IMPLICATIONS OF FUEL OIL CHANGE-OVER
A PRACTICAL GUIDELINES

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Issue and revision

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Executive summary

The importance of the report subject is determined by current trends in maritime transport, especially in the scope of energy efficiency and emissions of ships. Very ambitious emission reduction targets, as defined by IMO and EU, now set new directions for design and operation of vessels. Extremely significant achievement is related to energy efficiency of ships, as it stimulates the emission reduction of all exhaust components; CO_2, NO_X, SO_X, PM and HC. The improvement of ship's efficiency concerns all propulsions i.e. main and auxiliary engines and boilers, which leads to a significant drop in ship total emission.

Current and prospective regulations regarding the marine environment protection are strongly focused on the reduction of SO_X and CO_2 emissions. In both cases, this is combined with the long-term development of ship propulsion systems, engines, and installations, mostly their construction and in lesser extent operation. The creation of SECA and the planned global reduction of SO_X emissions in 2020 brings a serious challenge on a enormous scale for the global maritime economy. The current technical solutions and the capabilities of the refining industry indicate the possibility of meeting the planned global and already existing regulations (local) to reduce SO_X emissions, using low-sulfur fuels.

Chapter 2 presents list of marine hydrocarbon fuels: residual, distilled ones supplemented with a new type - hybrids, which basically allow to meet fuel sulphur requirements. However, due to the various SO_X emission limits (globally and locally), the content of sulphur in fuel 0.5% (from 2020) and 0.1% (already in force in SECA) introduces the necessity of using different fuels on the ship, as discussed in the chapter 3.

Chapter 4 presents a systematic review of ship fuel installations and a number of changes have been proposed, that will significantly improve the operational measures, related to fuel change-over (Chapter 5). Several years of SECA limits and gathered experience with low-sulfur, distillate and hybrid fuels use, allow to formulate wide-ranging conclusions and introduce important changes in the current fuel operating rules.

The selected set of observations related to the performance of marine engines and operational problems due to various fuel aspects and applications are described in Chapters 6 and 7. Next, Chapter 8 is devoted entirely to a detailed description of procedures for all important operations related to fuel bunkering and fuel changes, when entering and leaving SECA. Due to the diversity of ship constructions, the problem selection was applied in order to create universal rules for dealing with different fuels.

Fuel grade properties significantly affect the performance of marine engines and their reliability. Therefore, modern engines require the analysis of many factors and parameters in order to eliminate failures. The basis for such operational analyses are laboratory tests of fuels and lubricating oils as well as periodic engine diagnostics. The appendix shows exemplary results of fuel and cylinder oil analyzes and diagnostic sheets for the main propulsion engine supplied with residual and hybrid fuel.

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Acronyms and abbreviations

BDN	Bunker Delivery Note
BN	Base Number
CR	Common Rail
CE	Chief Engineer
DNV	Det Norske Veritas
DFO	Diesel Fuel Oil (e.g. MDO/MGO – marine diesel/gas oil)
ECA	Emission Control Area
FGO	Fuel Gas Oil
HFO	Heavy Fuel Oil
GL	Germanische Lloyd
HSHFO	High Sulphur Heavy Fuel Oil
IMO	International Maritime Organization
ISO	International Organization for Standardization
LLA	Low Level Alarm
LSHFO	Low Sulphur Heavy Fuel Oil
MEPC	Marine Environment Protection Committee
NOP	Note Of Protest
PRS	Polish Register of Shipping
RFO	Residual Fuel Oil (e.g. HFO – heavy fuel oil)
SECA	Sulphur Oxide Emission Control Area
SFOC	Specific Fuel Oil Consumption
ULSFO	Ultra-low Sulphur Fuel Oil

1 Background

Rules on the emission of sulphur oxides into the atmosphere by seagoing vessels

The *International Convention for the Prevention of Pollution from Ships* was adopted on November 2nd,1973. In 1978, the Convention was amended by adding the 1978 Protocol adopted by the International Conference on Tanker Safety and Air Pollution Prevention. This convention was abbreviated to MARPOL 73/78 (PRS, 2014) and was to be in force after a period of 12 months following the adoption by a group of 15 countries with a share exceeding 50% of the tonnage of the world merchant fleet. The Convention entered into force on October 2nd, 1983 and replaced the existing International Convention for the Prevention of Pollution of the Sea by Oil, 1954 *(as amended in 1962 and 1969*). MARPOL 73/78 is the most important piece of legislation globally governing the pollution of the seas and ambient air from ships. Currently, MARPOL 73/78 contains 6 annexes, each of which regulates one specific type of pollution (PRS, 2007; Wiewióra, 2002) and these are:

1. Annex I - Regulations for the Prevention of Pollution by Oil;
2. Annex II - Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk;
3. Annex III - Prevention of Pollution by Harmful Substances Carried in Sea in Packaged Form;
4. Annex IV - Prevention of Pollution by Sewage from Ships;
5. Annex V - Prevention of Pollution by Garbage from Ships;
6. Annex VI - Prevention of Air Pollution from Ships.

Existing legislation on sulphur oxides emissions

The provisions for the prevention of atmospheric pollution from ships are contained in Annex VI of MARPOL 73/78. Annex VI was introduced by the Protocol of September 25th, 1997. Its creators referred to the principles of the so-called Rio Declaration, defining the balanced development as the foundation for the formation of ecological law (Duda, 2014; Koziński, 2015). The arrangements of the Protocol were implemented on 19.05.2005 (Koziński, 2015). The application of Annex VI in accordance with regulation 5, chapter 2 covers all ships of 400 gross tonnage and above, as well as any fixed and floating equipment or a drilling platform (PRS, 2014; Wiewióra, 2002). The scope of the regulations includes the following types of pollution:

1. ozone-depleting substances: as defined in paragraph 4 of Article 1 of the Montreal Protocol and included in Annexes A, B, C or E;
2. gases and vapours from tankers, chemical and product tankers;

3. toxic components of exhaust gas from incinerators using energy from the incineration of solid waste, oil and polyvinyl chloride;
4. toxic components of exhaust gas from marine diesel engines, the composition of which includes:
   - nitrogen oxides *(NO_x);*
   - sulphur oxides *(SO_x);*
   - carbon monoxide (*CO*);
   - particulate matter *(metal compounds, soot, heavy hydrocarbons*);
   - unburned hydrocarbons *(C_nH_m).*

The second chapter of Annex VI of MARPOL 73/78 presents the SO_X Emission Control Area defined as "the area where special mandatory measures for SO_X emissions from ships are required to prevent, reduce and control air pollution by SO_X and associated adverse impacts on land and marine areas" (PRS, 2007). Initially, the Sulphur Emission Control Areas (SECAs) included:

- the Baltic Sea area;
- any other sea area, including port areas, designated by the IMO in accordance with the criteria and procedures for the designation of SO_X emission control areas with regards to the prevention of air pollution from ships (PRS, 2007).

The requirements of Regulation 14 within the SECAs as of 01.07.2010 imposed the need to meet one of the conditions:

- combustion of fuel with sulphur content not exceeding 1.5%;
- the applications of an exhaust treatment system that has been approved by the administration for the main and auxiliary engines to reduce sulphur oxides emissions, limiting these emissions to 6.0 g SO_X/kWh or less *(total sulphur dioxide weighted emissions*);
- the application of other methods approved by the IMO, ensuring that SO_X emissions are reduced to 6.0 g SO_X/kWh or less.
- If ships use fuels other than the standard fuel to meet the requirements, the fuel system should be cleared of fuel with a sulphur content greater than 1.5% before the ship enters the SECA (Sulphur Emission Control Area). Any of such operation shall be evidenced by an entry in the logbook and in the machinery logbook, as prescribed by the Administration (Wiewióra, 2002; PRS, 2007; MEPC, 2008; MEPC, 2009).

Regulation 18 of Annex VI plays an important role in meeting the requirements to limit the sulphur content of marine fuel. It requires that fuel suppliers should comply with fuel quality requirements. The fuel oil supplier must highlight the sulphur content in the fuel delivery document, which is subject to inspection and must be kept on board with a representative sample of the fuel. This sample should be adequately secured and confirmed by the handwritten signatures of the supplier and the officer responsible for the fuel collection operation (Koziński, 2015; Wiewióra, 2002; PRS, 2014; MEPC, 2008).

The repeated updating of Annex VI of MARPOL 73/78 has led to the introduction of new sulphur limits for marine fuels and the establishment of new SO_X emission control areas. The new arrangements have changed the previous deadline; the Sulphur Oxide Emission Control Area (SECA) to the Emission Control Area (ECA). New emission control limits have also been set (shown in Figure 1.1):

- The Baltic Sea area;
- The North Sea area (Resolution MEPC.132(53) - effective since November 22nd, 2006;
- The North American area (Resolution MEPC.190(60) - effective from August 1st, 2011;
- The United States Caribbean Sea area (Resolution MEPC.202(62) - effective from January 1st, 2013;
- Any other sea area, including the port area, designated by the IMO.

Figure 1. 1: Existing emission control areas according to Annex VI of the Marpol 73/78 Convention

Source: www.egcsa.com

In the ECA areas designated by the IMO, ships should use fuels the sulphur content of which does not exceed the stated limits by weight:

1.50% before July 1st, 2010

1.00% from July 1st, 2010 and thereafter;

0.10% from January 1st, 2015 and thereafter.

In areas not covered by exhaust emission controls, the IMO has introduced values for the sulphur content of marine fuels with a clear downward trend:

4.50% before January 1st, 2012;

3.50% from January 1st, 2012 and after that date;

0.50% from January 1st, 2020 and thereafter.

An outline of the changes to the limits on the permissible sulphur content of fuel is presented in Table 1.1. However, it should be noted that the 0.5% sulphur limit for the year 2020 has been assessed by an expert group set up by the IMO. As a result of the evaluation, it was decided to maintain the target date for the introduction of this limit. On the other hand, an alternative solution in the case of a negative assessment was the postponement discussed.

Table 1. 1: Limits of sulphur content in fuel

<table>
<tr><th rowspan="2">Date</th><th colspan="2">Limit of sulphur content of fuel [%]</th></tr>
<tr><th>SO_X ECA</th><th>Globally</th></tr>
<tr><td>2000</td><td>1.5%</td><td rowspan="2">4.5%</td></tr>
<tr><td>07.2010</td><td rowspan="2">1.0%</td></tr>
<tr><td>2012</td><td rowspan="2">3.5%</td></tr>
<tr><td>2015</td><td rowspan="2">0.1%</td></tr>
<tr><td>2020</td><td>0.5%</td></tr>
</table>

Source: PRS, 2007; www.dieselnet.com/standards/inter/imo.php

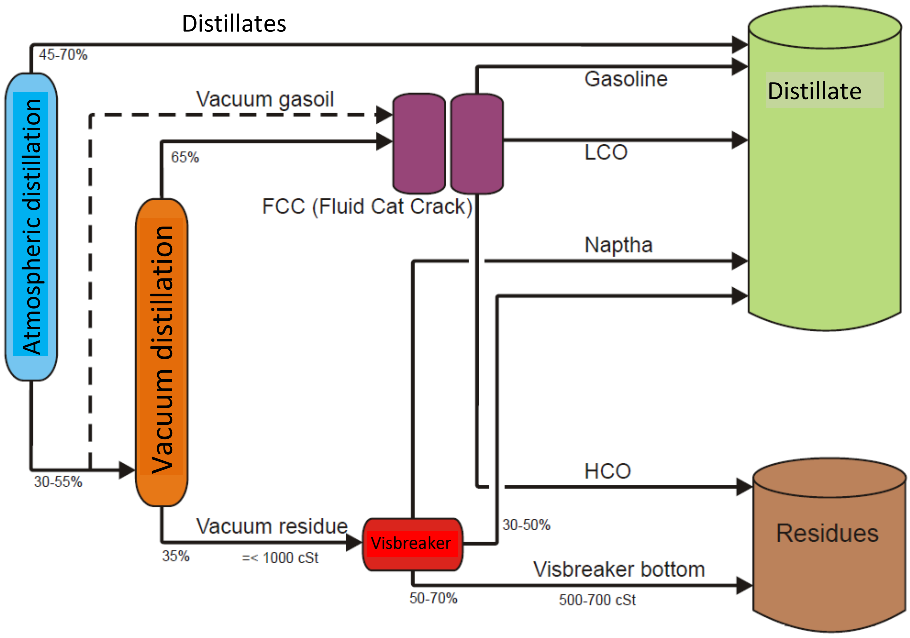
2 Contemporary marine fuels – characteristics

During the multi-stage distillation of crude oil, two groups of products are obtained in particular:

- distillation products of low viscosity, not exceeding several cSt at reference temperature of 15°C;
- residual products of high viscosity, which can even reach 700 cSt at reference temperature of 15°C.

Both groups of products, apart from a clear difference in viscosity, differ significantly in chemical composition and other parameters such as the density, the calorific value, the cetane number, and the flash point. Figure 2. 1 shows an example diagram of an oil distillation installation (DNV, 2014).

Figure 2. 1: The scheme of crude oil distillation installations



Source: DNV, 2014

2.1 Distillate fuels

Distillate fuels are distinguished among marine fuels by their low viscosity *(at 40°C)* and density *(at 15°C)*. In addition, these fuels have a very low or zero asphaltene content *(DMA type).* The list of ship distillate fuel parameters is presented in Table 2. 1. Example results of the analysis of a sample of ship distillate fuel taken under actual ship operating conditions are presented in the *Appendix 1*. In the past, distillate fuels were the primarily used in shipping for main and auxiliary engines supply. At present, mainly due to their high price, most merchant vessels use this type of fuel only as a back-up fuel at conditions which do not allow the use of residual fuels.

Table 2. 1: Requirements for distilled fuels according to standard IS08217/2017

Characteristic	Limit	Category ISO-F-				Test method reference
		DMX [4]	**DMA**	**DMZ**	**DFB**	
Appearance		Visual		-	-	
Density at 15°C, kg/m^3	max.	[1]	890.0	890.0	900.0	ISO 3675 or ISO 12185
Viscosity at 40°C. mm^2/s [2]	min. max.	1.40 5.50	2.00 6.00	3.00 6.00	2.00 11.0	ISO 3104 ISO 3104
Flash point, °C	min.	43	60	60	60	ISO 2719
Pour point (Winter), °C [3] Pour point (Summer), °C [3]	max. max.	- -	-6 0	-6 0	- 6	ISO 3016 ISO 3016
Cloud point (Winter)°C Cloud point (Summer)°C	max.	-16[4] -16	- -	- -	- -	ISO 3015
Sulphur, % (m/m)	max.	1.0	1.0	1.0	1.5	ISO 8754
Cetane number	min.	45	40	40	35	ISO 5165
Carbon residue, %, (m/m) (v/v)	max. max.	0.30 -	0.30 -	0.30 0.30	- -	ISO 10370 ISO 10370
Ash, % (m/m)	max.	0.01	0.01	0.01	0.01	ISO 6245
Sediment, % (m/m)	max.	-	-	0.07	-	ISO 3735
Total existent sediment, %	max.	-	-	-	0.10	ISO 10307-1
Water, % (v/v)	max.	-	-	0.3	0.3	ISO 3733
Vanadium, mg/kg	max.	-	-	-	100	ISO 14597
Aluminum plus Silicon,	max.	-	-	-	25	ISO10478

1) In some geographical areas, there may be a maximum limit.

2) 1 mm^2/s = 1 cSt.

3) Purchasers should ensure that this pour point is suitable for the equipment on board, especially if the vessel operates in both the northern and southern hemispheres.

4) This fuel is suitable for use without heating at ambient temperatures down to - 15 °C.

Such condition includes but are not restricted to lack of thermal energy (steam or thermal oil) required for residual fuels usage. Typical operations and incidents in the operation of a ship engine room when distillate fuels are used (partially or fully) are as follows:

- flushing all engine room fuel systems before the ship enters the dry dock;
- flushing the auxiliary or the main engine fuel system before carrying out repairs to their fuel system components (this operation may be required by the engine manufacturer);
- malfunction of heating system;
- malfunction of residual fuel oil supply or treatment system;
- operation of a ship in an area where the use of other types of fuel is not permitted (SECAs).

2.2 Residual fuels

The most frequently used fuels in the shipping for the main and the auxiliary engines are residual fuels, mainly because of their lowest price when compared to other marine fuels. Their main features are high viscosity *(at 45°C*) and density *(at 15°C*). Additionally, these fuels are characterized by high sulphur content *(max. 3.5%),* which limits their use in SECAs. The list of ship residual fuel parameters is presented in Table 2.2. Example results of the analysis of a sample of ship residual fuel taken under actual ship operating conditions are presented in the *Appendix 2*.

Due to their high viscosity, these fuels can only be used to supply engines and boilers if a source of thermal energy is available to properly prepare this type of fuel for injection into the combustion chambers of the engines. For this reason, fuel installations based on the use of this type of fuel need to be extended by additional equipment for heating up the fuel and the continuous control of its parameters, particularly temperature and viscosity. At the same time, it is necessary to heat up *(to 40÷45°C*) storage tanks and pipelines to allow fuel transfer operations. Additional elements that will require heating in the ship engine room will be: settling tanks *(70÷80°C*) and fuel service-tanks *(90÷95°C*), fuel filters and entire fuel transfer pipelines.

Table 2. 2: Requirements for residual fuels according to standard - IS08217:2017

Characteristic	Limit	Category ISO-F-														
		RMA 10	**RMB 10**	**RMC 10**	**RMD 15**	**RME 25**	**RMF 25**	**RMG 35**	**RMH 35**	**RMK 35**	**RMH 45**	**RMK 45**	**RML 45**	**RMH 55**	**RMK 55**	**RML 55**
Density at 15°C. kg/m^3	max.	920	960		975	991		991		1010	991	1010	-	991	1010	-
Kinematic viscosity at 100 °C, mm^2/s	max.		10.0		15.0	25.0			35.0			45.0			55.0	
Flash point, °C	min.		60		60	60			60			60			60	
For point (upper), °C																
winter quality	max.		24		30	30			30			30			30	
summer quality	max.		24		30	30			30			30			30	
Carbon residue. % (m/m)	max.	10		14	14	15	20	18	22		22	-		22	—	
Ash. % (m/m)	max.		0.10		0.10	0.10	0.15	0.15	0.20			0.20			0.20	
Water, % (v/v)	max.		0.5		0.8	1.0			1.0			1.0			1.0	
Sulphur, % (m/m)	max.	To comply with statutory requirements as defined by purchaser														
Vanadium, mg/kg	max.	150		300	350	200	500	300	600			600			600	
Aluminum plus silicon, mg/kg	max.		80		80	80			80			80			80	
Total sediment, potential, % (m/m)	max.		0.10		0.10	0.10			0.10			0.10			0.10	

Annex C gives a brief viscosity/temperature table, for information purposes only. 1 mm^2/s = 1 cSt

2.3 Hybrid fuels

Hybrid fuels are produced as a mixture of residual and distillate fuels to meet the maximum sulphur content of 0.1% required in the SECA. At present, there are many marine fuels of this grade available on the market, the specifications of which are presented in Table 2.3. Main, but not the only, manufacturers are:

- BP (*product – 0.1RMD*);
- LUKOIL (*product - EMF*);
- SHELL (product - ULSFO 0.1);
- Exxon Mobil (*product - HDME 50*);
- CEPSA (*product - DMB 0.1*);
- SK Energy (*product - 0.1ULSFO*);
- Chemoil (*product – 0.1%S FO*).

Table 2. 3: Specifications of selected hybrid fuels

Characteristics	Unit	Limit	HDME 50 EXXON-MOBIL	Fuel Oil Chemoil	DMB Chemoil	Fuel Oil Chemoil 2	ULSFO Shell	SK ULSFO BP 0.1 SK Energy	RMD B	ECO Marine Fuel Lukoil
Kinematic viscosity at 50 °C	mm2/s	min. max.	25 to 45	16.84	10.5	26.3	10-60	30~40	6-13	65
Density at 15 °C	kg/m3	max.	895 - 915	0.8589	0.885	0.896	790-910	0.928	850-890	0.91
Cetane index	—	min.			40					
CCAI	—		795 - 810			795	800	790~800	760-820	860
Sulphur	mass %	max.	0.1	0.084	0.085	<0.1	<0.1	<0.1	0.10	0.095
Flash point	°C	min.	70	>60	70	>60	>60	70	60	60
Hydrogen sulphide	mg/kg	max.	1		0.1		<2		2	2
Acid number	mg KOH/g	max.	0.1		0.1	2.35	<0.5		2.5	2.5
Total sediment ex-istent	mass %	max.	0.01 0.01 0.050	0.01	0.05		0.01-0.05	0.02		
Total sediment aged	mass %	max.	0.01	0.01		0.01	0.01-0.05	0.02	0.07	0.1
Oxidation stability	g/m3	max.	0.01							
Carbon residue: mi-cro method	mass %	max.	0.3	<0.10	0.1	3.8	2	6	4	14
Cloud point	°C	max.			—					
Pour point (upper) W	°C	max.	9 - 15	-20	-4	-6	18	20~25	+27	20
Pour point (lower) S	°C	max.	9 to 15							
Appearance	—	—	brown/green-opaque	Not clear and bright	Not clear and bright	Not clear and bright		Black	—	
Water	vol %	max.	0.05			0.05	0.05	0.02	0.03	0.01
Ash	mass %	max.	0.01	0.003	0.005	0.06	0.01	0.05	0.04	0.07
Lubricity at 60 °C	µm	max.	320			310				
Vanadium	mg/kg	max.	1			<1	2	0.7	50	2
Sodium	mg/kg	max.	1	4		1	10	2	50	2
Al & Si	mg/kg	max.	3	<3		<10	12-20	10~20	25	17
Calcium	mg/kg	max.	1	13		175	free of ULO			free of ULO
Phosphorus				7		<1	free of ULO			free of ULO
Zinc	mg/kg	max.	1	2		<1	free of ULO	1		free of ULO

Although hybrid fuels are produced to meet the 0.1% sulphur limit, they do not always meet the requirements of ISO 8217. However, their share in the marine fuel market is expected to increase as an alternative to typical distillate fuels. Still, when ordering a hybrid fuel from a supplier, one should check if there are any deviations from ISO 8217.

Currently, much of the information on operational properties of hybrid fuels in marine engines is published by the manufacturers of these fuels themselves. Despite this, many shipowners and shipping companies have decided to test hybrid fuels under real ship operating conditions. However, before deciding to use hybrid fuels in a given engine room, it is the responsibility of the vessel operator to check:

1. manufacturer's statements *(related to the main engines, the auxiliary engines and the boilers*) on the readiness of equipment for safe operation using hybrid fuels;
2. information from engine lubricating oil producers on the readiness for use with hybrid fuels;
3. information from manufacturers of centrifuges and filters *(fuel treatment system components*) on the readiness for use in hybrid fuel systems;
4. information for manufacturers of oil separators *(components of bilge water treatment systems*) about readiness to purify water contaminated with waste of hybrid fuel.

In addition, it should be noted that compliance with the condition imposed by Annex VI of the MARPOL Convention defining the maximum sulphur content in fuel at the level of 0.1% in ECAs may be insufficient. For example, in the U.S., one of the California Air Resources Board regulations also requires that low sulphur fuels should meet the specifications for typical distillate fuels. For this reason, ship operators operating in California waters using hybrid fuels must be authorised to do so (Lloyd’s Register, 2014).

3 Rules for the use of marine fuels in the areas of controlled sulphur oxide emissions

3.1 General rules on fuel type change-over in SECAs

In connection with the introduction of controlled sulphur oxide emission areas, ship crew are obliged to prepare the fuel systems of the ship engine room in an appropriate manner. The primary task is to ensure the combustion of low sulphur fuels *(if the ship is not equipped with adequate exhaust gas cleaning system*) already before the ship enters such an area. Operations related to the change of the type of burned fuel must be documented by means of entries in the engine logbook and appropriate record books. The following information required for fuel change-over operation should be recorded:

- date and time of procedure commencement – when leaving SECA;
- the geographical position of the vessel at the time of commencement – when leaving SECA;
- quantity of low sulphur fuel *(distillate or hybrid one*), specifying the individual tanks at the commencement – when leaving SECA;
- date and time of completion commencement – when entering SECA;
- the geographical position of the vessel at the time of completion – when entering SECA;
- quantity of low sulphur fuel *(distillate or hybrid one*), specifying the individual tanks at the completion – when entering SECA.

In addition, a document confirming the low sulphur content of fuel burned in a SECA should be available on board. This document is a *Bunker Delivery Note* (BDN), which should be kept on board for three years from the date of fuel delivery. Checking all the above-mentioned entries and documents is often the reason for inspections in ports located in SECAs. Port inspection are also entitled to collect a representative sample of the fuel in-use for further analysis. This means that the crew of the vessel is obliged to collect a sample from the fuel supply system of the running engine or boiler in the presence of administration representative. On several occasions, inspectors of these services control the temperature of fuel system pipelines *(in different places*) with the view to detect possible connections of systems that allow the combustion of prohibited fuel.

As an extension of SECAs, there are areas in which local authority ordinances require a change-over from high sulphur fuel to fuel with a sulphur content not exceeding 0.1% or 0.5% *(depending on the port*) within one hour of the mooring of the ship or with the first mooring rope *(depending on the local regulations*). This means that the main engine fuelling system does not require a change in the type of used fuel *(if only a stay in port is planned*). Currently, such areas are found in many Asian and European ports *(Hong Kong, Zhejiang, Ningbo, Shenzen, Algeciras*). However, the requirements for relevant entries and documents proving fuel changing operations are the same as for other areas of controlled sulphur oxide emissions.

The operation of the return to the use of fuels with high sulphur content in the engine room also requires appropriate entries in the ship log books. In this case, however, once the ship has left the SECA, a set of relevant information is required from the moment when the change of the type of burned fuel commences. In additional areas designated by local authorities where the use of low sulphur fuels is required *(some ports in Asia and Europe*), it is allowed to start use high-sulphur fuels one hour before leaving the port or dropping the last mooring line *(depending on local regulations*).

3.2 Recommended procedures for high and low sulphur fuels operation

The appropriate preparation of marine engine room fuel systems for the combustion of low sulphur fuels shall mean the removal from all parts of the fuel system of fuel with a higher sulphur content than is permitted in the concerned area. Depending on the type of fuel pre-treatment and purification systems and supply, the operation may take several to several dozen hours *(especially when using hybrid fuels)*. In the case of the simplest systems with one settling and fuel service-tank, the change-over from residual to hybrid fuel will require flushing of the entire fuel installation.

The duration of this process will depend mainly on the load level of the main engine and the auxiliary engines and on the construction of the fuel system itself *(the capacity of the settling and day-tank as well as mixing tanks, fuel heaters, filters, pipelines*). In this case, additional spreadsheets shall be prepared by the shipowner's or operator's organisational units, which shall enable the determination of the time required for flushing the system with low sulphur fuel content when data on engine load levels, sulphur content of mixed fuels and volumes of individual components of the ship fuel system are entered. There is also commercial, specialized software to perform such functions *(for example, BunkerMaster - DNV-GL, BunkerCalc – Shell, Fobas – Lloyd Register*).

In case of a change-over from residual high sulphur fuel to distillate fuel, this process will be shorter due to the use of a separate pre-treatment and purification facility for the distillate fuel. In practice, this operation requires the ship engine room crew to change the position of the appropriate valves so that all relevant equipment may be supplied with distillate fuel. It is also important to ensure that pre-treatment and purification systems are adequately prepared to prevent unwanted mixing of different fuel types.

The time required for the operation of changing-over from residual high-sulphur fuel to distillate fuel in case of the main engine will primarily depend on its load and the design of the fuel supply system *(the capacity of the mixing tank, fuel heaters, filters, and pipelines*). Designated fuel calculators easy the determination, of the time required to flush the fuel system adequately to meet requirements for entering SECA. It is also important to comply with the recommendations of the engine manufacturers, which clearly state conditions of the fuel change-over procedure. For example, engine maker - Wärtsilä requires for marine two-stroke engines that the temperature drop of fuel at the inlet to the engine does not exceed 15°C/min. Especially in the case of smaller vessels, this may mean that the process is longer than resulting from the very design of the fuel system.

In the case of auxiliary engines *(mid-power ones*), the operation of fuel change-over may be further simplified by the possibility of using an additional fuel feed pump. In this case, the supply system operates in single-stage mode *(single-pressure mode without the use of circulation pumps)*. The practical change of fuel supply type consists in appropriate override of the required valves, taking into account the time required for flushing the system pipelines. It should be remembered at this point that it is possible to implement the procedure of changing the type of fuel supply in case of using a selective fuel supply system in a given ship engine room. In the case of this type of system, the entire auxiliary engine power supply system with residual fuel may remain in operation without any crew action.

Only for selected auxiliary engines, changing the settings of the relevant valves allows for a very quick change of the type of fuel supplied to the engine. Despite this simplification, it is once again important to bear in mind the recommendations of engine manufacturers concerning procedures for changing the fuel supply type. For conventional mid-power engines, it is generally recommended to change the fuel contained in the inlet and return fuel pipelines when the engine is at a standstill *(which lasts from a few to several minutes*). The flushing of fuel remaining in injection pumps, high pressure pipes and injectors takes place after the engine start and is very fast. In the case of electronically controlled engines with high-pressure common rail *(CR*), it is recommended to change the fuel supply from residual fuel to distillate fuel during engine operation *(under the load specified by the manufacturer).* This is due to a different specification of the fuel injection control components for the combustion chambers of CR engines.

Regardless of the design of the fuel supply system, there is a risk of increasing the temperature of distillate fuel in the system itself. Therefore, it is extremely important to stop the heating system of fuel pipelines before starting the procedure of changing the type of burnt fuel from the residual to distillate one. As distillate fuels have a significantly lower viscosity, the fuel supply systems are equipped with additional coolers, which can be put into operation if necessary. That significantly reduces the risk of fuel injection components seizing due to decreased lubricating properties of the hot distillate fuel.

4 Ship fuel oil systems

The ship fuel system *(for distillate, residual and hybrid fuels*) consists of several basic sub-systems, including:

- fuel bunkering and storage system;
- fuel pre-treatment and purification system;
- fuel supply system for auxiliary engines;
- fuel supply system for boilers;
- fuel supply system for the main engines.

4.1 Fuel oil bunkering and storage systems

The procedure of vessel fueling from shore installations or from designated vessel is called bunkering. The basic information about the fuel and its supplier required to start the bunkering process is contained in the *BDN*. This information includes:

1. the name and IMO number of the bunker ship or the name of pier;
2. The place and date of commencement and completion of fuel bunkering;
3. The name and details of the fuel supplier;
4. the name and basic data of the supplied fuel, including:
   - bunkered fuel grade according to ISO-8217;
   - quantity*(MT*);
   - density (*kg/m³ @ 15°C*);
   - kinematic viscosity (*cSt @ 40°C / 50°C*);
   - sulphur content (*% $^{m}/_{m}$*);
   - water content (*% $^{m}/_{m}$*);

All parameters shall be within the permissible ranges for the fuel input type as specified in ISO-8217. IMO regulation states that sulphur content is expressed by value with two decimal places and any additional terms such as; “less than”, “max”, “not as much” are not allowed. Any violations are the grounds for the ship crew responsible for the bunkering process *(Chief Engineer Officer and the Master*) to refuse to accept the delivered fuel. The only parameter presented above that can be verified just after the bunkering process is the amount of received fuel. The measurement of the quantity of fuel in the respective tanks on the supplier's vessel and on the supplied vessel shall be carried out jointly by the representatives of both parties. In addition, an independent inspector can be employed to supervise all fuel bunkering operations.

Any difference resulting from the quantity of fuel delivered and ordered is the basis for issuing a NOP *(it should be signed by the representatives of all involved parties*). Further legal processes resulting from the supplier's failure to deliver fuel quantities are the responsibility of the supplier's and customer's representatives on land.

During the bunkering process, four fuel samples shall be taken on board of the receiving vessel for the following purposes:

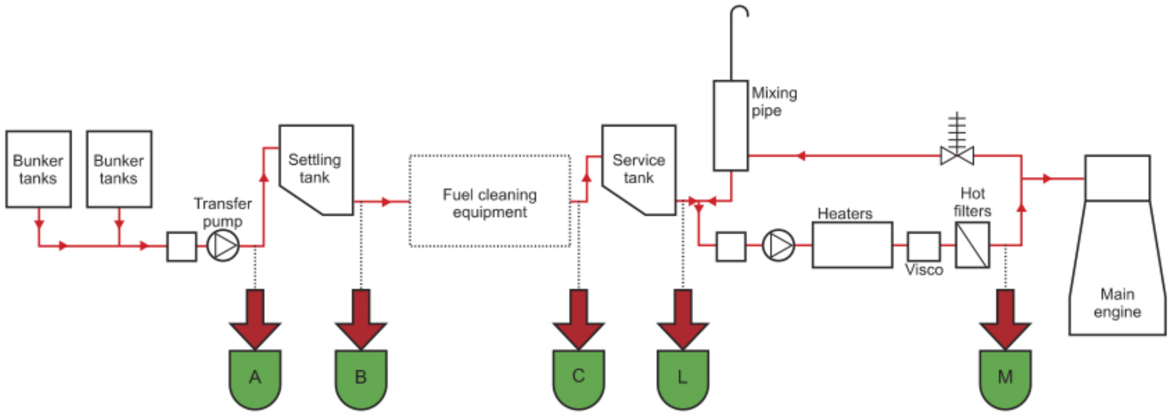
1. a sample sent to the laboratory for analysis;
2. a sample handed over to the fuel supplier;
3. a sample to be kept on board for reference;
4. a sample to be kept on board, marked as MARPOL.

Supplier’s representative should be invited to witness the sampling procedure. If such invitation is declined, it must be noted in the ship’s log book. All above samples should be collected into containers, marked with the date and place of bunkering, grade and quantity of fuel, signed by suppliers and recipient representative and if possible by bunker surveyor. Containers should be sealed with numbered seals, and the seal number should be copied on the container label. It is recommended that samples are taken continuously to a common, secured container during the entire bunkering process. In addition, the fuel supplier should take fuel samples during fuel transfer *(supplier's transfer line*), two of which are handed over to the recipient. Both of these samples should be kept on board of the tanker *(one of which must be marked as MARPOL*). The MARPOL sample should be kept on board at least until the fuel is fully consumed, but not less than 12 months from the time of its collection. An inventory of bunker samples with the seal number, date of bunkering and date of disposal should be provided on board.

In case of operating problems in the ship engine room related to the quality of the previously taken fuel, companies involved in fuel analysis *(DNV-GL, VISWA*) recommend taking additional samples from various points of the ship fuel system. Based on the samples taken, it will be possible to exclude the incorrect operation of fuel system components as a cause of operating problems and prevent possible further legal actions that may be taken by the fuel recipient.

The figure 4. 1 presents fuel sampling points proposed by DNV-GL from the main engine supply system. It should be remembered that in the case of fuel tanks, no samples should be taken from their drainage lines, as they may be contaminated *(the samples will not be representative*).

Figure 4. 1: Recommended fuel sampling locations



where: A- outlet of the fuel transfer pump, B- outlet of the fuel settling tank, C- outlet of the fuel pre-treatment system *(the number of samples depends on the design of the system*), L- outlet of the fuel day-tank, M- outlet of the fuel supply system.

Source: DNV, 2014

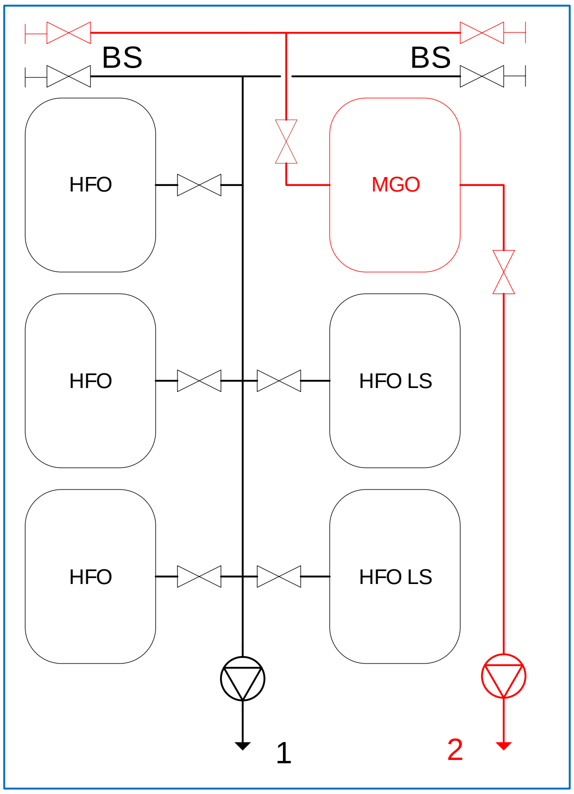
Typically, distillate and residual fuels, are stored in designed tanks. This applies to storage, settling and fuel service-tanks. Transfer and purification systems for different grades of fuel are also separated. Exceptions from this rule are possible, in the event of failure of some fuel system equipment fuel system should enable:

1. the possibility of replacing the residual fuel transfer pump with the distillate fuel transfer pump by an appropriate operation of shut-off valves and removal of pipe blanking flanges;
2. the possibility to operate one of the residual fuel centrifuges as a distillate fuel centrifuge by an appropriate operation of shut-off valves and removal of pipe blanking flanges;

The latter condition may occur during standard operation, which is not necessarily associated with a failure of components of the distillate fuel purification system. This may occur if the ship operates for a long period of time in SECA and all engines and boilers have to be supplied with low sulphur fuel. As a standard the distillate fuel centrifuges have lower capacity than the residual fuel centrifuges. For this reason, it may be necessary to replace it with a centrifuge with higher capacity at high fuel consumption condition. Parallel operation of these devices is also possible.

In addition to the need to ensure appropriate sulphur content *(which forces storage in dedicated tanks*), it is also important that hybrid fuels have the tendency of washing out the impurities accumulated in the tanks (DNV-GL, 2015), which were previously used to store residual fuel. This may cause serious disturbances in the operation of fuel purification systems *(centrifuges, heaters, filters*) during the ship operation. These may be impurities that have precipitated from the stored fuel during operation, which accumulate at the bottom and on the surface of horizontal structural elements of the tanks, which strengthen the ship structure. It is also important to consider mixing previously stored fuels which remain at the bottom of the tanks and cannot be pumped out during standard ship operation. Again, upon contact with hybrid fuel, this can cause a significant amount of asphalt to precipitate, resulting in serious disruptions to fuel purification systems or, in extreme cases, to engines themselves. For this reason, separate dedicated tanks are used for the storage of different grades of fuel. In order to simplify the ship structure, a common transfer manifold is often used for residual fuels – heavy fuel oil (HFO) *(low and high sulphur and hybrid* ones*)*. An example of a typical fuel bunkering and storage installation is shown in the figure 4. 2.

Figure 4. 2: Fuel bunkering system with a common manifold for the bunkering and transfer of residual fuel

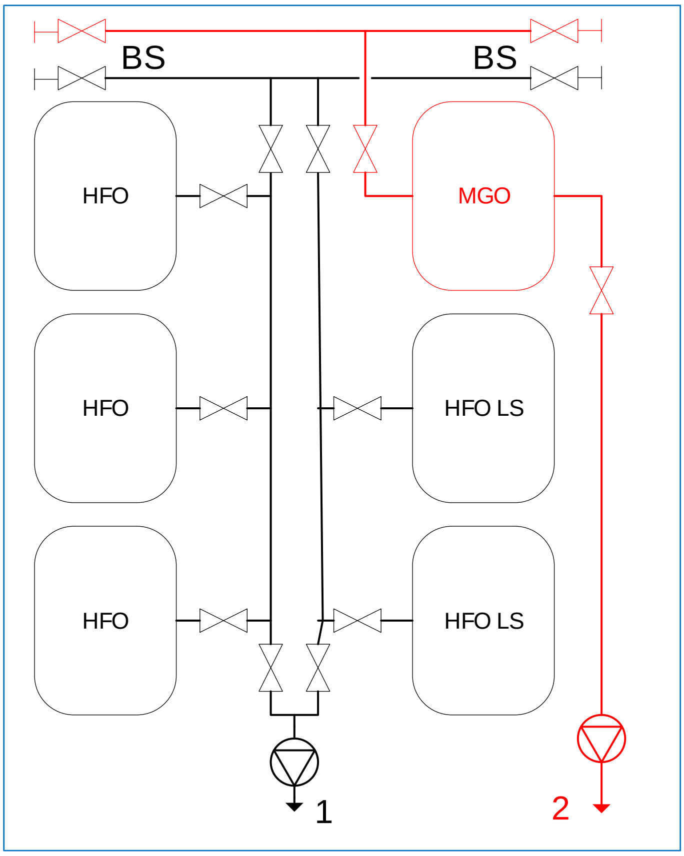


where:

BS- bunker station, HFO – heavy fuel oil - residual fuel with high sulphur content, HFO LS - residual fuel with low sulphur content *(e.g. hybrid one*), MGO - distillate fuel, 1- residual fuel transfer pump, 2- distillate fuel transfer pump.

Due to the propensity of hybrid fuels to wash out contaminants accumulated in tanks previously used to store other types of fuels, but also their mixing with the fuel stored in the transfer manifold may cause disturbances in the engine room of fuel systems; it is recommended to use an additional line enabling separate transfer of this type of fuel. This complicates the fuel installation and increases the cost of building a fuel bunkering and transfer system, but at the same time it increases the reliability of the ship operation. An example diagram of fuel bunkering and storage installations with a separate transfer manifold is shown in the figure 4.3, where the description of system components as in Fig. 4.2.

Figure 4. 3: A system with separate manifold for the bunkering and transfer of residual fuel



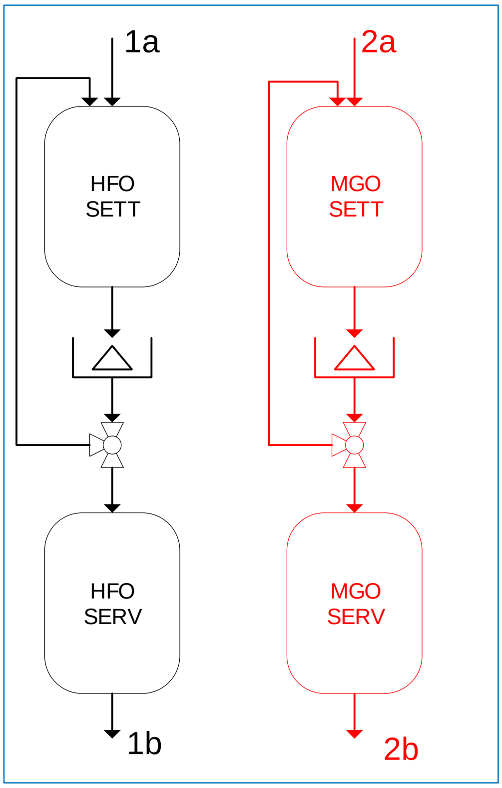
4.2 Fuel pre-treatment and purification systems

One of the fuel systems task is purification of the fuel before it may be safely supplied to consumers. The main components of fuel preparation and purification systems are:

1. settling tanks (tank);
2. fuel centrifuges;
3. fuel service tanks (tank).

In principle, purification systems are separated for residual and distillate fuels *(apart from the possible sharing of fuel centrifuges*). An example diagram of fuel preparation and purification system is shown in the figure 4. 4.

Figure 4. 4: A system with one settling tank for residual fuel



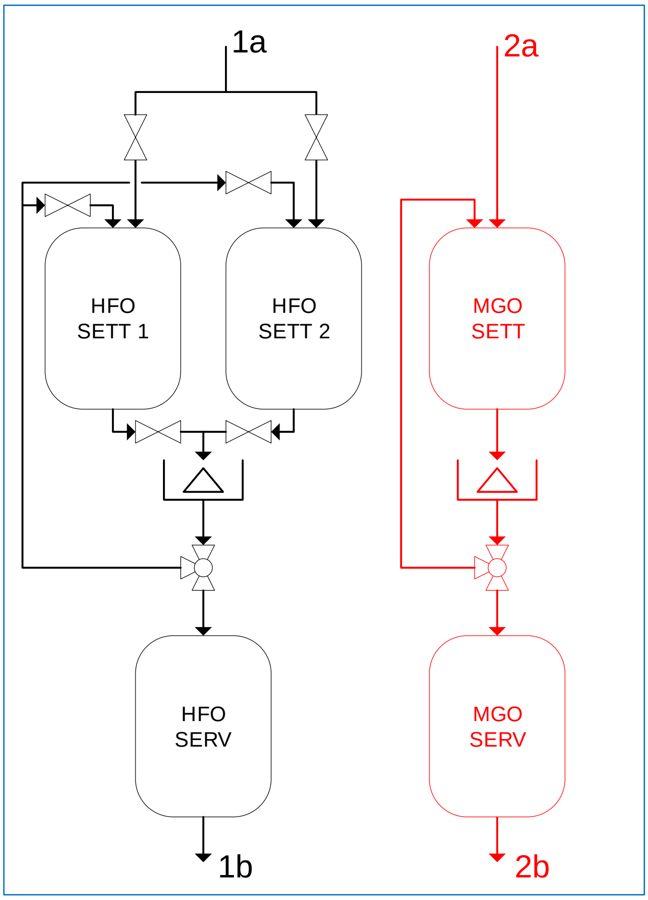
where:

HFO SETT - residual fuel settling tank, HFO SERV - residual fuel service tank, MGO SETT - distillate fuel settling tank, MGO SERV distillate fuel day-tank, 1a - residual fuel transfer pump inlet, 2a - distillate fuel transfer pump inlet, 1b - residual fuel supply system outlet, 2b - distillate fuel supply system outlet.

The main disadvantage of the system shown in Fig. 4. 4 is the need to replenish only one residual fuel settling tank with fuel *(from the fuel storage system*) during the operation of the ship engine room. This means the need to supply the fuel that has not undergone an appropriate sedimentation process after mixing with the fuel contained in the tank directly into fuel centrifuges. Another major disadvantage of this system is the need to mix residual fuels, for example in the case of a fuel type change before a ship enters the SECA. This will mean a significant extension of the time required to purge the fuel system from fuel with excessively high a sulphur content for such an area *(Chapter 3*).

Another major disadvantage of such a pre-treatment and purification system is the possibility of washing out residual impurities *(e.g. by hybrid fuels)* or the precipitation of some of its components, especially paraffins from mixed fuels that are not compatible. For this reason, in spite of higher construction costs and the complexity of the system, extensive systems for pre-treatment and purification of residual fuel are much more frequently used on ships. Their composition includes an additional settling tank, the correct use of which allows for the proper sedimentation of fuel. However, the main advantage of such a system is the possibility to use an additional settling tank to be filled up with residual fuel *(after previous emptying)*, without the need to mix it with other types of residual fuel.

Figure 4. 5: A system with two settling tanks for residual fuel

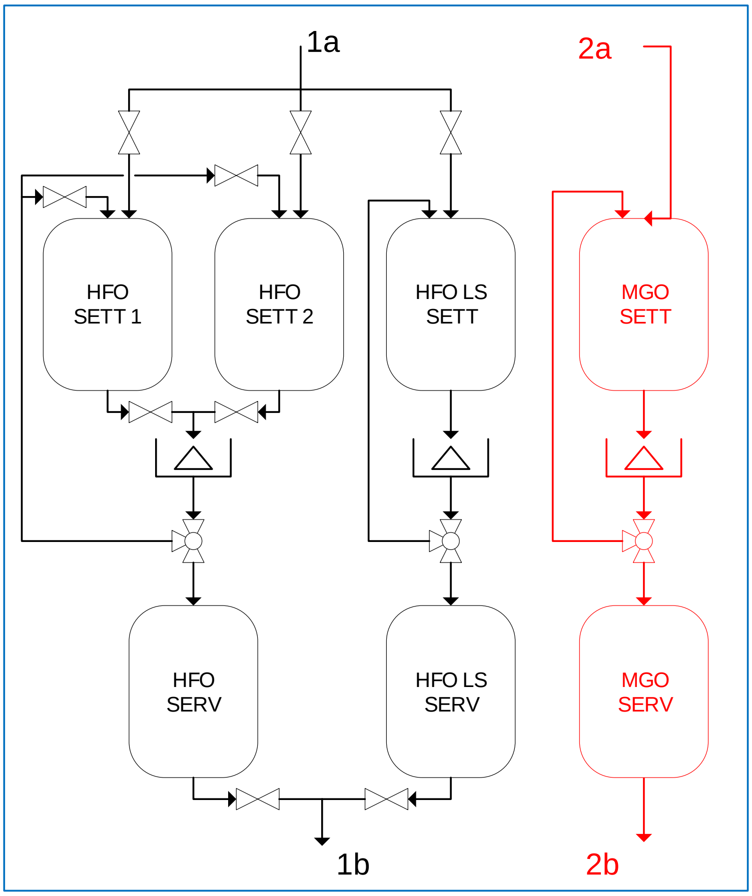


where: HFO SETT 1- settling tank no. 1 of residual fuel, HFO SETT 2 settling tank no. 2 of residual fuel *(other designations of system components as shown in Fig. 4. 4)*

Despite the improvement of the system functionality shown in Fig. 4. 5, it is still necessary to mix the residual fuels transferred from the tanks in a fuel service tank, which cannot be emptied during standard operation of the ship engine room. An additional disadvantage of such a system is the need to share fuel centrifuges and appropriate pipelines with residual fuels of different types or hybrid fuel, which may be located in separate settling tanks.

In order to improve the safe and trouble-free operation of the ship, more complex fuel pre-treatment and purification systems have been put into operation, in which lines for different types of residual fuels *(standard, low sulphur or hybrid ones)* have been completely separated. The main feature of these systems is the introduction of an additional fuel service tank, fuel centrifuges and appropriate pipelines to prevent the mixing of different fuel types during the entire process of fuel preparation and purification. An example of such a complex installation diagram is shown in the figure 4. 6.

Figure 4. 6: A system with separate installation for treatment and purification of low sulphur residual or hybrid fuel

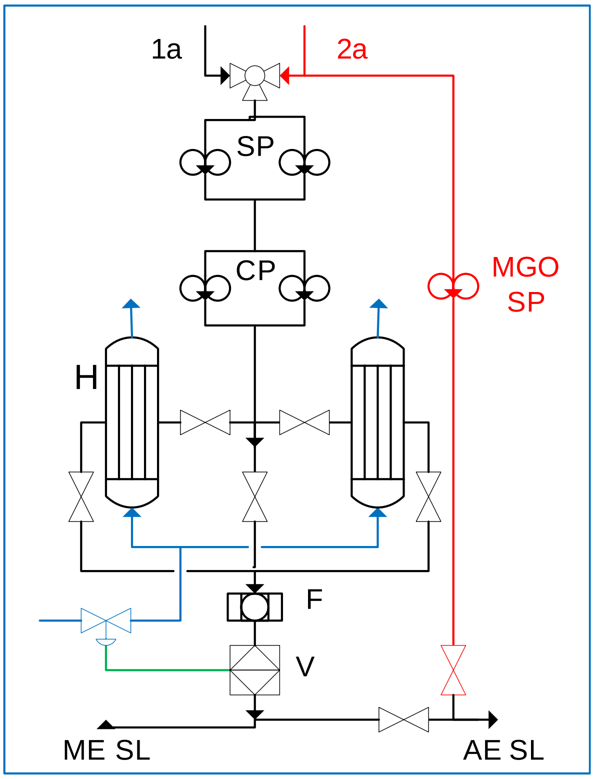


where: HFO LS SETT - low sulphur residual fuel settling tank, HFO LS SERV - low sulphur residual fuel service-tank *(other elements of the system as shown in Figure 4. 4*)

4.3 Fuel supply system

The task of the fuel supply system is its final, very accurate filtration and, above all, maintaining the viscosity of the fuel *(currently controlled by the viscometer*) at the level specified by the manufacturer of the supplied engine. In the case of residual fuels, this value is in the range of 12÷15 cSt (depending on the type of engine), which means that it must be heated *(in fuel heaters*) to 120÷150 °C *(depending on the fuel grade*). Due to such high fuel temperature, it will be necessary to increase fuel pressure in the engine supply system to reduce the risk of certain fuel fractions evaporation. Additional circulation pumps installed in the system perform this task. In the case of distillate fuels with lower viscosity than that of residual fuels, there is no need to heat them up. It is therefore not necessary to install additional circulation pumps in distillate fuel supply systems. An example of a fuel system that enables the supply of the main engine and the auxiliary engines is shown in the following figure (Fig. 4. 7).

Figure 4. 7: Combined fuel supply system for the main and the auxiliary engine



where:

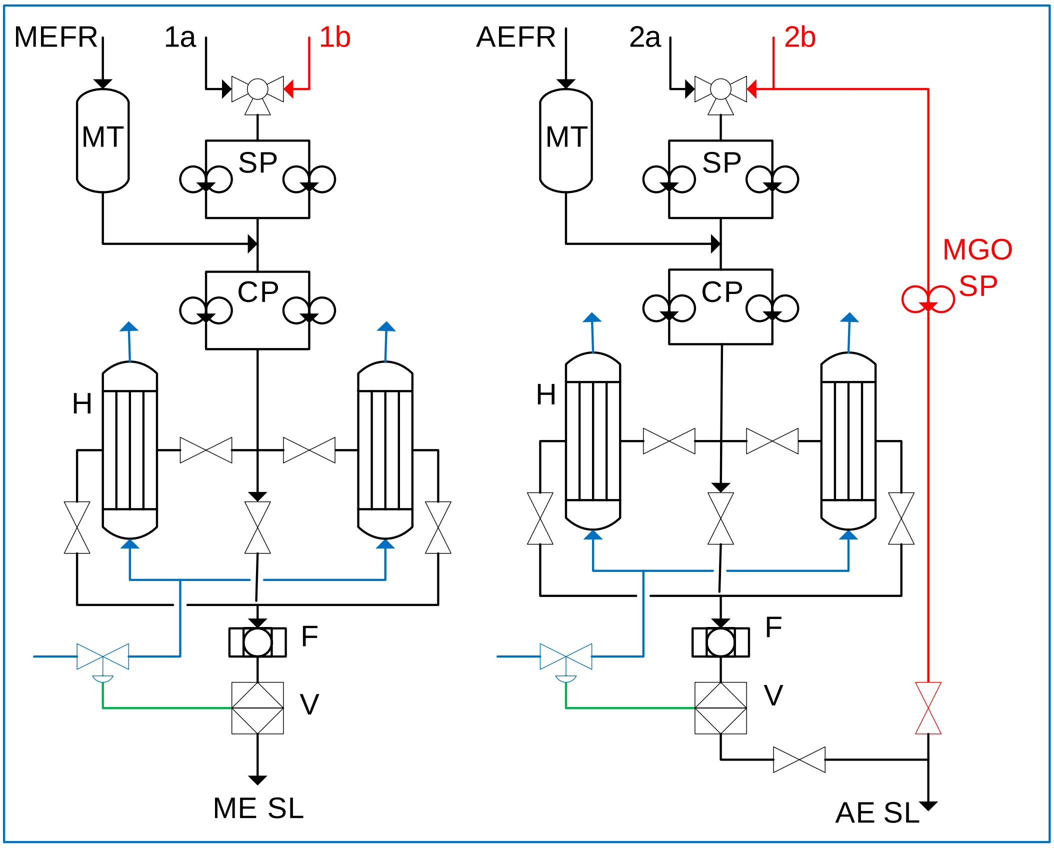
SP- pumps supplying residual fuel *(possibly distillate fuel*), CP- circulating pumps for residual fuel *(possibly distillate fuel*), MGO SP- pump supplying distillate fuel for auxiliary engines, H- heaters for residual fuel, F- filters, V- viscometer, 1a- inlet from the service-tank for residual fuel, 2a- inlet from the service tank for distillate fuel, ME SL - fuel supply line for the main engine, AE SL - fuel supply line for the auxiliary engines.

This is the simplest version of the fuel supply system, as the main engine and the auxiliary engines are powered by a common set of devices included in its composition. This system enables all engines to be supplied with residual or distillate fuel by means of a three-way inlet valve to the supply pumps. Apart from the obvious simplicity and low cost of construction, this type of system has many drawbacks, which primarily include:

- the need to supply all engines with residual fuel of the same viscosity;
- directing excess fuel supplying the engines to the fuel service tank;

In the case of a change from residual to distillate fuel for the main engine, the auxiliary engines must also be fuelled with the distillate fuel. The separate fuel supply system for the main engine and auxiliary engines shown in Fig. 4. 8 is free of the above disadvantage.

Figure 4. 8: Separate fuel supply system for the main and the auxiliary engine



where: MEFR- excess residual fuel return *(or distillate* fuel return) from the main engine, AEFR- excess residual fuel *(or distillate fuel* return) from the auxiliary engines, 1b- inlet to the main engine fuel supply line from the distillate fuel service tank, 2b- inlet to the auxiliary engines fuel supply line from the distillate fuel service tank *(other elements of the system as shown in Figure 4.7*)

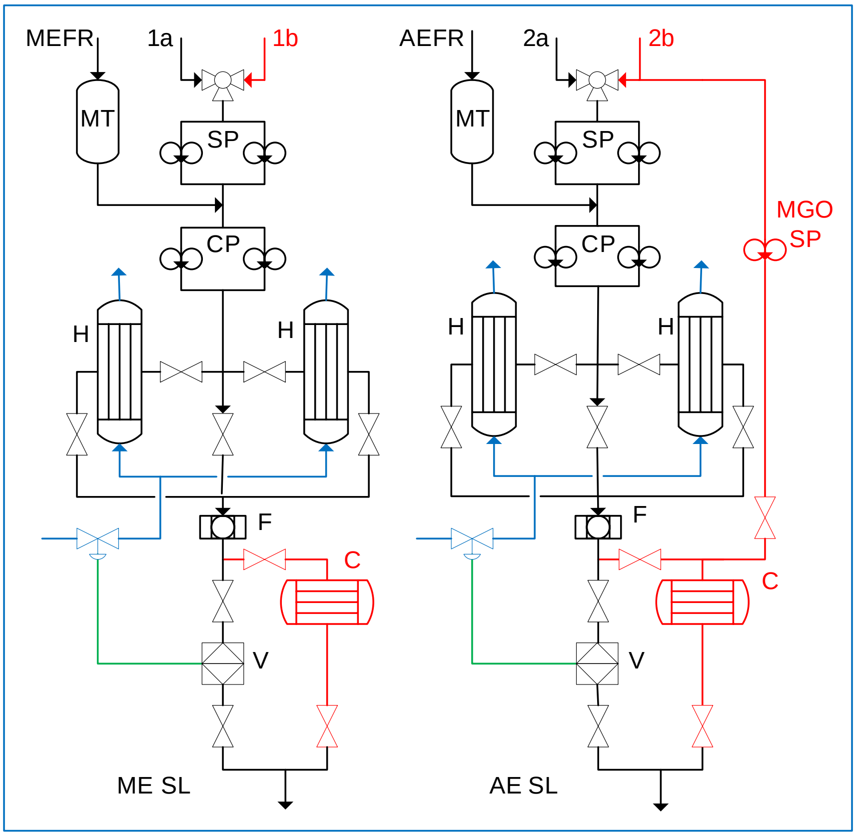
In the case of such construction of fuel supply systems additional elements were applied, allowing for the return of excess fuel supplied to the engines directly to the fuel circulation line *(through the mixing tank*). It should be noted that in case of any failure, it must be possible to return this fuel to fuel service tanks, by-passing the fuel circulation line. Thanks to the extensive construction, the separation of these systems allows for undue changes in the type of fuel used for the main and the auxiliary engines. This is important in the event that it is necessary for a ship to enter the SECA. The ship engine room staff can independently select the time of change of fuel type supplying the engines depending on the ship speed *(engine load*) and electricity demand *(auxiliary engines load*).

5 The adaptation of marine fuel supply systems to use low sulphur fuels

Ship operation in SECAs often requires the long-term use of low sulphur fuels *(distillate or hybrid* ones). Therefore, a significant reduction of fuel lubricating properties *(at low sulphur content*) involves many risks related to the possibility of failure of injection equipment of the main or the auxiliary engines. An additional risk that may occur in this case is the increase in fuel temperature in the engine supply system, which is very dangerous, especially in the case of distillate fuels. For this reason, fuel supply systems have been equipped with additional coolers, which, if necessary, may be set into operation. An example of such a complex installation diagram is shown in the figure 4.9.

An additional advantage during the operation of marine fuel systems is the possibility of selective feeding of selected auxiliary engines with residual or distillate (*low sulphur*) fuel. This possibility results from the use of additional supply lines for auxiliary engines with distillate fuel on many ships (Fig. 4. 10), which is transferred by a separate pump.

Figure 5. 1: Separate fuel supply system for the main and the auxiliary engines with additional fuel coolers

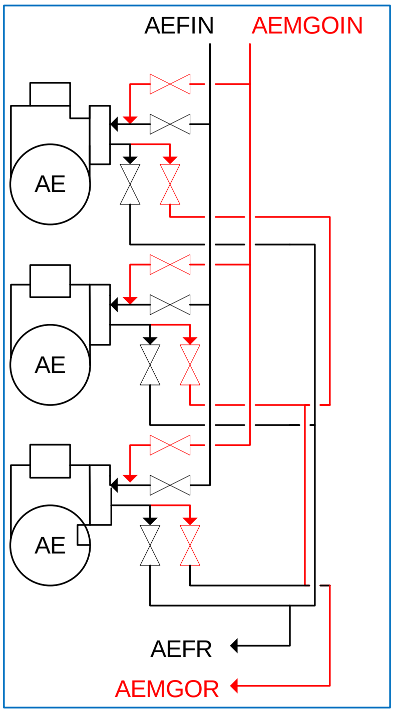


where:

C- fuel cooler *(other elements of the system as shown in Fig. 4.8*)

This function is of a great importance in the SECA, which are limited only to the ship berth, where the local government has ordered an enforced change-over of high-sulphur fuel to fuel with a sulphur content not exceeding 0.1% or 0.5%.

Figure 5. 2: Selective fuel supply system for auxiliary engines



where:

AE- auxiliary engine, AEFIN- residual fuel inlet *(or distillate fuel inlet*) to the auxiliary engines, AEMGOIN- distillate fuel inlet to the auxiliary engines, AEFR- return of excess residual fuel *(or distillate fuel*) from the auxiliary engines, AEMGOR - return of excess distillate fuel from the auxiliary engines.

6 Marine engine performance determined by the use of low sulphur fuels

Hybrid fuels are currently available on the market as an alternative to expensive distillate, low sulphur fuels. Although fuels of this type have not been widely used in shipping so far, the several years of their use allow for the assessment of the performance of marine engines supplied with this type of fuel in comparison with residual and distillate fuels. As an example, the results of tests are presented, which were carried out on a vessel with a direct propulsion system and a slow-speed engine of MAN 6S50ME type, which during the period of its operation was powered by the following fuels:

1. residual fuel (383cSt@50°C, 987 kg/m^3@15°C, S=2.2%);
2. distillate fuel (3.0 cSt@50°C, 884 kg/m^3@15°C, S=0.1%);
3. hybrid fuel (20 cSt@50°C, 894 kg/m^3@15°C, S=0.1%).

The measurements and recordings of parameters were carried out for similar engine loads under comparable vessel operating conditions. During tests the basic engine operation parameters did not show any significant deviations. The results of measurements of engine working process parameters such as: the mean indicated pressures (Fig. 6.1) and the maximum combustion pressures (Fig. 6. 2) prevailing in individual engine cylinders show high similarity to the average values.

Figure 6. 1: Mean indicated pressure for 6S50ME engine

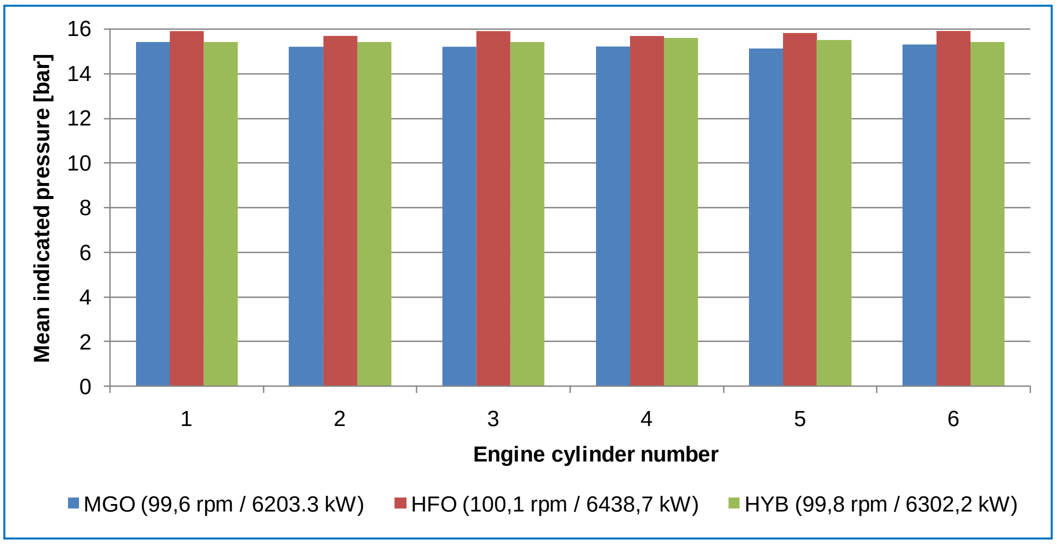
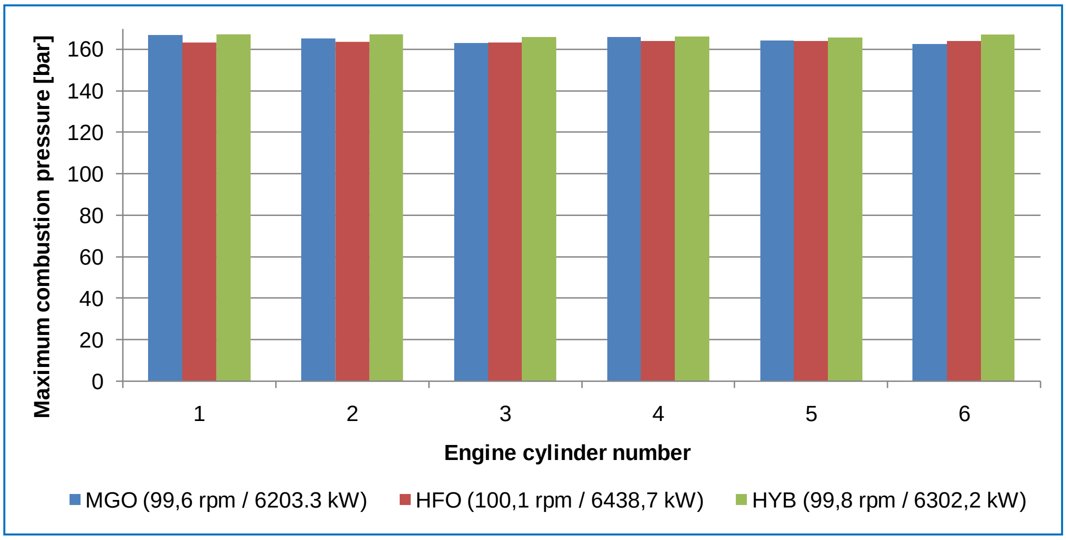
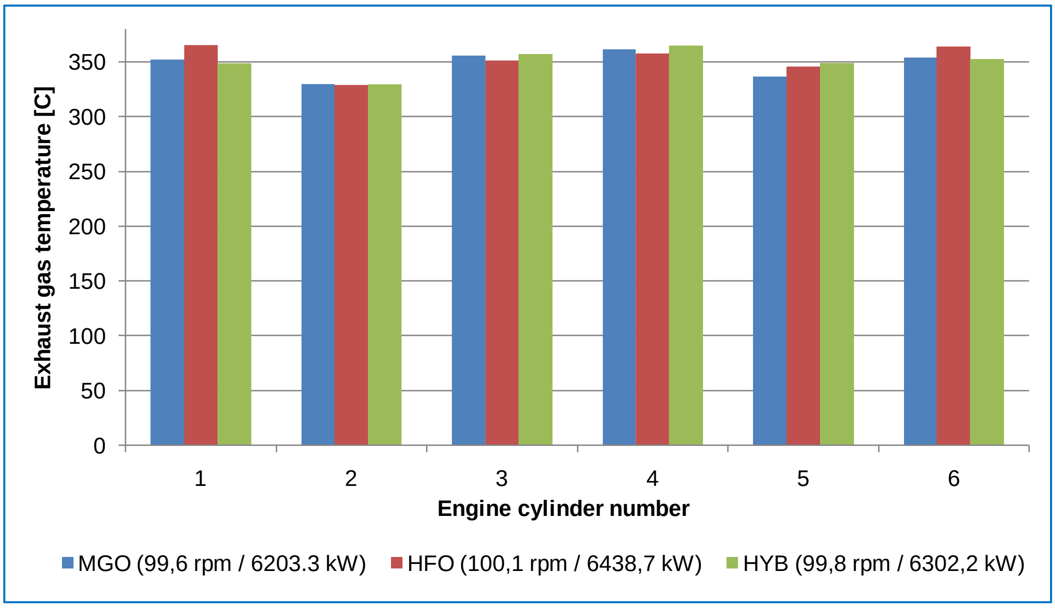


Figure 6. 2: Maximum combustion pressure for 6S50ME engine



However, in a characteristic manner, the results of measurements carried out for hybrid fuels and distillate fuels are almost identical. Additionally, during the series of measurements, the outlet gas temperature of individual cylinders was recorded (Fig. 6.3).

Figure 6. 3: Exhaust gas temperatures for 6S50ME engine



Figures 6. 4 to 6. 6 additionally show for each of the analysed parameters the absolute values of deviations of the measured parameters from the average value for all cylinders.

Figure 6. 4: Deviations from the mean indicated pressure

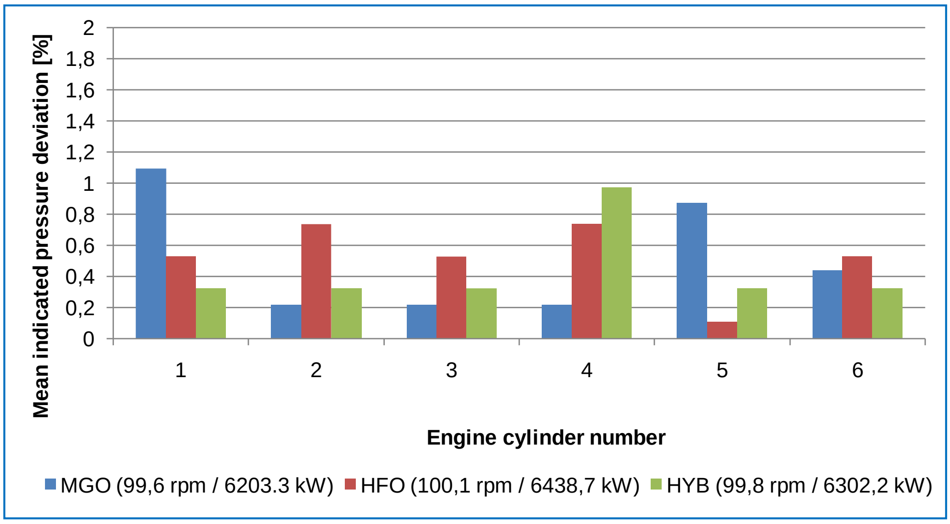


Figure 6. 5: Deviations from the maximum combustion pressure

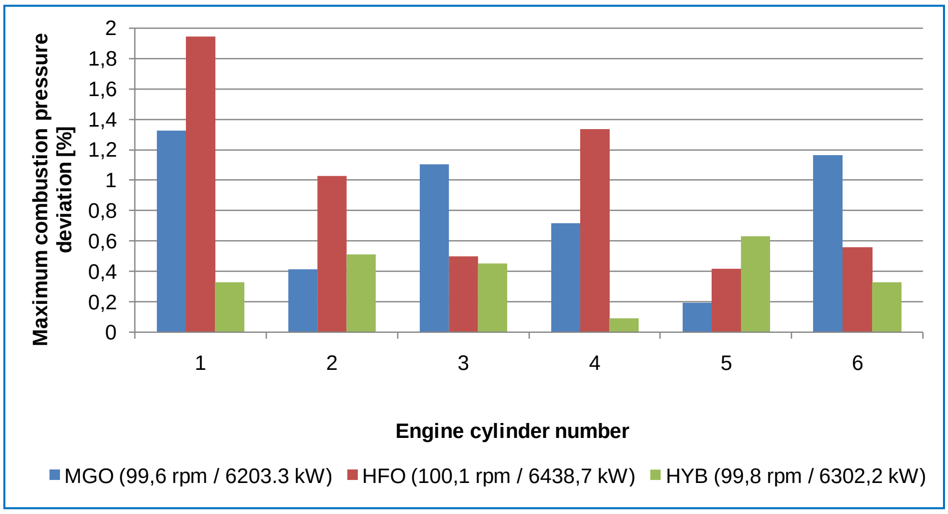
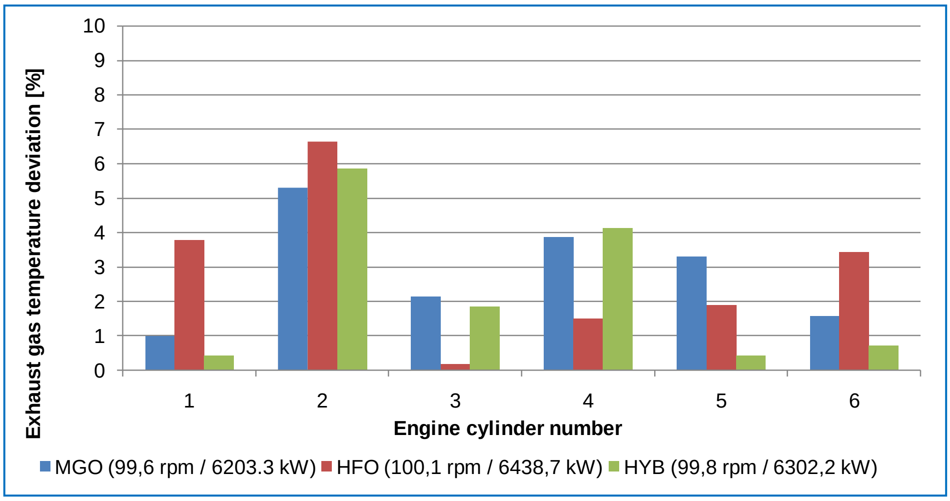


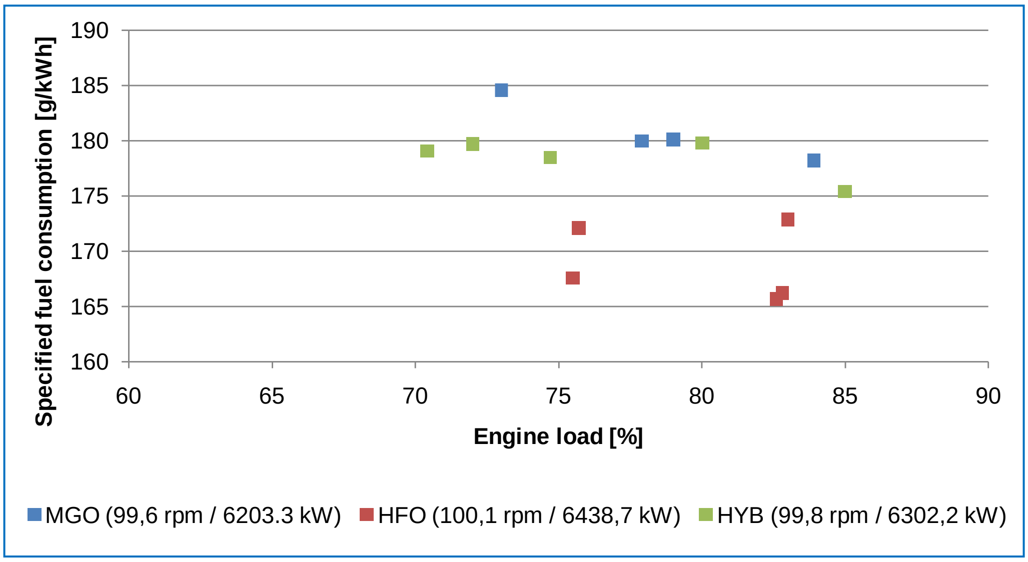
Figure 6. 6: Deviations from outlet gas temperatures



As in the case of the previously presented engine operation parameters, no significant deviations were observed in this case, which could result from a change in the type of used fuel. The detailed results of the measurements are set out in Annexes 3, 4 and 5. It should also be noted that the ship was operated for a long time in the SECA and at that time there were no technical problems during the operation of equipment supplied with hybrid fuel *(the main engine, the auxiliary engines, and the auxiliary boiler*). For this reason, the shipowner decided to use this type of fuel during further operation of the ship in this area.

During the series of measurements, fuel consumption was also recorded and SFOC calculated. Figure 6. 7 shows the results which indicate a slightly higher consumption of distillate and hybrid fuels when compared to residual fuels in a comparable engine load range. In addition, attention should be paid to nearly identical consumption of the hybrid and the distillate fuels, which in the present case was due to their comparable calorific values (*average value - 42.6 MJ/kg*).

Figure 6. 7: The comparison of specific fuel oil consumption



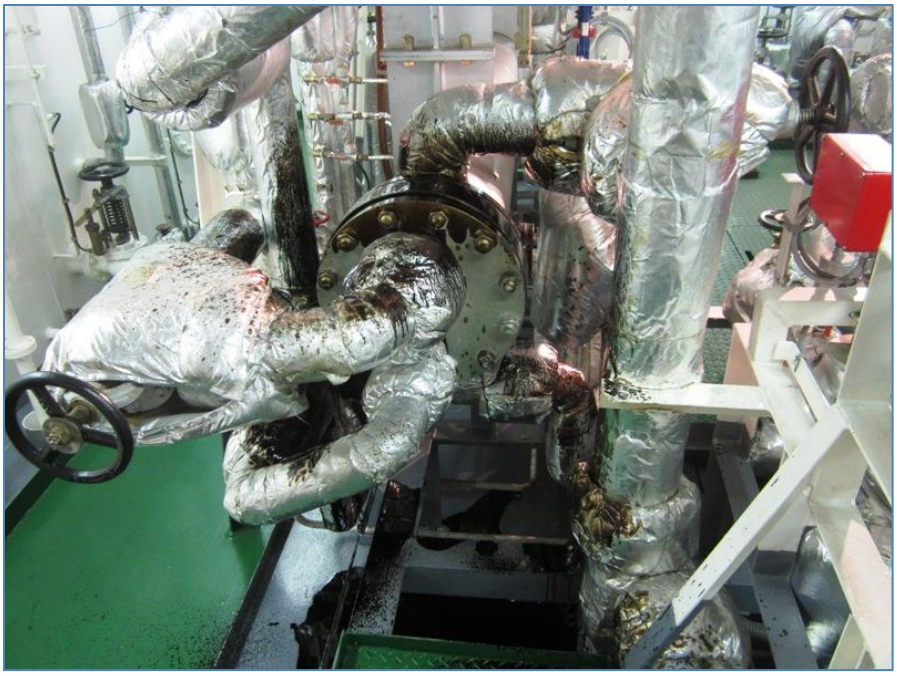
7 Operation problems due to incompatibility of fuels

Due to high content of aliphatic hydrocarbons, hybrid fuels show a high tendency to form deposits of precipitated wax, which may lead to the blockage of fuel filters, especially before transfer pumps and centrifuges (Figure 7. 1). For this reason, such fuels should not be stored in storage tanks in direct contact with seawater through the ship bottom or side plating so as to ensure fuel temperature of at least 10°C above its pour point. In practice, despite low viscosity, this requires the use of tank heating systems in which hybrid fuel is stored. An additional inconvenience related to the storage of hybrid fuel in storage tanks, which were previously used to store a different type of fuel, is its tendency to wash out contaminants deposited in different areas of the tank, most often bottom ones (DNV, 2014).

At the further exploitation stage, even after the process of fuel change-over, previously accumulated paraffin or asphaltene deposits, forming certain internal sealings of many connections are washed out. This can lead to dangerous fuel leaks from equipment that worked correctly during the operation with residual fuel; an example of such an accident is shown in Figure 7. 2.

Figure 7. 1: Heavily stained and blocked fuel filter of the transfer pump

Figure 7. 2: Leakage in the heater after the change of fuel from residual to distillate, low sulphur one.



Released paraffin and asphaltene deposits *(washed away by distillate or hybrid fuels*) in the fuel system may accumulate in the filter or between fuel heater plates. In the case of electric heaters, this situation may lead to their overheating and damage as shown in figure. 7.3. As a result, it will require replacement of the entire heating module before reusing the residual fuel.

Figure 7. 3: Defective electric fuel heater

As a rule, a change in the type of fuel supplied to the ship engine room equipment entails the risk of mixing different fractions of residual, distillate and hybrid fuels in the fuel system components. The incompatibility of fuels often leads to a loss of stability of the resulting mixture. Centrifuges are particularly sensitive components of mixed fuels, which can therefore be completely blocked after a very short period of operation; an example of such a dirty fuel centrifuge, which requires immediate inspection and cleaning as a result is shown in Figure 7.4.

Figure 7. 4: Fully contaminated and blocked fuel centrifuge [9]

Source: Shell

In addition to the many hazards arising from the mixing of incompatible fuels in fuel systems, there is also a serious risk to the injection equipment of engine due to the fuel change-over procedure itself. Particular caution should be exercised by the ship engine room staff during the change-over to distillate fuel. Distillate fuel with low viscosity and very low sulphur content is also characterized by very low lubricating properties. Too rapid fuel change-over procedure leads to a drastic decrease in fuel viscosity as a result of temperature increase resulting from the operation of the entire system with residual fuel *(120-150°C*), including the injection equipment of engines.

Such a rapid drop in the viscosity of distillate fuel - low sulphur fuel, below 10 cSt, may cause dangerous and irreversible damage to injection pumps or injectors; an example of such damage in the injection pump in the form of seizure is shown in the figure 7. 5. For this reason, it is very important to strictly follow the recommendations of engine manufacturers concerning the procedure of changing the engine fuel supply from residual to distillate or hybrid fuels and vice versa.

Figure 7. 5: Damaged plunger of the injection pump as a result of too rapid change of the residual fuel to distillate, low sulphur fuel

8 Recommended fuel handling procedures

This manual shall describe procedures for safe fuel oil handling, starting from bunkering to change-over from HSFO to DFO or Hybrids and vice versa. Due to differences in various ships fuel oil system construction, one single universal procedure cannot be created. The below information may be taken as a general guidance, but on board every single vessel her specific procedures must be prepared in written form.

The ship's specific fuel oil change-over instruction with all required attachments has to be presented to authorities any time upon request. Usually 3-4 days before expected entering SECA, Ship's master should be consulted for expected vessel speed and weather forecast. The ships speed strategy may be agreed at that time. Due to difference in the distillate and residual fuel price it might be recommended to increase the speed before entering SECA and reduce after fuel change-over. Possible sudden alteration of sailing condition may also affect proper process of fuel change-over, therefore careful observation of most recent weather forecast is an important part of preparation. Sulphur content in HSFO and LS distillate or hybrid fuel to be used for change-over should be checked with Bunker Delivery Note – BDN, if there are several LSFO onboard. It is recommended to use HSFO with lowermost available sulphur content and change it over to distillate/hybrid fuel with lowermost sulphur content too. This will reduce significantly the time of entire process.

8.1 Marine fuel oils designation and limits

1. **Ship engine types**:
   A. Main engine:
      - Two-stroke, slow speed, large bore,
      - Four-stroke, medium speed, large bore,

   B. Auxiliary engine: four-stroke, medium speed, small bore.
2. **Auxiliary boiler:** steam or thermal-oil.
3. **Distillate fuels –** marine diesel fuel oil / gas oil (MDO/DFO/GO).

ISO 8217, CIMAC no. 21, British Standard MA 100 Class M2, ASTM Classification of diesel fuel oil D975 grade No. 4 or similar: may be used. If deviating qualities are applied, the engine must be prepared for this.

4. **Residual Fuel – High Sulphur Fuel Oil (HSFO) specification**

Fuel oils limited by this specification have, to the extent of the commercial availability, been used with satisfactory results on two stroke low speed diesel engines.

Table 8. 1: Marine fuels - limit values

Guiding specification	Unit	Fuel oil (maximum value)
Density at 15 °C	kg/m3	1010
Kinematic Viscosity at 100 °C	cSt	55
Kinematic Viscosity at 50 °C	cSt	700

Flash point	°C	>600
Pour point	°C	30
Carbon residue	%(m/m)	20
Ash	%(m/m)	0.15
Total sediment after ageing	%(m/m)	0.10
Water	%(v/v)	0.5
Sulphur	%(m/m)	Statutory requirements
Vanadium	mg/kg	450
Aluminum Silicon	mg/kg	60

Equal to ISO 8217 RMK 700/CIMAC H700

NOTICE: The residual fuel oil data refers to the fuel as supplied, i.e. before any onboard cleaning. If the bunkered fuel analysis reveals that the product exceeding the above limits, especially with regard to viscosity and specific gravity, the engine maker should be contacted for advice regarding possible fuel oil system adjustment. In extreme cases the non-standard-complying fuel has to be discharged to the port facilities.

8.2 Fuel oil bunkering process

Fuel oil bunkering is critical process on the ship. It requires utmost care to prevent any kind of accident like tank overflow or spillage. Number of crewmembers is involved in that process usually and when considered that at the same time usually cargo operation and some maintenance is in progress it is clear, that the operation is of a high risk. The Chief Engineer is responsible for preparing and conducting the bunkering and he should calculate and check which bunker oil tanks are to be filled. It might be required to empty some tanks and transfer the oil from one tank to other. This is required to prevent mixing of two oils and prevent fuel oil incompatibility. The sounding of all fuel storage tanks should also be taken and recorded to verify amount of fuel already stored onboard. Simplified set of recommendation for bunkering are as follows:

Bunker plan

The quantity of fuel oil to be received is decided in consultation with the Master and company management. Chief Engineer decides which tanks to be bunkered and consults it with the Chief Officer, to ensure proper draft and trim of the ship is maintained and also to avoid mixing of fuels as much as possible. Sometimes bunker plan made by the Chief Engineer is also sent to the owner for approval.

Finally, bunker plan needs to be compiled and following items stated:

- which tanks are to be filled
- sequence order of tanks to be filled
- how much fuel oil is to be taken and types of fuel, if different grades are needed,
- bunkering safety procedures:
    1. emergency procedure in case of accident (spill on the deck, overflow tanks, pressure increase in bunker line)
    2. responsibilities of each crew member appointed for bunkering and communication procedure
    3. communication means with fuel supplier (barge or terminal).

Fuel oil system

The following operations in engine room should be performed:

- checking of the high-level alarms in storage tanks;
- isolating of the storage tanks (valves, tanks not to be used for bunkering);
- isolating of the transfer system (valves, pumps);
- operating (opened/closed) remotely controlled valves for the selected bunker tanks;
- emptying of any overflow tanks and verification of proper functioning of alarming device,
- installing fuel sampling flange (if bunkering manifold not equipped).

NOTICE: In order to obtain a representative sample of the fuel oil bunkered, minimal amount has to be drawn continuously throughout the entire bunkering. To achieve this, it is strongly recommended the use of sampling device and drip line sampler (collection container). An example is presented in Figure 8. 1.

Figure 8. 1: Fuel oil sampling flange and container

Source: https://www.cmtechnologies.de/

Deck preparation

- emptying of drip trays;
- blocking of all scrappers;
- preparing of the firefighting safety equipment (fire extinguishers, fire fighting lines...);
- preparing of the oil spill collecting equipment (sawdust, soaking pads...);
- preparing of the communication systems (phone lines, VHFs...);
- displaying of a red signal flag or red signal light on the top mast.
- securing adequate light at the bunker station.

Bunkering method - preparation

Often, the shipowner appoints an inspector to supervise bunkering, which cooperates with the ship's crew, ensuring fuel bunkering in accordance with the PSC requirements. Once the barge or truck is alongside the ship, the Chief Engineer and duty engineer should check fuel oil specifications stated in BDN.

Before the bunkering commencement duty engineer should agree with the supplier representative the following:

- the maximum permissible transfer rate,
- the maximum permissible pressure at the bunker manifold,
- the sampling procedure to be used,
- which oil to be taken first (in case of more than one grade of oil is to be taken),
- emergency stop signals (to be commonly well understood),
- ship safety checklist,
- supplier safety checklist (*if required*).

Normally, the quantity of fuel delivered will be determined by shore/barge meters or measurement of barge tanks. The Chief Engineer or duty engineer should attend to witness meter readings or barge soundings and fuel temperature. Typically, checking of the content of supplier's bunker barge / shore fuel tanks / installation is performed as follows:

- if truck: the loading certificate and all required seals (valves, flaps...);
- if barge is NOT equipped with the mass flow meter: repeat the same procedure as for the ship's fuel tanks;

- if barge is equipped with the mass flow meter: flow meter initial figures, calibration certificate and seals (manual sounding to be carried out only if required);
- if shore bunkering installation: procedure may vary depending on local regulations.

In case of hybrid fuels bunkering, additionally the following issues need to be considered:

- are different grades of fuel oils compatible?
- how can the ship crew verify the risk of incompatibility?

If mixing of residual and hybrid fuels is foreseen the compatibility test should be carried out.

Preparation of fuel oil transfer line:

- connect fuel transfer hose (proper condition to be confirmed, proper seals to be used);
- Only after hose connection required valves may be opened at bunker manifold, fuel transfer system, fuel bunker tanks;

Bunkering operations

Once all the checks are done and manifold valve is open for bunkering, the bunkering can proceed:

- start bunkering with reduced fuel flow rate (*check whole fuel transfer system for leakages, check that the fuel is transferred to the tank to which the valve is opened*);
- after confirming that fuel is filling up proper tank, no leaks and pressure is low the pumping rate is increased as agreed with supplier,
- during bunkering, sounding is taken frequently until the tank is near 85% of total volume,
- the maximum allowable volume to which tank is filled with high rate is typically 90 %, then it may be topped up to 95 % at reduced transfer rate,
- Changing over to another tank must be always don at reduced transfer rate and as a rule first the valve for a new tank should be opened and after confirmation of opening is received the valve for already filled tank may be closed,
- the temperature of the fuel oil is also to be observed and should be consistent with supplier declaration.

Take fuel oil samples during whole period of bunkering as described in chapter 4.1.

After bunkering operations:

Once the bunkering is completed, it is a common practice to blow the bunkering line for emptying all the fuel oil trapped. Be aware of introducing air to froth up the fuel oil and "*cappuccino effect*" result.

- avoid dismantling the bunkering supply line, before the final volume of delivered fuel oil is established. In case of any discrepancy, the supplier may agree to compensate the shortfall and resume bunkering operation,
- check content of ships fuel tanks (*the same way as "just before bunkering"*);
- check content of supplier's bunker barge/truck/installation fuel tanks:
  - if truck: the content of the truck's tank (bearing *in mind temperature, lean...*);
  - if barge **NOT** equipped with the mass flow meter: repeat the same procedure as for the ship's fuel tanks;
  - if barge equipped with the mass flow meter: flow meter closing figures for bunkering operation;
  - if shore bunkering installation: procedure may vary depending on local regulations.
- collect supplier's samples taken at barge/truck/installation manifold:
  - supplier's sample be retained on board of the ship, to be marked as MARPOL;
  - supplier's sample to be retained on board of the ship;
- if everything is settled, the hose connection may be removed

Bunkering completion

- the BDN is signed if received amount of fuel corresponds to the stated amount;
- distribution of fuel oil samples as described in chapter 4.1.
- the Chief Engineer makes the entry of the operation in oil record book along with received BDN.

NOTICE: The appropriate action against fuel oil supplier is taken if delivered fuel oil is not compliant with BDN. Issue NOP (*Note Of Protest*), inform Master, act according to the company/local regulations.

8.3 Change-over between residual and distillate or hybrid fuel when engine is running

Before the intended change-over from HSFO to DFO and vice versa, it is recommended to check the compatibility of the two fuels, preferably at the bunkering stage. The compatibility can be checked either by an independent laboratory or by using fuel test kits on board. As incompatible fuels may lead to filter blockage, there should be extra attention on filter operation in case of incompatibility.

Change-over of fuel can be somewhat harmful for the fuel equipment, because hot HSFO is mixed with relatively cold DFO. The mixture is not expected to be immediately homogeneous, and some temperature/viscosity fluctuations cannot be avoided. The process therefore needs careful monitoring of temperature and viscosity. In general, the viscosity controller should be sufficient to control the heat source (i.e. steam or thermal oil flow or eventually electric power) for the fuel oil heater. However, the PID controller typically is tuned for relatively slow viscosity fluctuations, therefore automatic process during change over might be instable and controlled value might be overshoot easily. Finally, the process is typically controlled manually to secure sufficiently slow changes of temperature to protect the fuel system components. During manual control observation of the temperature and viscosity is crucial factor for entire process safety. During fuel change-over process two limitations must be observed:

- the fuel viscosity must not drop below 2 cSt and not exceed 20 cSt,
- the rate of temperature change of the fuel, at inlet to the engine fuel pumps must not exceed 2 ^{o}C/min in order to protect the fuel equipment from thermal shock (thermal expansion problems), resulting in sticking and seizing.

It should be noticed that when operating on low viscosity fuel, internal leakages in the fuel equipment may increase. With worn pump elements this can result in engine starting difficulties, and increased fuel pump start index might be observed. The wear in the fuel pumps should be monitored by comparing the fuel index at fuel injection pumps for the new engine and during service. At a 10% increase of the fuel index for the same load the plunger/barrels can be considered as worn out and should be replaced or sealing renewed. When the engine is permanently supplied with LSFO it has to be carefully observed for eventual fuel leaks. High risk of leakage comes from alteration of dimension due to temperature variation. An important factor is also condition of fuel system seals and gaskets. If the seals are not being replaced according to maker's recommendation they become hardened and brittle, what results in tendency to leak after change-over to distillate fuel.

The entire change-over procedure must be started sufficiently in advance to ensure that it is completed before entering SECA. A few hours before commencement, HFO separators and preheaters may be stopped. Heating of HSFO service tank may be stopped. The LS fuel service tank should be refilled. On board some ships of older construction there is only one service tank available. In such a case the level of HSFO in service tank has to be reduced

Required time of fuel oil flushing period has to be determined based on the system volume and fuels used sulfurization. Several approved change-over time calculators are available like FOBAS calculator, LR calculator or DNV-GL calculator. The currently built ships are equipped with a certified list of fuel oil installations with calculated volumes, which should be used for the purpose. When there is no such list on board, it is compulsory to carry out detailed calculations and draw up an appropriate list. An example of a list prepared in such a way for a particular ship can be presented as:

1. pipelines for distillate fuel oil: ~0.02 m^3(to FO supply unit),
2. pipelines for residual fuel oil: ~0.05m^3 (to FO supply unit),
3. pipelines for fuel oil at engines (ME & DG's) in/outlet: ~0.19 m^3 (after FO supply unit),
4. pipelines of FO supply unit including de-aerating tank: ~0.36 m^3,
5. total volume of FO pipelines ~0.62 m^3.

Only after proper flushing of the system, preferable at least 2-3 days after commencement of operation, the fuel leaks and overflows from the supply system may be redirected to LSFO tanks, i.e. LSFO fuel leak tank and service tank. To early change over may result in contamination of LSFO tanks with HSFO fuel.

8.4 Change-over of main engine from residual to distillate or hybrid fuel oil

Procedure:

- Ensure that temperature of the fuel oil in the service tank is at an acceptable and ssufficient quantity. The following must be taken into consideration:

- constant viscosity at engine inlet must stay in acceptable range 8 – 15 cSt,

- heat transmission from metal parts of the fuel system to the fuel will occur,
- cooling capacity of the fuel oil in the system.

– Reduce the preheating of the fuel oil by increasing the set point of the viscosity controller to a maximum viscosity your engine may accept. Most of low speed engines accept for short period viscosity up to 20-24 cSt. In doubts the engine maker should be consulted. Manual control of the heater might be necessary if it is observed that viscosity controller exceeds the maximum temperature change gradient of 2°C/min at engine inlet.

– If fuel oil change over unit is available, input fuel change over time, target time must also be set greater than minimum and start the change-over process. If not, manual operation is advised and proper the 3-way valve can be slowly adjusted.

– Stop heating of system fuel pipes tracing and heating of automatic fuel filter.

– On automatic fuel oil filter reduce the time between back flushing to 20-30 minutes, to reduce the filter blockage in case of rapid sediment precipitation.

– Reduce the engine load when fuel reaches a temperature corresponding to 18 cSt, during the change-over main engine load preferable should be 25-40%MCR, to ensure a slow re-duction of the fuel oil temperature at engine inlet, and max. change gradient 2°C/min is advised.

– Once some amount of distillate fuel enters the supply system, monitor fuel viscosity and temperature parameters, do not exceed temperature change gradient at engine inlet of 2°C/min, at the same time viscosity at engine inlet must not drop below 2cSt.

– Depending on viscosity or temperature, fuel oil cooler can be engaged if ship's fuel systems are adequately equipped.

– The load of main engine can be changed to a higher level-up to 75 % MCR, as long as the change gradient is kept below2˚C/min.

– After fuel oil change-over completed:

  - Record time and date of switching in relevant log book, (Engine log book and/or SECA-log book may apply).
  - Mixture of fuels circulates during a flushing period and needs to be consistent with fuel oil change-over calculator time, however, mostly depends on actual engine load.

- When switching to LSFO it is often necessary to switch to low-BN (15-40) cylinder oil at the same time. A sufficient quantity of low BN cylinder oil to be stored on board in advance if required, while when switching between fuels with same sulfur content cylinder oil BN remains same as before.

– Special attention should be paid to:

1. Fuel filters: be aware that filters in system may become clogged due to compatibility issues or dissolved residues from present in HSFO in piping system. Have clean spare filters ready and switch over duplex filters if required.
2. Use viscometer during transient time after switching. Ensure that viscosity in system never exceeds 20 cSt (temporarily max 24 cSt) or drops below 2 cSt.
3. Temperature gradient not to exceed 2°C/min, engine load to be adjusted accordingly, fuel temperature to be monitored.
4. Perform starting tests astern and ahead before entering a port. If engine does not start on first attempt, cancel limiter to allow 10% more fuel index, check injection pump wear on next occasion.
5. Cylinder condition to be inspected soonest, in next port whenever possible, in view of liner scuffing and piston ring seizure. Engine MCR might not be achieved at max. fuel index while running on distillate fuels, observe injection pump wear.
6. Ensure lowest possible fuel temperature on engine inlet.
7. There are no restrictions regarding engine load or duration of operation while distillate or hybrid fuel in use.

8.5 Change-over of main engine from distillate or hybrid to residual fuel oil

During fuel change-over two parameters are to be kept under observation:

- the viscosity must not drop below 2cSt and not exceed 20cSt,
- the rate of temperature change of the fuel inlet to the engine fuel pumps must not exceed 2°C/min in order to protect the fuel equipment from thermal shock (expansion problems), resulting in sticking.

Procedure:

- Ensure that RFO in the service tank is at normal service temperature (75-90˚C) and sufficient fuel quantity intended to use.
- Reduce the engine load that should be 25-40%MCR during change-over process to ensure a slow heat up of fuel oil supply to normal RFO service temperature at engine inlet (up to 150˚C) and maximum change gradient 2°C/min.
- Set the fuel change-over time (if fuel oil change-over unit is available) and target time must be set greater than minimum.
- The main engine load can be changed to a higher level, up to 75%MCR, as long as the fuel temperature change gradient is kept below 2°C/min.
- Stop the fuel oil cooler (if it was in operation) when the viscosity exceeds 5 cSt. A slow stop of fuel cooler can be done by controlling the oil flow through the cooler, the cooling medium flow or combination of both.
- Open steam to pre-heater and check that the set point is at normal level (10-15 cSt). Manual control of the heater might be necessary if it is observed that the viscosity control exceeds the maximum temperature change gradient of 2˚C/min at engine inlet.
- Open steam tracing when the fuel oil pre-heater is operating normally.
- After change-over completion ensure all valves in fuel system are positioned properly.
- Record low sulphur fuel content in tanks and time and date of switching in relevant log book.
- When switching to high sulphur fuels it is necessary to change over the cylinder oil system to high-BN cylinder oil (70-100), at the same time.
- Calculate consumption of cylinder oil before change-over procedure in order to have empty service cylinder oil (daily tank) for filling it with high BN cylinder oil (usually cylinder oil tank is equipped with level alarm – LLA (Low Level Alarm) at 10% of maximum volume.

8.6 Change-over of main engine from distillate to hybrid fuel oil

Always refer to piping scheme of fuel oil system.

- Sufficient quantity of fuel in distillate FDO/FGO service tank to be provided.
- Set the fuel change-over time (if fuel oil change-over unit is available) and target time must be set greater than minimum.

- Open all trace heating of fuel system, if any are closed, ensure that fuel preheaters steam valves are ready and open manually if required.
- Note: preheaters provided with a by-pass line, you can use it if you need. Monitor viscosity and temperature parameters, do not exceed temperature change gradient at engine inlet below 2°C/min, and viscosity at engine inlet must not drop below 2 cSt.
- A distillate and hybrid fuels mixture circulates during a flushing period. Actual presence of MDO circulating in system can be determined by means of the Lloyd's Register change-over calculator and time depends on the system volume and engine consumption.
- After change-over completed, record time and date of change-over in relevant log book (Engine log book and/or SECA-log book may apply).
- When switching between fuels with same sulphur content (less than 0.1%S) cylinder oil BN remain same as before.

Precautions

1. Fuel filters: be aware that filters in system may become clogged due to compatibility issues or dissolved residues present in piping system. Have clean spare filters ready and switch over duplex filters if required.
2. Use viscometer during transient and after switching. Ensure that viscosity in system never exceeds 20 cSt or drops below 2 cSt.
3. Temperature gradient not to exceed 2°C/min, engine load to be adjusted accordingly, fuel temperature to be monitored.
4. Perform main engine starting tests astern and ahead before entering a port. If engine does not start on first attempt, cancel limiter to allow 10% more fuel index, check injection pump wear on next occasion.
5. Cylinder condition to be inspected soonest, in next port whenever possible, in view of liner scuffing and piston ring seizure.
6. Engine MCR might not be achieved at maximum fuel index while running on hybrid, observe injection pump wear.
7. Ensure lowest possible fuel temperature on engine inlet.
8. There are no restrictions regarding engine load or duration of operation on hybrid fuel.

8.7 Switching auxiliary engines from RFO to FDO

Engine type: **Four stroke – medium speed**

1. Fuel related issues

– Ensure that remaining HFO in system is of sufficient compatibility to avoid sludge formation resulting in filter clogging, refer to relevant analysis report total sediment potential and compatibility index.

– FDO intended to be used must comply with following minimum requirements:

- Viscosity @40°C not less than 2 cSt.
- Lubricity not exceeding 460 μm.
- Sulfur concentration content as required by relevant regulation.

2. Fuel service system setup sequence (refer to piping scheme)

– Sufficient quantity of fuel in FDO service tank to be provided.

– Flush only systems of auxiliary engine(s) which is/are presently not in service.

– Flush system(s) trough engine(s) fuel return line to RFO-service tank until fuel temperature dropped.

– The number of engine(s) to be switched shall be assessed on the power requirements.

– Choose one of the fuel supply pumps and start flushing. Set other pump on stand-by mode. It's a good practice to check stand-by mode function before putting auxiliary engine on busbar.

– Depending on which engine(s) are intended to be switched appropriate system's valves to be set in correct position.

– Record fuel content in tanks, time and date of switching in relevant log book (engine log book and/or SECA-log book may apply).

3. Engine operation issues

– There is no oil change to lower BN-oil required.

– Fuel filters: be aware that filters in system may become clogged due to compatibility issues or dissolved residues from HSFO present in piping system.

– Wait sufficient time after flushing to allow temperatures in fuel injection pumps to equalize avoiding sticking.

– After auxiliary engine(s) start ensure that all cylinders are firing.

- Connect generator(s) to busbar.
- Observe that engine(s) properly take load as desired and not exceed operational limits (refer to maker's instructions).
- Ensure lowest possible fuel temperature on engine(s) inlet.
- After a few running hours draw a lubricating oil sample and conduct a viscosity comparison test in view of possible contamination resulting from FDO leakage through injection pumps into oil sump, repeat the test if required.
- Engine high load might not be achieved at maximum fuel index, check injection pump wear in abnormal engine behavior.
- There are no restrictions regarding engine load or duration while operating on FDO.
- Only engine(s) with sufficient fuel supply index shall be selected for stand-by mode.

8.8 Switching auxiliary boiler from RFO to FDO

- Fuel service system setup sequence (refer to piping scheme)
- Sufficient quantity of fuel in FDO service tank to be provided. Auxiliary boiler burner before change-over must be stopped.
- Fuel oil tracing and heaters should be stopped. Ensure that fuel preheaters blocked steam supply and close valve manually if required.
- Change position of the fuel system valves (if fuel cooler is installed - turn on).
- Start auxiliary boiler initial program and automatic fuel flush sequence.
- Supply pumps should run only when burner is firing to avoid increase of temperature of the FDO circulating in system.
- Burner control does not require alterations (pre- and post-purge, flame safe guard, etc.).

9 Conclusions

The introduction of regulations aimed at limiting the emission of sulphur oxides to the atmosphere by sea transport has resulted in many changes, primarily in the way ship fuel systems are operated. The basic means of meeting the emission limits imposed by the IMO has been the combustion of low sulphur fuels, including distillate and hybrid fuels, in designated ship areas. Hybrid fuels have not been widely used in shipping worldwide so far, but their share in the marine fuel market is expected to increase as an alternative to distillate fuels. Trials conducted on ships powered by this type of fuel *(hybrid one*) have been successful, which encourages the shipowners to use them.

New regulations require from the ship proper maintain of sulphur level in bunkered fuel. Therefore, any contamination of low sulphur fuels with any amount of high sulphur fuel must be avoided. Together with the incompatibility of some grades of fuels, especially hybrid, bunkering, storage and even supply systems are being adopted on new and existing ships. On existing ships retrofit is always expected to reduce the costs of ship operation, however the initial cost are usually high. Such retrofitting carried out on existing ships leads to alterations in operational procedure and frequently alterations in ship stability. That poses additional challenge for the crew – the routines are broken triggering higher risk of incidents. Proper training and familiarization should be provided by the owners especially during starting up.

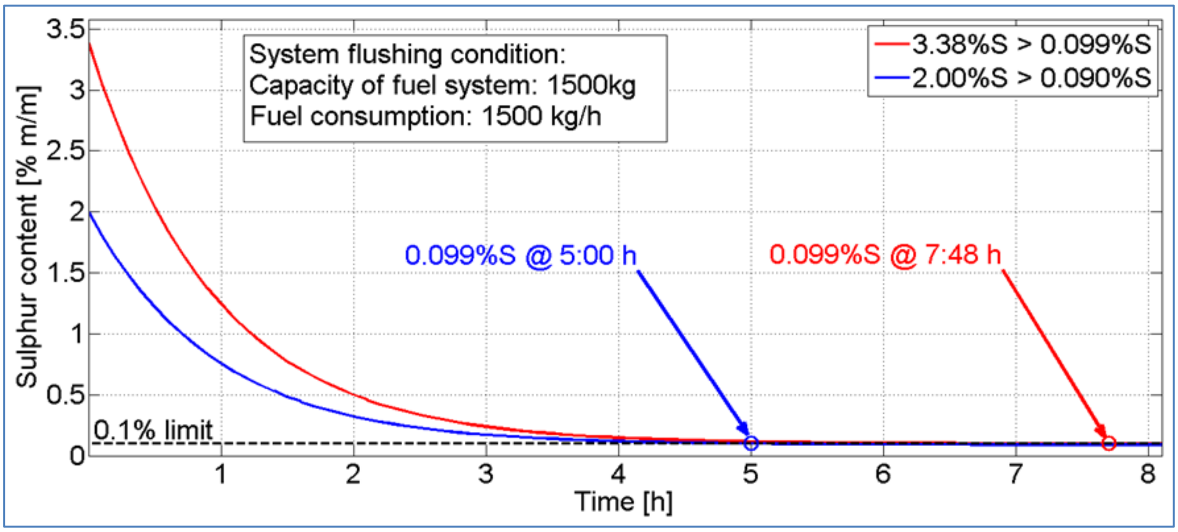
Entire process of change-over always brings some level of hazard. The exact properties and compatibility of fuels to be used are never fully known on board. The resulting blend properties vary with the change of concentration. There is a number of parameters which has to be observed and controlled at the same time: viscosity, temperature, pressure, engine load. Therefore, even engine makers recommend carrying out the change-over procedure in a safe area, remotely from intense traffic and shore or port vicinity (MAN Diesel & Turbo, 2014). There are different risks assigned for entering and leaving the SECA. When changing-over to distilled/hybrid fuels a risk of filter blockage, to low viscosity and increased fuel leaks are high. When leaving SECA the highest risk is related to fuel injection components seizing due to thermal expansion.

The clear example is discussion of change-over procedure commencement time. The MARPOL convention requires that the vessel has to use low sulphur fuels in all machinery already when entering SECA. That means, the entire supply system has to be flushed from high sulphur fuels in advance.

The flashing time varies and depends on several factors. Some of them, like the fuel supply system volume are constant and specific for every vessel. Other, like actual fuel consumption or fuel sulphation are various and specific for the actual voyage. On the figure 9.1 the difference in flushing time for various sulphur content of high and low sulphur fuel is presented.

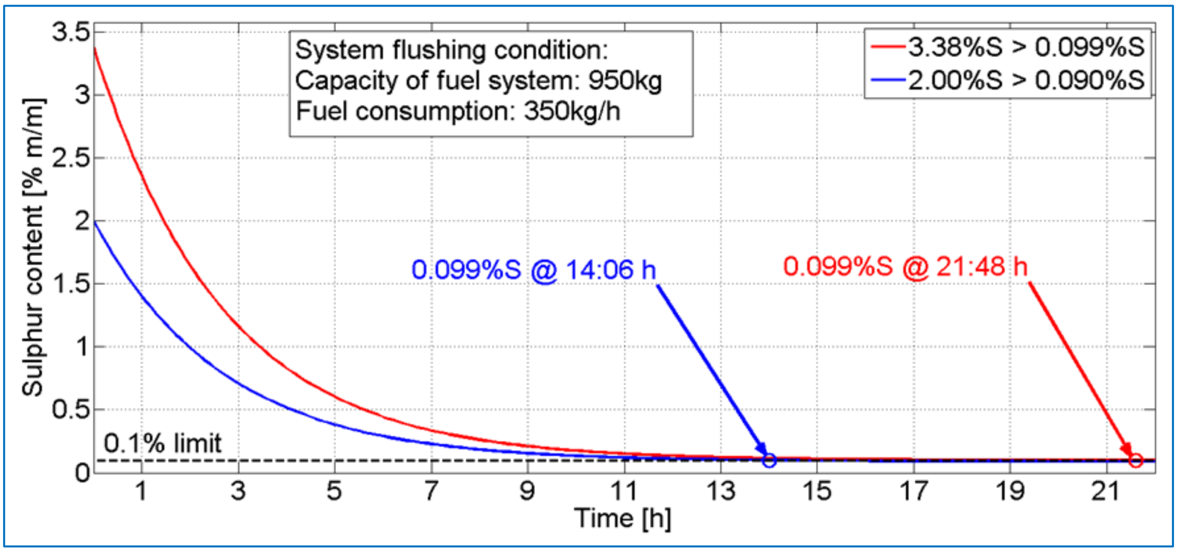
Proper management of fuel on board and selection of fuels with the lowermost sulphur content helps in reduction of flushing time. That reduces the cost of more expensive low sulphur fuels consumption during flushing. The flushing process may take significantly long time in case of relatively large fuel supply system volume and low consumption. An example of such situation may be a container carrier auxiliary engines fuel supply system. If the vessel has high capacity of refrigerated containers carriage, she usually is equipped with 3, 4 or even more auxiliary engines. In case the refrigerated containers capacity is not utilized, typically one auxiliary is operating on low partial load, but the fuel supply system remains of high throughput and consequently volume.

Figure 9. 1: Main engine flushing time comparison for two combination of fuel sulphur content



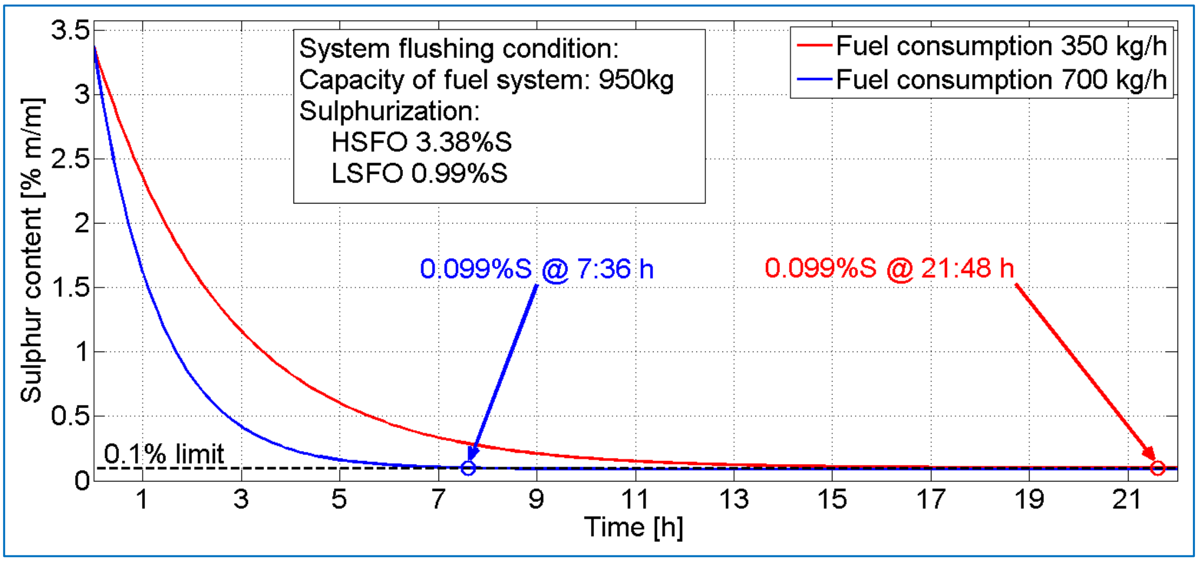
On figure 9.2 an example of flushing period for container carrier with four auxiliary generators of 4250 kW each and nearly no refrigerated containers on board is presented. Depending on the sulphur contend in fuels used for change-over, the flushing time may take tens of hours. Comparing to the flushing time presented on the Figure 9.1 it is clear that the flushing commencement may differ for various consumers. Finally, the consumer load, i.e. the fuel consumption influences the time of flushing significantly too.

Figure 9. 2: Auxiliary engine flushing time comparison for two combination of fuel sulphur content



While the main engine load may be relatively easily controlled by adequate vessel speed setting, the load of auxiliaries or boilers depends exclusively on the actual electric or heat load. The crew has very limited means on the load adjustment. The only way is by starting additional unnecessary consumers, what not always is possible. On the figure 9.3 the flushing time for auxiliary engines in case of two different loads is presented.

Figure 9. 3: Auxiliary engine flushing time comparison for two for two different loads and fuel consumptions



If the electric load might be increased twice (resulting in approximate fuel consumption from 350 to 700 kg/h), the flushing period would be reduced from nearly 22 to around 7.5 hours.

The resulting low sulphur fuel total consumption during flushing period is 5.3 t for high load and 7.6 t for low load condition respectively.

Above presented examples proves that the crew may significantly contribute in economic and environmental costs of the process. However, all activities related to fuel management are very time consuming. This is additional burden mainly for engine crew. The time sacrificed for fulfilling SECA regulations has to be derived from other routines as additional crew very seldom was engaged.

In addition to the unequivocally positive aspect of reducing sulphur oxides emissions, there have been many operations related to the use of distillate fuels for the long-term supply of combustion engines in SECAs. The procedures developed by engine manufacturers for changing-over supply from residual to distillate fuel are in many cases only a set of general guidelines, so the responsibility for the correct and safe fuel change-over falls on the ship engine room staff. Due to the properties of distillate and hybrid fuels, it may happen that even though the fuel change-over procedure has been carried out correctly, the engine operation may be disturbed by some equipment, such as filters, centrifuges, heaters, and the engine own components. As a rule of thumb, it is important to follow strictly the recommendations of engine manufacturer and the procedures developed for changing-over the type of fuel used in order to minimize the possibility of failure.

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Appendix

1) Table 10: 1. Hybrid fuel oil analysis

		Required	Tested
ISO-F Grade(2005)		RMD80LS	RMD80
K Viscosity at 50oC	cSt	80	13.3
K Viscosity at 100oC calc	cSt		4.0
Density @ 15°c	kg/l	0.9800	0.8913
Water Content	% v/v	0.50	< 0.05
Ash Content at 550oC	% m/m	0.10	< 0.010
Micro Carbon Residue	% m/m	14.0	0.06
Total Sediment	% m/m	0.10	< 0.01
Net Specific Energy	MJ/kg		42.50
Gross Specific Energy	MJ/kg		45.16
Sulphur Content	% m/m	0.10	0.08
Pour Point	°C	30	12
Flash Point	°C	60	> 70.0
CCAI	Index		802
Silicon	mg/kg		< 1
Aluminium	mg/kg		2
Vanadium	mg/kg	350	< 1
Sodium	mg/kg		< 1
Iron	mg/kg		1
Phosphorus	mg/kg	15	< 1
Lead	mg/kg		< 1
Calcium	mg/kg	30	< 1
Nickel	mg/kg		2
Zinc	mg/kg	15	< 1
Potassium	mg/kg		1
Magnesium	mg/kg		< 1
Aluminium + Silicon	mg/kg	80	2

Comments:

This sample appears to represent a new ECA-SOx fuel and comply with the 0.1% mm sulphur requirement. In the absence of an advised ISO 8217 standard grade, the results from this sample have been compared against an ISO-F-RMD80. The fuel, to the extent tested, corresponds to an ISO-F-RMD80 grade.

1. Viscosity is lower than generally expected for an ISO-F-RMD80 grade; It should be ensured that the viscosity controller is correctly functioning in order to give the actual temperature required for injection viscosity.
2. Due to the ultra-low sulphur content of this fuel, the engine manufacturer should be consulted before this fuel is put to use. Attention should be paid to maintaining recommended engine operating parameters/limits. In addition, the combustion profile should be monitored whilst using this fuel.
3. Total Sediment result indicates that the fuel will remain stable during normal storage, handling and use.
4. Pour point will require that storage and handling is maintained above 22 °C
5. Based on tested viscosity, we suggest purifier throughput temperature is maintained at approx. 40 Deg C. Please consult equipment manufacturer's guidelines for exact temperature recommendations.

2) Table 10: 2. HFO analysis

		Required	**Tested**
ISO-F Grade(2005)		RMG380	RMG380
K Viscosity at 50oC	cSt	380	371.4
K Viscosity at 100oC calc	cSt		34.0
Density @ 15°c	kg/l	0.9910	0.9898
Water Content	% v/v	0.50	0.05
Ash Content at 550oC	% m/m	0.15	0.017
Micro Carbon Residue	% m/m	18.0	13.80
Total Sediment	% m/m	0.10	< 0.01
Net Specific Energy	MJ/kg		40.21
Gross Specific Energy	MJ/kg		42.49
Sulphur Content	% m/m	3.50	3.08
Pour Point	°C	30	< 6
Flash Point	°C	60	> 70.0
CCAI	Index		851
Silicon	mg/kg		10
Aluminium	mg/kg		10
Vanadium	mg/kg	300	83
Sodium	mg/kg		7
Iron	mg/kg		6
Phosphorus	mg/kg	15	< 1
Lead	mg/kg		< 1
Calcium	mg/kg	30	1
Nickel	mg/kg		12
Zinc	mg/kg	15	< 1
Potassium	mg/kg		6
Magnesium	mg/kg		< 1
Aluminium + Silicon	mg/kg	80	20

Comments:

1. The fuel, to the extent tested, corresponds to an ISO-F-RMG380 grade.
2. Total Sediment result indicates that the fuel will remain stable during normal storage, handling and use.
3. Minimum transfer approximately 34 to 39 ºC
4. The fuel as tested complies with the Revised MARPOL Annex VI reg. 14.1.2 5. Fuel preheat approximately 136 ºC for 12 cSt viscosity at the engine fuel manifold.

3) Table 10: 3. The comparison of cylinder oil analysis – the main engine supplied with hybrid fuel oil and HFO

1	DURING SAMPLING% MCR		53,3		% S IN FUEL =	**0,0697**	KW =	4529
Hybrid fuel oil	BASE NUMBER	mgKOH/g	36,4	37,0	36,8	35,4	36,1	37,0
	BASE NUMBER	mgKOH/g	40,9	41,2	40,8	41,4	41,3	40,3
	TOTAL WATER	%vol	0,13	0,14	0,18	0,15	0,18	0,17
	IRON (Fe)	ppm	15	21	20	14	13	13
	IRON (Fe))	ppm	16	23	22	15	14	14
	MFA	ppm	32	61	47	31	26	27
	LEAD (Pb)	ppm	3	1				
	COPPER (Cu)	ppm	1	2	1	1	1	1
	ALUMINIUM (Al)	ppm	4	6	6	5	5	4
	SILICON (Si)	ppm	18	19	20	17	19	19
	NICKEL (Ni)	ppm	1	2	2	1		
	VANADIUM (V)	ppm	5	7	7	3	2	1
2	DURING SAMPLING% MCR		59,87		% S IN FUEL =	**1,678**	KW =	5090
HFO	BASE NUMBER	mgKOH/g	42,6	46,9	41,4	44,9	45,5	42,2
	BASE NUMBER	mgKOH/g	45,0	49,0	44,7	48,3	47,9	43,8
	TOTAL WATER	%vol	0,57	0,7	0,69	0,68	0,57	0,49
	IRON (Fe)	ppm	88	68	96	69	83	128
	IRON (Fe)	ppm	94	71	105	75	88	134
	MFA	ppm	128	110	138	100	132	173
	LEAD (Pb)	ppm	6	6	7	2	7	5
	COPPER (Cu)	ppm	11	15	17	7	13	21
	ALUMINIUM (Al)	ppm	18	19	21	17	18	18
	CHROME (Cr)	ppm	7	4	7	3	6	9
	SILICON (Si)	ppm	43	40	44	40	42	41
	NICKEL (Ni)	ppm	48	43	57	39	43	45
	VANADIUM (V)	ppm	181	159	203	153	158	171

4) Table 10: 4 The performance of main engine, when supplied with hybrid fuel oil

SERVICE DATA		Engine type: 6S50ME-B9			
Layout Power: 8,502 kW	Layout Speed: 105 RPM	Engine Mode: Economy	Sign.: 2 Eng	Test No.: 015	
Turbocharger(s)	No. T/C 1	Serial No.	No. Cyl: 6	Bore: 500 mm	Stroke: 2,214 mm
Maker: ABB	Type: A165-L37	1	Cylinder Constant: 0.7245	Mean Friction. Press.: 1.0 bar	
Max. Speed: - RPM	Max. Temp.: - °C	2			
Oil Brand: RMD 80		Cylinder Oil	CASTROL	Cyltech 40 SX	
Viscosity at 50ºC: 8 cSt	Heat Value: 42.79 MJ/kg	Circulating Oil	CASTROL	CDX 30	
Density at 15ºC: 864 kg/m³	Sulphur: 0.1 %	Turbo Oil	CASTROL	CDX 30	

Test Date	Test hour hh:mm	Engine speed RPM	Load %	Indicated Power kW	Indicated Fuel Consumption g/kWh	Speed Setting		Draft Fore / Draft Aft.	Log Speed / Obs. Speed
4/26/2017	9:17 AM	99.8	70.4	6,417.1	166.7	100		10.9 m / 9.7 m	15.9 knot / 15.6 knot
Total running hours hh:mm	**Ref. Pmax bar**		**Fuel index %**	**Effective Power kW**	**Eff. Fuel Consumption g/kWh**	**Ambient pressure mbar**		**Wind 11.0 knot / Wave Height**	**Wind Direction 40 deg / Wave Direction**
7521:20	-/-		76.3	5,983.0	178.7	1,001		0.5 m	40 deg

Cylinder No.		All	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Ave.
Pi	bar		14.7	14.9	14.8	14.7	14.8	14.8									**14.8**
Pmax	bar		159.4	160.1	160.4	159.6	158.9	158.9									**159.5**
Pcomp	bar		129.6	130.8	130.1	130.6	130.3	130.1									**130.2**
Pmax Offset	bar	-4	-0	1	1	1	-1	-1									
Pi - High Load Offset	%		-2.7	-1.7	1.7	2.4	-1.7	2.0									
Pi - Low Load Offset	%		0.0	0.0	0.0	0.0	0.0	0.0									
Chief Index Limit	%	95	100	100	100	100	100	100									
Exhaust Gas Temp.	°C		334.0	318.0	340.0	339.0	327.0	341.0									**333.2**
C.W. Outlet Temp.	°C		84.5	85.1	85.5	85.7	85.4	85.8									**85.3**
Piston Lub. Outlet Temp.	°C		55.1	55.3	55.1	55.0	54.6	55.1									**55.0**

Cooling Water Temp				Exhaust Gas Temp		Exhaust Gas Press.		Turbo Charger	T/C Nozzle Ring	Scavenge Air Pressure		
Main Engine		Air Cooler		Turbine		Receiver bar	Turb. Outl. mbar	RPM		Dp Filter mbar	Dp Cooler mbar	Receiver bar
Inlet	T/C Out	Inlet	Outlet	Inlet	Outlet							
78	1	1	1	1	1	-/-	1	1	1	1	1	2.71
Seaw Temp 19.	-/-	35.0	56	378.4	225.3		-/-	17,960	-/-	14	4.2	
	Ave.	Ave.	Ave.	Ave.	Ave.		Ave.	Ave.	Ave.	Ave.	Ave.	
	-	**35.0**	**56**	**378.4**	**225.3**		-	**17,960**		**14**	**4.2**	

Scavenge Air Temp.		Lub Oil Temperature					Lub oil Pressure	Aux. Blower	F.O. Pressure	Swash Plate pos.	Hydraulic Pressure
Scav. Rec.	Blower Inlet	Air Cooler		Turbocharger		Engine Inlet	System Oil	OFF=0 ON=1	Filter Inlet		
		Inlet	Outlet	Blower inlet	Turbine Outlet						
43.0	1	1	1	1	1	49.1	2.71	0	8.1	1	Pump inlet
	18.0	180.0	42.0	49	79.4	Thrust Segm.	Cooling Oil	Axial Vibr.	Filter Outlet	-/-	2.7 bar
	Ave.	Ave.	Ave.	Ave.	Ave.				**8.0**		
	18.0	**180.0**	**42**	**49**	**79.4**						

Fuel Oil Properties and SFOC

Density (15 Deg.C):	**864**	kg/m³	Engine Power:	**5,983.0**	kW
LCV:	**42.79**	MJ/kg	SFOC, calculated:	**178.7**	g/kWh
Sulphur:	**0.10**	%	SFOC (LCV):	**179.1**	g/kWh
F.O. Temp. at reading:	**42.0**	ºC			
Corrected Density:	**845**	kg/m³			

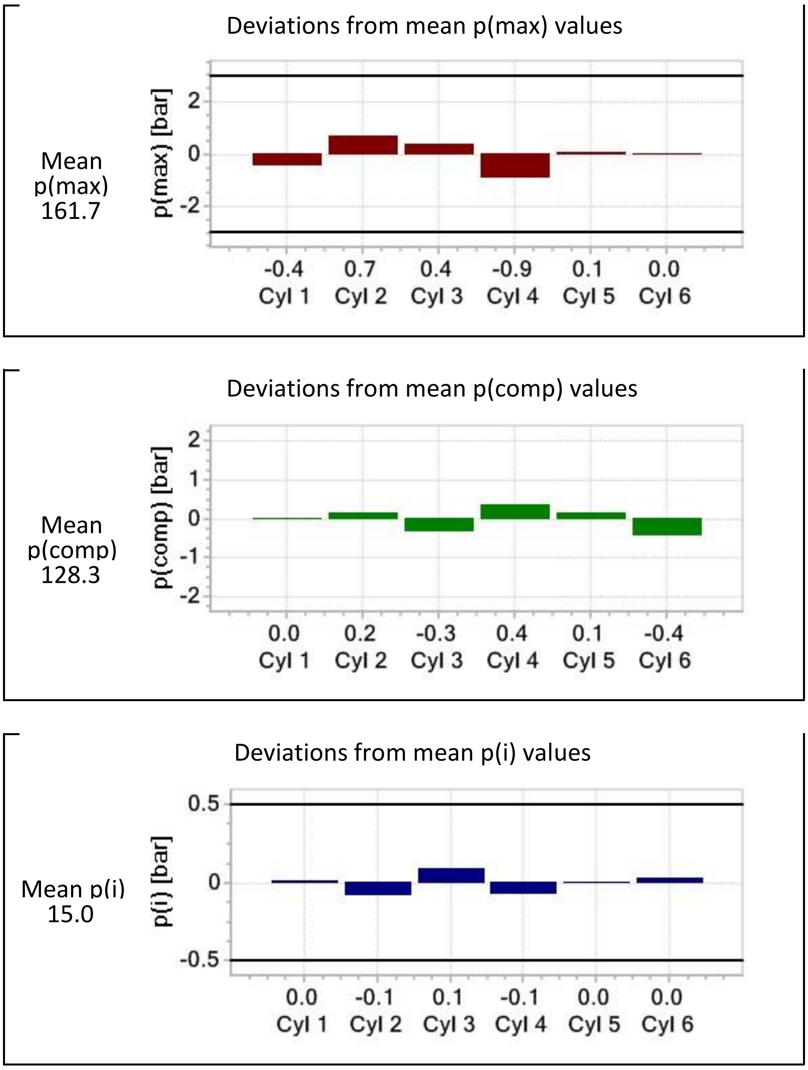
5) Table 10: 5 The main engine combustions, when supplied with hybrid fuel

Engine Speed [rpm]	p(scav) [bar]	Estimated Effective Power [MW]	Estimated Load [%]
100.0	2.73	6.4	76

Cylinder pressures

Cylinder Number	p(i) [bar]	p(comp) [bar]	p(max) [bar]	p(comp)/p(scav)[abs/abs]
1	15.0	128.3	161.3	34.7
2	14.9	128.4	162.4	34.7
3	15.1	128.0	162.1	34.6
4	14.9	128.7	160.9	34.8
5	15.0	128.4	161.8	34.7
6	15.0	127.9	161.7	34.6
Mean	15.0	128.3	161.7	34.7

Figure 10. 1: Cylinder pressures deviations – hybrid fuel operation



6) Table 10: 6 The main engine performance, when supplied with HFO

SERVICE DATA	Engine type: 6S50ME-B9				
Layout Power: 8,502 kW	Layout Speed: 105 RPM	Engine Mode: Economy	Sign.: 2ndEng		Test No.: 002
Turbocharger(s)	No. T/C 1	Serial No.	No. Cyl: 6	Bore: 500 mm	Stroke: 2,214 mm
Make: ABB	Type: A165-L37	1		Cylinder Constant: 0.7245	Mean Friction. Press.: 1.0 bar
Max. Speed: - RPM	Max. Temp.: - °C	2			
Oil Brand:	RMG 380	Cylinder Oil	CASTROL		Cyltech 100
Viscosity at 50ºC: 379 cSt	Heat Value: 40.49 MJ/kg	Circulating Oil	CASTROL		CDX 30
Density at 15°C: 981 kg/m³	Sulphur: 2.4 %	Turbo Oil	CASTROL		CDX 30

Test Date	Test hour hh:mm	Engine speed RPM	Load %	Indicated Power kW	Indicated Fuel Consumption g/kWh	Speed Setting			
1/19/2017	9:30 PM	100.0	87.0	7,492.9	158.2	100		Draft Fore 11.8 m Draft Aft. 11.8 m	Log Speed 14.9 knot Obs. Speed 14.7 knot
Total running hours hh:mm	Ref. Pmax bar		Fuel index %	Effective Power kW	Eff. Fuel Consumption g/kWh	Ambient pressure mbar			
847:00	-/-		91.0	7,058.2	167.9	998		Wind 1.0 knot Wave Height 0.5 m	Wind Direction 90 deg Wave Direction 225 deg

Cylinder No.		All	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Ave.
Pi	bar		17.3	17.1	17.1	17.3	17.3	17.3									17.2
Pmax	bar		178.4	178.9	177.2	177.8	177.5	177.9									177.9
Pcomp	bar		137.3	138.1	136.7	137.5	136.6	137.3									137.2
Pmax Offset	bar	10	1	3	0	-3	-0	-0									
Pi - High Load Offset	%		-1.8	-1.2	3.1	-7.5	1.2	6.2									
Pi - Low Load Offset	%		-0.5	0.0	0.0	-1.5	0.7	-0.2									
Chief Index Limit	%	95	100	100	100	100	100	100									
Exhaust Gas Temp.	°C		395.0	365.0	392.0	389.0	400.0	402.0									390.5
C.W. Outlet Temp.	°C		84.0	82.0	83.0	81.0	84.0	85.0									83.2
Piston Lub. Outlet Temp.	°C		62.0	58.0	60.0	59.0	62.0	59.0									60.0

Cooling Water Temp				Exhaust Gas Temp		Exhaust Gas Press.		Turbo Charger	T/C Nozzle Ring	Scavenge Air Pressure		
Main Engine		Air Cooler		Turbine								
Inlet	T/C Out	Inlet	Outlet	Inlet	Outlet	Receiver bar	Turb. Outl. mbar	RPM		Dp Filter mbar	Dp Cooler mbar	Receiver bar
74	1	1	1	1	1	2.50	1	1	1	1	1	2.70
Seaw Temp	-/-	33.0	52.0	438.0	317.0		-/-	17,925	-/-	8	4.0	
	Ave.	Ave.	Ave.	Ave.	Ave.		Ave.	Ave.	Ave.	Ave.	Ave.	
19	-	33.0	52.0	438.0	317.0		-	17,925		8	4.0	

Scavenge Air Temp.		Lub Oil Temperature					Lub oil Pressure	Aux. Blower	F.O. Pressure	Swash Plate pos.	Hydraulic Pressure
Scav. Rec.	Blow Inlet	Air Cooler Inlet	Air Cooler Outlet	Turbocharger Blower inlet	Turbocharger Turbine Out	Engine Inlet	System Oil	OFF=0 ON=1	Filter Inlet		
42.0	1	1	1	1	1	47.0	2.42	0	7.6	1	Pump inlet
	20.0	186	40.0	44	75.0	Thrust Segm.	Cooling Oil	Axial Vibr.	Filter Outlet	-/-	2.6 bar
	Ave.	Ave.	Ave.	Ave.	Ave.				13.0		
	20.0	186.0	40.0	44	75.0						

Fuel Oil Properties and SFOC

Density (15 Deg.C):	981	kg/m³	Engine Power:	7,058.2	kW
LCV:	40.49	MJ/kg	SFOC, calculated:	167.9	g/kWh
Sulphur:	2.40	%	SFOC (LCV):	159.3	g/kWh
F.O. Temp. at reading:	124.0	ºC			
Corrected Density:	908	kg/m³			

7) Table 10: 7 The main engine combustions, when supplied with HFO

Engine Speed [rpm]	p(scav)[bar]	Estimated Effective Power [MW]	Estimated Load [%]
100.0	2.59	7.4	87

Cylinder pressures

Cylinder Number	p(i) [bar]	p(comp) [bar]	p(max) [bar]	p(comp)/p(scav) [abs/abs]
1	17.3	137.3	178.4	38.5
2	17.1	138.1	178.9	38.7
3	17.1	136.7	177.2	38.3
4	17.3	137.5	177.8	38.6
5	17.3	136.6	177.5	38.3
6	17.3	137.3	177.9	38.5
Mean	17.2	137.2	178.0	38.5

Figure 10. 2: Cylinder pressures deviations – HFO operation