation of hard deposits on the piston crown land and ring land regions can cause bore polishing, which negatively impacts the cylinder honing. This causes poor lubricant film development, the need for greater lubricant use, increased friction, and scuffing (Jacobsen, 2016). Severe deposits can also cause piston rings to become stuck or even break and leads to catastrophic liner wear.

Low-sulfur fuels will generally require lower BN CLOs. However, reducing the BN may significantly reduce the detergency of the lubricant, which results in increasing risk of carbonaceous deposit formation from incomplete combustion and noncombustibles. The majority of VLSFOs are expected to be produced through blending of hydrocarbon streams, and the wide variability of fuel formulations will cause concurrent variability in deposit formation. Problems with varnish and asphaltene deposition from unburned or partially burned fuel may be characteristics of such fuels (Brice, Carney, and Brown, 2019).

Currently, CLOs for HFOs that are 70 BN and higher contain enough detergent to handle the wide variation of high-sulfur fuel oil composition and to control fuel-derived deposits well. Unfortunately, CLOs marketed for HFO use are not formulated to address VLSFO use. The lower CLO BNs for VLSFO will require rebalancing of the formulations with additional deposit control capability to keep engines clean. For example, Lubrizol is exploring the use of dispersants as a means of mitigating varnish or asphaltene deposits without the negative effects (ash buildup) associated with detergents (Brice, Carney, and Brown, 2019). Developments in CLO formulations for VLSFO are expected to be forthcoming.

Although this is somewhat speculative, it may be best for some ships (and engine types) to alternate between a lower (e.g., 25 or 40) and higher (e.g., 70 or 100) BN CLO as a routine part of operations with VLSFO (MAN, 2019). Some beneficial slight corrosion and lacquer removal could occur when using the low-BN CLO, but fuel-derived deposits might form because of insufficient detergency. Switching to a higher BN CLO would increase detergency, and the deposits should decrease. However, with the high-BN CLO, excessive base additives could cause hard deposits to form on piston top lands over time. This would indicate the need to switch back to the lower BN CLO to diminish the hard deposits. Time of use of the two different CLOs can be optimized for low wear and clean engine operation. Again, the latest bulletins and advice from engine OEMs and other experts concerning CLO use should be followed.

5.3.6 Cylinder Lubrication Process Overview

The CLO is pumped from the cylinder oil storage tank to the CLO measuring tank. Usually a separate CLO storage tank is needed for use with 0.1 wt.% sulfur ECA-compliant fuels. From the measuring tank, the cylinder lubricating oil is fed by gravity to the cylinder lubrication system. The cylinder lubricant is heated to approximately 45°C to maintain the desired flow properties. A control system governs the injection protocol of the cylinder lubricant. Proper injection rate is generally proportional to both the fuel sulfur level and the engine output.

Note that a piston rod gland, or stuffing box, provides a seal for the piston rod as it passes through the separating plate between the crankcase and the scavenge airspace. The stuffing box contains a series of rings (in contact with the piston rod) that serve to both scrape crankcase oil off the piston rod and prevent oil accumulation from entering the crankcase. The stuffing box has a drain to direct the scrape-down oil to a spent-oil tank.

5.3.7 Switching between Cylinder Lubricating Oils

Switching cylinder lubricants requires some understanding and planning. Most ships have only one CLO day tank, which must be carefully monitored to time the lubricant switching to coincide with the time of fuel switching. For ships using high-sulfur HFO, a potential risk occurs when the ship leaves the ECA and switches back to higher sulfur residual fuel. Without proper planning, it could take many hours until the remaining low-BN CLO has been consumed (Verbeeke, Sebrechts, and Weerdt, 2019). During this period, the engine is not adequately protected from potential rapid sulfuric acid corrosion in the cylinders (see Section 6.1). Owners and operators who do not make these corrections will expose their engines to significant acid levels and therefore cold corrosion. Crews should be aware of how long it takes to consume the remaining low-BN CLO in the system.

When a ship is using excessively high-BN CLO with low-sulfur distillate fuels, deposits will slowly build up in the cylinder. However, when the fuel is switched back to the residual fuel, the deposits will gradually be destroyed. Thus, intermittent periods of operation on distillate fuels using high-BN CLO is acceptable if the fuel is switched back to higher sulfur residual fuel in a short time. Proper CLO type and operational management is the key to mitigating deposit formation and corrosion (Verbeeke, Sebrechts, and Weerdt, 2019).

These issues are changing for ships using VLSFO but may remain similar for ships using scrubbers and burning high-sulfur HFO. However, until properly optimized low-BN cylinder oils are validated, CLO switching could continue to be a frequent requirement for ships burning VLSFO to prevent deposit buildup and other problems as described in Section 5.3.5.

5.4 LUBRICATION SYSTEM FOR MEDIUM- AND HIGH-SPEED 4-STROKE DIESEL ENGINES

Medium- and high-speed marine engines are essentially adaptations of diesel engines used to power on- and off-road vehicles and machinery. The key difference is that the fuel delivery system has been modified for residual fuel handling. The lubricating architecture is essentially the same, but there are noteworthy differences that relate to the lubricant. Residual fuels produce higher levels of soot, which enter the crankcase via blowby past the piston. Unburned fuel components, in particular asphaltenes, also enter the crankcase. The soot and asphaltenes become entrained by the lubricating oil; therefore, dispersants are critical lubricant additives for 4-stroke engines operating on residual fuel oils. The lubricating oils for 4-stroke engines are formulated to effectively disperse higher soot loadings compared with engines running on distillate fuels. They are typically SAE grade 50. For these engines, the combustion temperatures are hotter since they have a different design from 2-stroke engines and do not experience the slow steaming conditions discussed earlier. Therefore, the oils for 4-stroke engines generally do not encounter conditions that promote sulfuric acid condensation (and hence cold corrosion) in the combustion chamber.

As with 2-stroke crosshead engines, the BN of the lubricating oil is selected based on the sulfur level of the fuel. Often a BN 20–50 oil is used according to the engine and fuel combination. The important thing is to maintain a minimum BN in the lubricating oil during service as specified by the engine manufacturer.

5.4.1 Lubrication Circulation for Medium-Speed 4-Stroke Engines

The lubrication circulation pathway is similar for all 4-stroke trunk piston engines, regardless of the application and fuel type, which also includes gaseous fuels such as natural gas. An oil flow diagram for a trunk engine is shown in Figure 5.2. A pump takes the oil in the sump region and forces it into the oil galleries where it subsequently lubricates the main bearings, crankshaft journals, and connecting rods. The cylinder walls and piston-pin bearings are lubricated by oil that is dispersed (flung) by the rotating crankshaft. Excess oil on the cylinder walls is scraped off by the lower ring in the piston. Paths from the main supply passage feed the camshaft bearing, timing assembly on the camshaft drive, and the valve train in the head. All of these components require complete lubrication while they are rotating and moving. After lubricating the engine components, the oil drains back into the oil pan, which provides some oil cooling, and is recirculated after being filtered to remove the dirt and debris that was suspended in the oil. The oil and filter should be changed at recommended intervals to remove excess dirt, metal, and debris the engine oil and filter have accumulated between services.

Piston rings are the barrier between the fuel/air mixture and exhaust from the engine crankcase region. They also minimize oil ingress to the combustion chamber. However, in marked contrast to the crosshead design, blowby of exhaust gases to the crankcase occurs because the seal between the piston rings and the cylinder is not completely leak tight. Because of combustion products and unburned fuel blowby, 4-stroke engine system oil can become heavily loaded with soot. If blowby is significant enough, unburned fuel (including the asphaltene component) can also contaminate the lube oil. These contaminants can lead to sludge formation and excessive wear. As a result, the lubricating oil of 4-stroke engines operating on residual fuels is often circulated through a centrifugal separator to remove the sludge and soot.

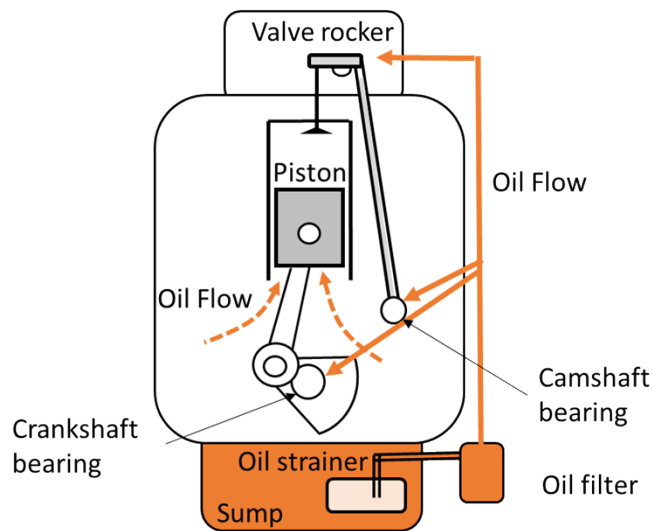


Figure 5.2. Oil Flow Diagram in a Trunk Piston Engine.

5.4.2 Lubrication Concerns in Medium- and High-Speed 4-Stroke Engines

In recent years, medium-speed engines have experienced problems of lacquer formation in the honing grooves of the cylinder liner. Lacquer formation effectively seals the hone, preventing oil retention in the honed grooves that is necessary to create the desired hydrodynamic lubricating film. As a result, friction increases, which subsequently reduces engine efficiency. Lubricant consumption and formation of carbonaceous deposits may also increase.

Lacquer formation is believed to be derived from cracking of the heavy fuel components, which subsequently condense on the cylinder walls. Once on the walls, the cracked components are believed to undergo polymerization and evaporation of the light ends. The fuel chemistry is known to influence lacquer formation, but the exact mechanisms are not fully understood (Woodyard, 2009).

Contamination of the lubricant by the blowby gases and raw fuel dilution is another concern. Residual fuel contamination can range from 2% to 15% of the oil in some cases. Unfortunately, the asphaltene content in residual fuels does not dissolve in lube oils but will instead coagulate and cause sludge formation in the engines, leading to filter clogging and overload of oil separators (Woodyard, 2009). The rate of renewal of oil charge in medium-speed trunk engines is important to maintain proper neutralization potential.

5.4.3 Impact of 2020 Sulfur Cap

For 4-stroke engines, the use of lower sulfur content and lighter fuels will mean that formation of sulfuric acid and the level of soot entrained in the fuel will be reduced. Hence, lower BN lubricants will be needed to neutralize the formation of sulfurous combustion by-products. The impact of using higher BN lubricants is unclear, but since there is a heightened possibility of hard deposit formation in the piston lands, lower BN should be used. The lower level of soot also means that the centrifugal separation times necessary to remove the accumulated soot would be lower as well. It is generally accepted that the asphaltenes, when present in the fuel, will still be a problem and that the formation of sludge is likely not to change drastically. Also, as fuels become more paraffinic the possibility of microbial contamination increases, which is also expected to increase microbial contamination in lube oils. This should be a risk only for engines that are idle for extended periods because the high temperature of oil in operating engines should eliminate microbes.

6. ENGINE DAMAGE RELATED TO FUELS AND LUBRICATION

According to The Swedish Club (a major marine insurance company), a vessel will suffer between one and two main engine damage events during its lifetime on a statistical basis. Medium- and high-speed diesel engines have a poorer track record than low-speed engines, but the repairs are less expensive compared with the low-speed 2-stroke engines. Turbochargers are insured as separate equipment from the engine and are also prone to failures that relate to fuels and lubricants. Leading contributing factors to engine failures and damage include lubrication issues, incorrect maintenance and repairs, and poor fuel management (Swedish Club, 2018).

With the widespread changeover from high-sulfur HFO to ships using VLSFO, the risk of occurrence of common causes of engine damage is expected to shift. The risk of occurrence of cold corrosion will go down, but deposit-related damage, including bore polishing, will become a greater risk. Damage induced by catalyst fines may also become a greater risk, but fines removal can be less difficult for lower viscosity/density fuels if the ship has the appropriate equipment and procedures. Cold corrosion will remain a considerable problem for ships burning high-sulfur HFO. An important method for limiting both cold corrosion and deposits is using the correct CLOs at appropriate flow rates.

6.1 COLD CORROSION

Cold corrosion is the term for sulfuric acid corrosion of metal surfaces—mainly the cylinder liners and piston rings of 2-stroke crosshead engines. Cold corrosion can be responsible for very high rates of wear in 2-stroke engines, but it generally is much less of an issue for 4-stroke engines (CIMAC, 2017). Ships using VLSFO and distillates will have a relatively low risk of cold corrosion but will need to avoid other types of engine damage. When high-sulfur fuel is used with scrubber technology, the risk of corrosion might increase because of the HFO having a higher sulfur content than in the past.

6.1.1 Conditions for Corrosion

Combustion of sulfur-containing fuels will form SO₂ and to a lesser extent SO₃. Formation of SO₃ is dependent on temperature, pressure, the amount of sulfur, and the concentration of other species produced by the combustion process. SO₃ in the water-rich combustion gases combined with relatively cool surfaces leads to aqueous sulfuric acid (H₂SO₄) formation (according to Equation 6.1) creating the acidic/corrosive condensate.



ENGINE DAMAGE RISKS WILL CHANGE

With widespread use of VLSFO, the risks of rapid cold corrosion will be greatly reduced but might increase for ships with scrubbers using high-sulfur HFO.

The risks of deposit-related engine damage may increase with the wide variety of VLSFO compositions expected. The required lower BN CLOs may or may not have adequate detergents and dispersants to cope with the variety of deposits and lacquering that could occur. Available CLOs are likely to improve in limiting and removing deposits as experience grows in 2020 and beyond.

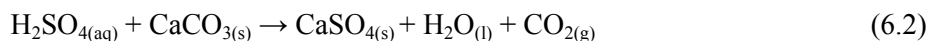
Subsequently, surfaces are corroded by the acid reacting with iron to form iron sulfate (FeSO_4).

Aqueous sulfuric acid condenses on surfaces at a higher temperature than does water alone. Engines operating at part-load for slow steaming will have lower cylinder liner temperatures than when operating at higher loads (and speeds). Newer, more efficient engines are designed with longer strokes, achieve higher pressures, and are usually optimized for high efficiency at part-load. These engines have lower liner temperatures and higher combustion pressures, both of which favor sulfuric acid formation and condensation (MAN Diesel & Turbo, 2016; CIMAC, 2017; Weber and Räss, 2016).

Engines may include adjustable cylinder liner cooling systems and other controls to lower condensation rates for certain operating conditions (MAN Diesel & Turbo, 2016; MAN Diesel & Turbo, 2013). Increasing the liner surface temperature and decreasing the scavenge-air water content can lower the rate of acidic condensation. It is known that engines operating in high humidity areas have been more challenged to keep cold corrosion at low levels than engines operating in more arid areas. If possible, the scavenge air should be cooled to the lowest temperature possible to decrease water vapor content (CIMAC, 2017; MAN Diesel & Turbo, 2016). Engine design companies have detailed information on their own specific engines and equipment and can assist in best practices to limit acidic condensation and cold corrosion. Lowering the condensate rate by various methods can also reduce the optimum CLO flow rate (saving oil and cost) or reduce the required oil BN.

6.1.2 Neutralizing Sulfuric Acid

In-cylinder acid condensate must be neutralized to prevent accelerated corrosion and wear. This is generally mitigated with high-BN lubricants, which when sprayed onto the liner and wiped on the liner surface (by the piston rings) allow the alkalinity (base) to neutralize the acid. Calcium carbonate (CaCO_3) complex compounds are common additives for acid neutralization (and act as detergents) in cylinder oil, which is removed with the oil. Equation 6.2 shows the formation of CaSO_4 :



Other acid-neutralizing additives can be in CLO. Nitric acid and formic acid are also be formed by the fuel oil combustion process, but these are not significant contributors to cylinder corrosion.

6.1.3 Corrosive Damage and Mitigation

Corrosion damage from sulfuric acid is caused by the acid reacting mainly with the cast iron surfaces, removing the protective oxide layer, and leaving a reactive surface. The softer components of the cast iron liner are preferentially removed, and the acid also attacks phase boundaries. The harder material protrudes and can fall away or be mechanically removed by the piston rings (CIMAC, 2017). These hard particles will likely become embedded in the rings, accelerate wear, and score the liner surface. It may seem counterintuitive, but for most 2-stroke engines a low rate of corrosion can help maintain a good cylinder liner texture that will hold a proper oil film. However, uncontrolled cold corrosion from high-sulfur fuel can progress very rapidly, forcing an engine rebuild and/or causing engine failure.

6.1.3.1 Signs of Damage

Damage can be observed from various inspections and oil testing. Deposits on the piston ring land between the top rings may indicate high cold corrosion rates and may also present itself as other ring pack deposits. Dark and light streaks on the liner surface indicate ongoing cold corrosion (see Figure 6.1). Analysis of the scrape-down oil will reveal unusually low BN and high iron content. Cold corrosion produces both nonmagnetic iron compounds and magnetic iron particles. Both magnetic and nonmagnetic

iron should be measured to detect and quantify cold corrosion rates and other modes of wear. The magnetic particles are indicative of harder material that has broken away from the liner surface. “Normal” engine liner wear or damage caused by abrasive catalyst fines produces mainly magnetic iron.



Figure 6.1. Upper cylinder liner after a sea trial showing white patches indicative of early cold corrosion.
Photograph courtesy of MAN Energy Solutions., 2013.

6.1.3.2 General Prevention Advice

Although the individual design of engines must be considered, the following general advice should be helpful in most cases (CIMAC, 2017).

- Higher BN lubrication oils provide better protection against cold corrosion and can lower oil feed rates.
- Feed rates should be optimized by analyzing piston underside drain oil (scrape-down oil).
- Liner cooling water temperatures should be kept at the upper limit to reduce condensation.
- Higher sulfur fuels bear the highest risk of corrosion and need for high-BN oils.
- Some engine types benefit from low scavenge-air temperature and some from higher temperature. Be sure to understand the ship’s specific engines and have the latest relevant bulletins.
- Scavenging equipment must be kept in good working order.
- Lubricant oil quills or injectors must be kept in good working order to maintain correct oil distribution.
- Drains (scavenge air, water mist catcher, receiver, and piston underside) must be kept clean and open.
- Perform scape-down oil testing (onboard tests supplemented by laboratory testing), scavenge port inspections, and wear measurements on a regular basis.

6.2 DAMAGE FROM EXCESSIVE LUBRICATION OIL BN

With the widespread use of VLSFO, the amount of cylinder oil BN being introduced to the cylinder needs to be relatively low compared with past HFO experience to counter sulfuric acid formation and cold corrosion. However, there is a benefit from small amounts of corrosion. The cylinder liner surface is meant to hold an oil film well, and new liners are machined to have a surface texture ideal for holding an appropriate oil film. Cylinder liners are made of cast iron alloys and have a complex heterogenous

structure that includes graphite. When the purposefully machined surface wears away, the presence of some acid corrosion leaves a texture that includes exposed graphite structures, which is helpful in holding oil films well (Jacobsen, 2016).

If the cylinder oil has an inappropriately high BN and/or feed rate, the excess additive (such as CaCO_3) tends to form deposits. Excessive BN and subsequent deposit formation can be detrimental in multiple and complex ways. The deposits can form in locations that interfere with ring movement. This situation contributes to scuffing and even ring breakage. Deposits may also directly interfere with the lubrication oil film. Hard deposits on the piston can contribute to polishing portions of the cylinder liner surface (Figure 6.2). In such cases, the excessive BN also prevents slow corrosion, which might otherwise aid in correcting the overly polished liner surface. A phenomenon known as “smearing” can occur, which is related to or is part of polishing. Smearing manifests as a thin layer of the iron material forming a coating to block or partially block the graphite structures within the liner surface. Unfortunately, these smeared and/or polished liner zones prevent the retention of oil and development of a proper oil film, which leads to increased wear, scuffing, and detrimental hardening of the liner surface (Jacobsen, 2016). The damage to rings and liners eventually leads to serious damage that requires rebuilding the cylinder.

The use of lube oils with excessive BN lubricants and the resulting deposits will be tracked by many interested parties carefully in the future (2020 and beyond) and countermeasures will continue to be developed. Consulting with the ship’s engine and lubricant suppliers and following the latest bulletins will guide use of the appropriate cylinder lubrication oils with proper detergent and dispersant additives to minimize risk of the problems described above. Engine companies and others track engine wear and repair trends to enable provision of operation and maintenance advice for specific ship engines and operating conditions (MAN Diesel & Turbo, 2014; MAN Diesel & Turbo, 2016; Weber and Räss, 2016).

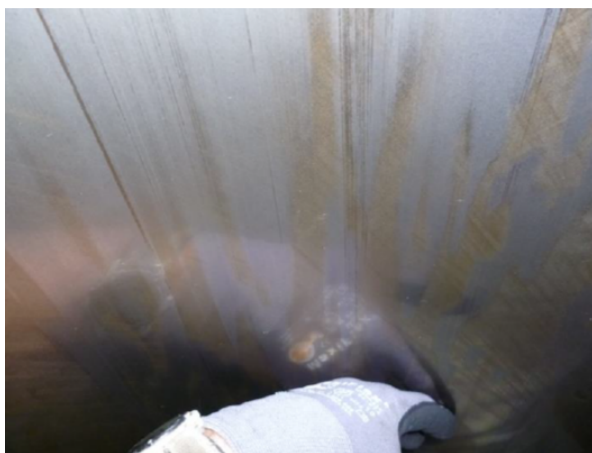


Figure 6.2. Example of a polished cylinder liner, reflecting a glove and watch during an inspection.
Photograph courtesy of MAN Energy Solutions, (LeFay, 2019).

6.3 INSUFFICIENT CYLINDER LUBRICANT DETERGENTS AND DISPERSANTS

The properties of VLSFO are expected to be highly variant. It may be difficult to know the propensity of a specific VLSFO to form deposits or produce varnish-like coatings from fuel components that are difficult to completely combust. The fuel components most responsible for varnishing are thought to be asphaltenes and resins. In general, deposits are an increased concern for switching from high-sulfur HFO to VLSFO (Brice, Carney, and Brown, 2019; Jukes 2019).

Excessive deposits on the piston, rings, and liner may be due to insufficient lubricant detergent and dispersants. This has been seen in the past with low-BN CLOs, as BN levels generally correlate positively with CLO detergency (see Section 5.3). The oil detergency should remove, dissolve, or prevent formation of deposits, and the dispersant additives will keep particles in suspension so they are flushed away in the oil (Brice, Carney, and Brown, 2019). Using a high-quality lubricating oil with detergents and dispersants developed for VLSFO use should be a high priority. Switching to a lubricant with different additives at the correct feed rate can often reverse deposit buildup and varnish formation. Improved low-BN CLO formulations are expected to be developed to address these problems.

6.4 CATALYST FINE DAMAGE

Excessive catalyst fines are often responsible for accelerated wear of 2-stroke and 4-stroke engine sliding surfaces (cylinder liner and piston rings) and are also responsible for other fuel system damage (Rolsted, 2013; JHC, 2013; MAN Diesel & Turbo, 2017a; Winterthur Gas & Diesel, 2016). This problem has been widespread with HFO, is expected to continue with VLSFO, and is even possible with ULSFO (Jacobsen, 2019). Fuels that contain catalyst fine levels exceeding the ISO 8217:2017 standards may overwhelm even a well-designed fuel cleaning system. Major engine designers have recommended limiting catalyst fines at the engine inlet to 5–10 mg/kg (ppm by mass), allowing up to 15 mg/kg for short periods. This means that there is a need for an efficient onboard fuel oil treatment system that can reduce fuel catalyst fines from 60 to less than 15 mg/kg. Furthermore, the particle size restriction recommendation is often for a 5 or 10 μm diameter or smaller, which would require using filters after the centrifugal purifier systems (and generally after the service tank, near the engine). A final 10 μm filter should always be used for fuel oil going to the engine (MAN Diesel & Turbo, 2017a; Winterthur Gas & Diesel, 2016). As mentioned previously, operation in rough seas and/or the use of some fuel formulations may increase the risk of re-entrainment of settled catalyst fines into the fuel. This can result in a fuel that met standards when purchased becoming contaminated with excessively high catalyst fines once onboard. Sudden increases in filter servicing/flushing can provide an indication of this problem.

6.4.1 Two-Stroke Engine Damage

Catalyst fines enter the combustion chamber and become embedded in surfaces, particularly in the soft graphite structure in the liner surface, but also in the piston rings as seen in Figure 6.3. The catalyst fine-induced wear rate is a function of the number and size of the particles, with larger particles doing more damage. Accelerated abrasive damage continues until the flow of excessive catalyst fines is eliminated by either properly cleaning the fuel or switching to a new fuel. If the excessive catalyst fine introduction is reversed, the wear rate will be reduced to normal. The trapped and embedded particles become dislodged over time and are washed away with the lubricating oil within a few days to a week (Rolsted, 2013; MAN Diesel & Turbo, 2017a), and normal wear rates are restored. Note that the abrasive wear from catalyst fines will also accelerate cold corrosion in the unfortunate event that both are a problem simultaneously.

Analysis of the cylinder scrape-down oil when excessive catalyst fine wear is ongoing will reveal a high magnetic iron content and a low nonmagnetic iron content. Diagnosing wear from excessive catalyst fines is made more difficult if cold corrosion is also occurring, as the occurrence of both magnetic and nonmagnetic particles may be high (MAN Diesel & Turbo, 2017a and 2017b). If there are excessive solids (including catalyst fines) in the fuel stream, the service interval for the 10 μm filter will decrease. The crew should monitor the time between required cleanings of the filter as a potential indicator of this problem. Testing of fuel beyond the centrifugal purifiers can also reveal the presence of excessive catalyst fines. Appropriate maintenance, testing, and operational procedures will help prevent catalyst fine damage.

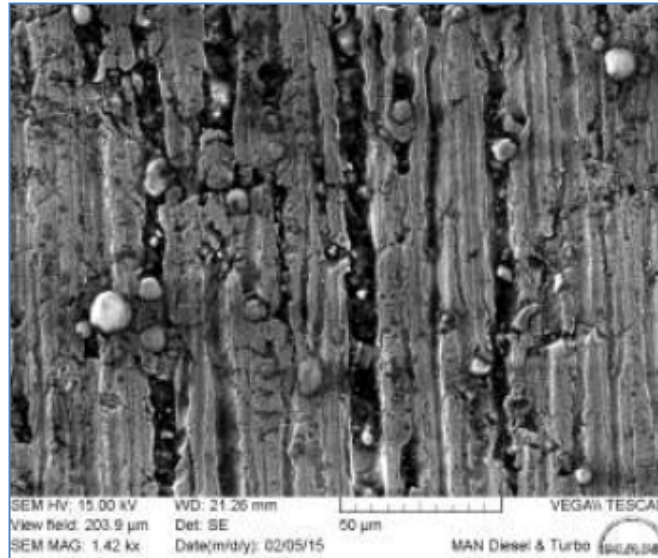


Figure 6.3. Catalyst fines imbedded in a piston ring surface.

Photograph courtesy of MAN Energy Solutions, 2017a.

6.4.2 Four-Stroke Engine Damage

For 4-stroke engines, the injector nozzles are often the first components to show damage with nozzle holes becoming altered in size and shape, as shown in Figure 6.4. The spray combustion process becomes compromised causing abnormal combustion and fouling. This in turn causes sticking or broken valves and can damage the turbochargers. Abrasive particles can become entrained in the exhaust stream, eroding the turbocharger nozzle ring (MAN Diesel & Turbo, 2017b).

Catalyst fines will damage 4-stroke engine cylinders as well, although splash lubrication can wash the fines away more effectively than the systems used with 2-stroke lubrication. Despite this, catalyst fines become trapped between the piston rings and liner and between the piston rings and grooves causing accelerated wear. Particles will also damage fuel pumps. Plunger-type pumps can have abrasives trapped between the plunger and barrel causing wear and/or pump seizure. This damaging wear can alter the fuel injection pressure and timing, leading to poor engine performance and perhaps other subsequent problems.

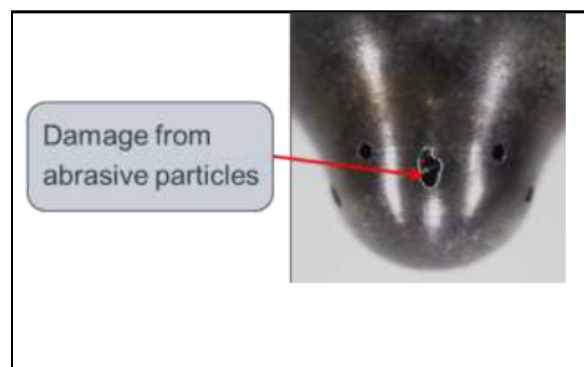


Figure 6.4. A 4-stroke nozzle damaged by catalyst fines

Photograph courtesy of MAN Energy Solutions, 2017a.

7. ENERGY AND FUEL USE REDUCTION

There are a great many energy-saving technologies for OGVs, and many require at least a modest specific ship study for applicability and optimization (ABS, 2013). This section gives descriptions of selected energy- and fuel-reduction technologies, mainly related to slow steaming. Slow steaming, which is currently widely practiced, can significantly lower fuel use and is expected to be increasingly emphasized in 2020. Slow steaming often involves some reoptimizing of the powertrain and auxiliary equipment using multiple fuel-saving techniques.

7.1 ECONOMIC AND OTHER INCENTIVES

A great deal of economic uncertainty is associated with the IMO 2020 sulfur cap. However, it is certain that the economic impact of fueling with higher priced VLSFO (compared to HFO) will cause fuel to become an even larger share of ocean vessel shipping costs. This will add significant fuel costs for most ships other than those using scrubber technology or alternative fuels. Choosing appropriate energy-saving methods can be highly dependent on the individual ship and powertrain design, specific routes, cargo, age of the ship, and other factors. Sometimes multiple energy-saving methods are not additive. The application of one technology or method can reduce the effectiveness of another technology or method (but may nevertheless be well worth pursuing and implementing).

With fuel costs expected to rise significantly for use of VLSFO, a variety of viable fuel-saving methods will receive greater consideration. Certainly slow steaming will be given even greater consideration, and numerous other technologies will be employed.

A significant barrier to instituting fuel-saving technologies that require investment and drydock time stems from a lack of clarity about which parties will benefit from the fuel savings. Often the ship owner or operator has no guarantee of directly benefitting (at least in the short term), as the benefits mainly go to the party responsible for purchasing fuel: generally, the charterer (ABS, 2013; Winkel, 2015). Business arrangements that reward the investor will increase the use of cost-effective energy-reduction measures. It is reasonable to think that fuel-efficient ships would bring higher usage fees to the ship owner in the long term.

The IMO passed a regulation (in 2011 and enforced since 2013) to require ships to be built according to the Energy Efficiency Design Index. This index lowers the allowed CO₂ emissions per capacity-mile for different ship types and sizes. This has given greater attention to hull form and propeller optimization as well as a large number of energy-saving technologies.

Beyond the regulatory and economic incentives, some shipping entities will care about having low fuel use and low CO₂ emissions as part of their “branding.” This type of incentive will likely have a modest influence on shipping.

7.2 FUEL SAVINGS BY SLOW STEAMING

Slow steaming is already a widespread practice. Expansion of this practice (“slower steaming”) is likely to occur through further decreases in ship speed. When reducing speed is optimized for overall cost and business considerations, it may be known also as “smart steaming.” This strategy may be possible for only certain shipping sectors but is expected to become a trend in 2020. In the past, instituting slow steaming required operational and powertrain equipment changes to be successful and to avoid serious problems. If OGVs are going to employ lower engine loads and speeds than have already been tested for the ship, a review and update of powertrain and operating procedures may be in order, and lessons from the past should be carefully considered.

The idea of smart steaming or optimizing speed includes the idea of lowering speed to match just-in-time arrival in port. The concept requires improved real-time communication of when a ship can berth and other information. This avoids using more fuel than needed to come to port early and then anchor waiting for a port call. There is a more general push toward intelligent speed and route optimization, involving more communication. Considerations include overall schedules, contracts, voyage time, weather, delays, risk, etc., which indicates rather sophisticated decision-making may be required.

7.2.1 Slow Steaming Methods and Challenges

Current slow steaming often involves reducing the average engine load from about 65% to 45% of rated engine power; but this can vary significantly (Weber and Räss, 2016), and lower engine loads can be used (Schmuttermair, 2010). Because of piracy, bad weather, and other considerations, it is preferable to retain the ability to travel at high speeds (Weber and Räss, 2016). Many newer ship builds have been optimized for high efficiency at slow speeds, including both the ship (hull) design and the powertrain (engine, turbochargers, economizer, rudder, and propeller). Earlier builds with powertrains optimized for higher speeds have likely had existing equipment and control strategies modified significantly to re-optimize for slow steaming. Slow steaming has successfully dropped fuel costs and consumption greatly, often with a modest drop in vessel speed (Schmuttermair, 2010; see especially Figure 3 in the reference).

Because slow steaming became widespread in a relatively short time span about 10 years ago, many ships used today were not originally designed for slow steaming. If even slower steaming is to be employed because of high fuel costs, past challenges may still be relevant to successfully instituting further reductions in ship speeds. Lowering the speed and engine load of a ship on a continuous basis, beyond what has been instituted in the past, should be subjected to an engineering study. Powertrain hardware and operational changes may be necessary and auxiliary equipment (boilers, generators, blowers, and others) may be affected. Engine, turbocharger, and equipment companies have knowledge, services, and products to help make slower shipping possible and successful.

HULL FORMS AND ONBOARD RENEWABLE ENERGY GENERATION

Additional means for reducing energy use by ships are available and include both modifications to hull shape and the use of wind and solar power collection on board. The use of hull forms to reduce energy use is already finding applications on today’s ships. Onboard wind and solar energy collection have not been considered economically viable to date, but could find use in the future. Both of these technologies are beyond the scope of this report, except to note that their use may also have some influence on the issues and measures encountered during slow steaming.

Note that all powertrain alteration must follow environmental law. Generally, engine emissions drop with properly executed slow steaming. Attention to, or even proof that changes are “NO_x neutral,” is often required.

A list of some specific concerns associated with slower steaming follows, but careful implementation can eliminate many of these.

- A large capital investment may be needed.
- Proper lubricant and lubrication rates must be maintained.
- Low engine load operation can lead to turbochargers producing inadequate air flow, causing scavenging problems and improper combustion.
- Increased or continuous operation of auxiliary blowers is required to supplement the turbocharging system and prevent blower failure.
- Turbochargers may become fouled because of poor combustion.
- Fouling of exhaust gas economizers and a buildup of soot in the exhaust system could occur, creating a fire hazard and diminishing heat transfer. Other boilers would then have to be used for the steam system, requiring use of additional fuel.
- Buildup of unburned products in the scavenge air zones and on pistons could occur.
- Returning to full load could cause a breakdown or could be hazardous because of the buildup of combustibles in various places.
- The possibility of cold corrosion increases due to cooler operation and more condensation of sulfuric acid in the cylinders (particularly for HFO).
- Increased inspections, as well as additional cleaning, might be needed for deposits in the exhaust and exhaust turbine.
- Sea trials might be needed to understand what alterations are necessary.

Issues with increased cold corrosion will be reduced or eliminated due to use of VLSFO. Fuels containing high distillate content (and good combustion properties) might reduce fouling concerns and require less heating.

7.2.1.1 Two-Stroke Engine Changes

The major engine companies have years of experience and information to be followed on any changes to the engine that need to be made for extended low-load operation. Generally, there are slow steaming “kits” and operating procedure changes and alerts available for each type of engine. Some changes may be needed before going to lower loads, and some changes can be made when an overhaul is needed (such as different piston rings).

It is also helpful to have high-quality calibrated measurements of fuel consumption and engine power, which enables efficiency to be tracked. Sophisticated systems that monitor the combustion and health of

all cylinders are available and allow electronic control to balance and optimize engine performance on a continuous basis (ABS, 2013). This can also help with compliance with NO_x regulations.

Large main engines at best efficiency will convert 50%–55% of the fuel energy to mechanical work and provide heat to recovery systems, which are important to lowering overall energy use. These heat recovery systems are affected by load reduction. Capital-intensive energy recovery systems are sometimes used on large engines and can include a final exhaust gas turbine and steam turbine combination electrical generating system. Other systems might include a steam turbine for electric generation or use the steam only for other purposes. A powertrain re-optimization could include changes to heat recovery systems and perhaps auxiliary boilers and generators.

7.2.1.2 Turbocharging and Scavenging Air Supply Options

Turbocharging is a complicated topic, and continuous operation at low load has very often required turbocharger alterations. Changes will be needed if the lower exhaust flows will not generate adequate air flow for scavenging and proper combustion and may also be needed for turbocharger and engine efficiency reasons. Turbine alterations such as re-blading the exhaust turbines for better matching or refitting with a variable geometry system can allow efficient slow steaming. If the engine has two or more turbochargers, it is possible to use turbocharger cut-out to enhance low-load operation and fuel savings. A turbocharger can be disabled by blanking it off (or even by partial removal for long-term engine de-rating). Also, the use of swing gates may be desirable, which allows the turbocharger to be blanked off for low-load operation and put back in service for high loads using hydraulically actuated sliding plates (Schmuttermair, 2010). This allows the engine to be switched between low and high load while preserving efficiency. For some cases, installation of waste-gates can allow high- and low-load operation when needed without reaching an overpressure boundary, but with fuel penalties compared with other options. Using turbocharger cut-out often has efficiency advantages over waste-gate use. Variable geometry turbocharger technology may have increased cost but will often effect the best efficiency over a broad engine load range (Schmuttermair, 2010).

Low-load operation can be accomplished using auxiliary blowers to supplement the turbochargers when the engine load drops below the turbochargers' ability to supply appropriate scavenging air. However, the blowers are often not built and maintained for continuous operation. Alterations can be made, or new blowers can be installed if greatly increased blower use is desired. This may require increased maintenance and on-hand spares.

8. CONCLUSIONS

Marine shipping of goods has been referred to as the invisible industry (George, 2013) since the average world citizen is completely unaware that well over 80% of all goods are at some point transported using marine cargo/container vessels. The size of this sector is huge, and the heavy residual fuel oils used to fuel cargo vessels are significant contributors to global pollutant emissions, especially sulfates. This industry is no longer hidden and is now being regulated to improve public and environmental health through emission-reduction mandates. The most immediate and impactful regulation is the IMO 2020 sulfur cap, which reduces the upper limit of fuel sulfur from 3.5% to 0.5%. This reduction, when enacted, will dramatically lower sulfur and particulate emissions. A number of reputable studies by Corbett and others (Sofiev, 2018; Corbett, 2007; Winebrake, 2009) have estimated that premature mortality caused by ship-borne particulate emissions will be reduced by up to 34% (a significant improvement). The reduction in sulfate emissions also translates into a reduction of acid rain and its propensity to degrade infrastructures and the environment. The environment will also benefit from reduced particulate matter emissions, which means less contamination to marine ecosystems and deposits on polar ice.

The implementation of the IMO 2020 sulfur cap will not be seamless. Reducing the sulfur content in marine fuels alters the chemistry of the applicable blend streams from the refinery, making compatibility a concern. The likelihood of higher catalyst fines in compliant fuel blends will also increase. These changes are expected to impact the compatibility of marine fuels when mixing fuels cannot be avoided, thereby requiring ship operators to undertake special precautions and more stringent oversight of fuel properties prior to bunkering. These precautions include the following:

- Proper documentation of fuel compliance or the unavailability of compliant fuel.
- Rigorous testing for compatibility of fuel prior to bunkering.
- Adequate numbers of storage tanks to minimize potential incompatibilities associated with fuel mixing.
- Special attention to risks associated with higher catalyst fines.
- Ensuring that onboard fuel handling and storage systems function well with new fuel properties.
- More frequent monitoring and cleaning of fuel lines and filters.
- More attention to cylinder oil formulation choice and deposit formation monitoring.

Fuel switchover from heavy fuel oils to distillates, and back, is especially problematic. The wise operator will be the one who has properly identified and upgraded equipment and controls to ensure compliance and minimize the chance for loss of propulsion. It is important when switching fuels to maintain a temperature rate of change of 2°C/minute or less and to monitor pump operation.

The lowered heavy-sulfur level will also present challenges to engine operation, particularly lubrication. New CLO formulations and operational protocols are being developed specifically for lower combustion temperatures and sulfuric acid formation. Matching the proper BN of the CLO with the fuel sulfur content is critical to keeping deposit formation and buildup to a minimum. Proper selection of CLO will require that the ship operator is knowledgeable about the role of BN and other lubricant properties.

Ship owners and operators are responsible for ensuring that they are complying with the IMO 2020 sulfur regulation, which was enacted to benefit public health and the environment. VLSFOs will present operational challenges to ships designed to run on high-sulfur HFOs. A loss-of-power incident on a ship can be problematic to devastating. A prudent ship owner/operator is one who is fully informed of the potential operational impacts accompanying the IMO 2020 sulfur regulations and has made the necessary adjustments to minimize disruptions.

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