Bundesstelle für Seeunfalluntersuchung
Federal Bureau of Maritime Casualty Investigation

Investigation Report 236/20

Serious Marine Casualty

Fire in the main engine scavenge air duct on board the EBBA MAERSK on 29 July 2020

25 May 2023

This investigation was conducted in conformity with the Law to improve safety of shipping by investigating marine casualties and other incidents (Maritime Safety Investigation Law – SUG). According to said Law, the sole objective of this investigation is to prevent future accidents. This investigation does not serve to ascertain fault, liability or claims (Article 9(2) SUG).

This report should not be used in court proceedings or proceedings of the Maritime Board. Reference is made to Article 34(4) SUG.

The German text shall prevail in the interpretation of this investigation report.

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List of Abbreviations

A/S	Aktieselskab (Danish: stock corporation / public limited company)
ABS	American Bureau of Shipping (classification society)
APMM	A. P. Møller-Mærsk A/S
ASTM	American Society for Testing and Materials (standards institution)
ATR	Attenuated total reflection, a method of infrared spectroscopy
BSH	German Federal Maritime and Hydrographic Agency
CBM	Condition-based maintenance
CEST	Central European Summer Time
CIMAC	Conseil International des Machines à Combustion
Class NK	Japanese classification society Nippon Kaiji Kyokai
CSSC	China State Shipbuilding Corporation
DIN	German Institute for Standardisation
DM	Distillate marine (distillate fuel oil; does not need to be stored heated)
DNV	Det Norske Veritas (classification society)
DNV GL	Det Norske Veritas Germanischer Lloyd (classification society)
ECA	Emission control area (sea area with emission limits)
EGCSA	Exhaust Gas Cleaning Systems Association
FAME	Fatty acid methyl ester
HFO	Heavy fuel oil
ICU	Injection control unit
ICV	Injection control valve
IMO	International Maritime Organization
ISM	International Safety Management
ISO	International Organization for Standardization
LNG	Liquefied natural gas
LONO	Letter of no objection
LSMGO	Low-sulphur marine gas oil
MARPOL	International Convention for the Prevention of Pollution from Ships (“marine pollution”)
MCR	Micro carbon residue
MDO	Marine diesel oil ('marine diesel')
ME	Main engine
MEPC	Marine Environment Protection Committee

MGO	Marine gas oil ('gas oil')
MW	Megawatt
NO_X	Collective designation for oxygen compounds with nitrogen (nitrogen oxides); NO and NO_2 are relevant for internal combustion engines
pH	*Potentia hydrogenii*, Latin for 'potential of hydrogen'
RM	Residual marine (residual fuel; must be stored heated)
RPM	Rotations per minute, unit of a rotational speed (e.g. of an engine)
SECA	Sulphur emission control area or SO_X emission control area (sea area with emission limits for sulphur (oxides))
Ship Safety Division	German Social Accident Insurance Institution for Commercial Transport, Postal Logistics and Telecommunication (BG Verkehr)
SO_X	Collective designation for oxygen compounds with sulphur (sulphur oxides); SO, SO_2 and SO_3 are relevant for internal combustion engines
TBN	Total base number (measure of the alkalinity or acid neutralisation reserve of a cylinder lubricating oil)
TBO	Time between overhauls
TEU	Twenty-foot equivalent unit
THB	Täglicher Hafenbericht (German daily newspaper for the maritime industry)
TSS	Traffic separation scheme
TUHH	Hamburg University of Technology
ULCS/ULCV	Ultra-large container ship/vessel
ULSFO	Ultra-low-sulphur heavy fuel oil
USGS	United States Geological Survey
UTC	Coordinated Universal Time (time at the prime meridian)
VDI	Association of German Engineers
VLSFO	Very low-sulphur heavy fuel oil
VTS	Vessel traffic service
WECS	Wärtsilä Engine Control System
WinGD	Winterthur Gas & Diesel
XRF	X-ray fluorescence analysis

1 SUMMARY

On 29 July 2020, the EBBA MAERSK was en route from Felixstowe (UK) to Hamburg (Germany). After the changeover from a conventional heavy fuel oil to a low-sulphur light fuel oil, a fire broke out in the main engine's scavenge air duct.

The EBBA MAERSK has a common-rail engine as her main engine. The ship sails on the high seas with open-loop scrubbers and has to change to a low-sulphur fuel for voyages in a SECA. The amount of *heavy* low-sulphur fuel on board that day was not sufficient for the voyage segment up the River Elbe to the pier in Hamburg. Accordingly, the main engine was changed over (contrary to usual practice) to a *light* low-sulphur fuel, which was available in sufficient quantity.

Shortly after the changeover was completed, the exhaust gas temperatures of three cylinders successively began to rise above the normal level. One cylinder had to be disengaged electronically. After a brief cooling period, this cylinder's exhaust gas temperature began rising again, even though the cylinder was no longer being actuated.

Shortly afterwards, 'Fire in scavenge air duct' alarms sounded for the forward six of the 14 cylinders. The engine department quickly verified this. It was immediately communicated to the bridge that the engine had to be shut down without delay. They anchored immediately, initially to the east and just outside of the Elbe Approach traffic separation scheme.

The fire in the scavenge air duct was extinguished using the designated system. A thorough inspection of the scavenge air duct was carried out after the engine had cooled down. No damage to the cylinder units was found. However, two of the injection control units (ICUs) were clogged with a tar-like substance. They were overhauled and reinstalled.

During the investigation of this accident, the BSU was especially interested in whether the characteristics of the relatively 'young' low-sulphur heavy fuel oils could have played a role in the development of the fire.

The investigation section of this report begins with two chapters providing fundamental knowledge, one on the subject of limiting sulphur in marine fuels, and one on marine fuels in general. The chapters that follow describe the ship and then the engine, in particular the technical functionality of the ICUs.

Furthermore, the fuel changeover process is considered in greater detail, as are various laboratory analyses. Publications from Wärtsilä (concerning the observed problems, some of them released years before the accident) were also included in the investigation.

A bachelor thesis on the subject of this damage delivered important findings for the investigation report.

2 FACTUAL INFORMATION

2.1 Photograph of the ship

Figure 1: The EBBA MAERSK approaching Hamburg[1]

2.2 Ship particulars

Name of ship:	EBBA MAERSK
Type of ship:	Full container carrier
Flag:	Denmark
Port of registry:	Copenhagen
IMO number:	9321524
Call sign:	OXHW2
Owner (according to Equasis):	Mærsk A/S
Shipping company:	Mærsk A/S
Year built:	2007
Shipyard:	Odense Staalskibsværft (Lindøværft)
Classification society:	American Bureau of Shipping
Length overall:	398.9 m
Breadth overall:	56.40 m
Draught (max.):	17.00 m
Gross tonnage:	171,542
Deadweight:	174,239 / 14,770 TEU[2]

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[1] Source: Hasenpusch Photo-Productions, 2018.

[2] TEU: Twenty-foot equivalent unit, standard 20-foot container.

Engine rating:	80,080 kW at 102 min^{-1}, limited to 54,000 kW
Main engine:	Doosan/Wärtsilä 14RT-flex96C (built under licence)
Service speed:	24 kts
Hull material:	Steel
Hull design:	Conventional (closed hatches, cell guides)
Minimum safe manning:	13

2.3 Voyage particulars

Port of departure:	Felixstowe, UK
Port of call:	Hamburg, DE
Type of voyage:	Merchant shipping/international
Cargo information:	Containers
Crew:	25
Draught at time of accident:	$D_f = 11.5$ m, $D_a = 11.8$ m
Pilot on board:	Yes
Number of passengers:	None

2.4 Marine casualty information

Type of marine casualty:	Serious marine casualty (SMC); fire in the main engine scavenge air duct
Date, time[3]:	29 July 2020, 0707
Location:	Approach to the River Elbe, Elbe Approach traffic separation scheme
Latitude/Longitude:	φ = 53° 59.3' N, λ = 008° 09.6'E
Voyage segment:	Pilotage waters
Place on board:	Main engine, scavenge air duct
Human factors:	No
Consequences:	– About ten hours of repair work, initially directly east of the Elbe Approach traffic separation scheme, later just west of Outer Elbe anchorage – Neither physical injuries nor environmental damage – No lasting damage to the engine

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[3] All times shown in this report are local = Central European Summer Time CEST = UTC + 2 h (local time at the scene of the accident).

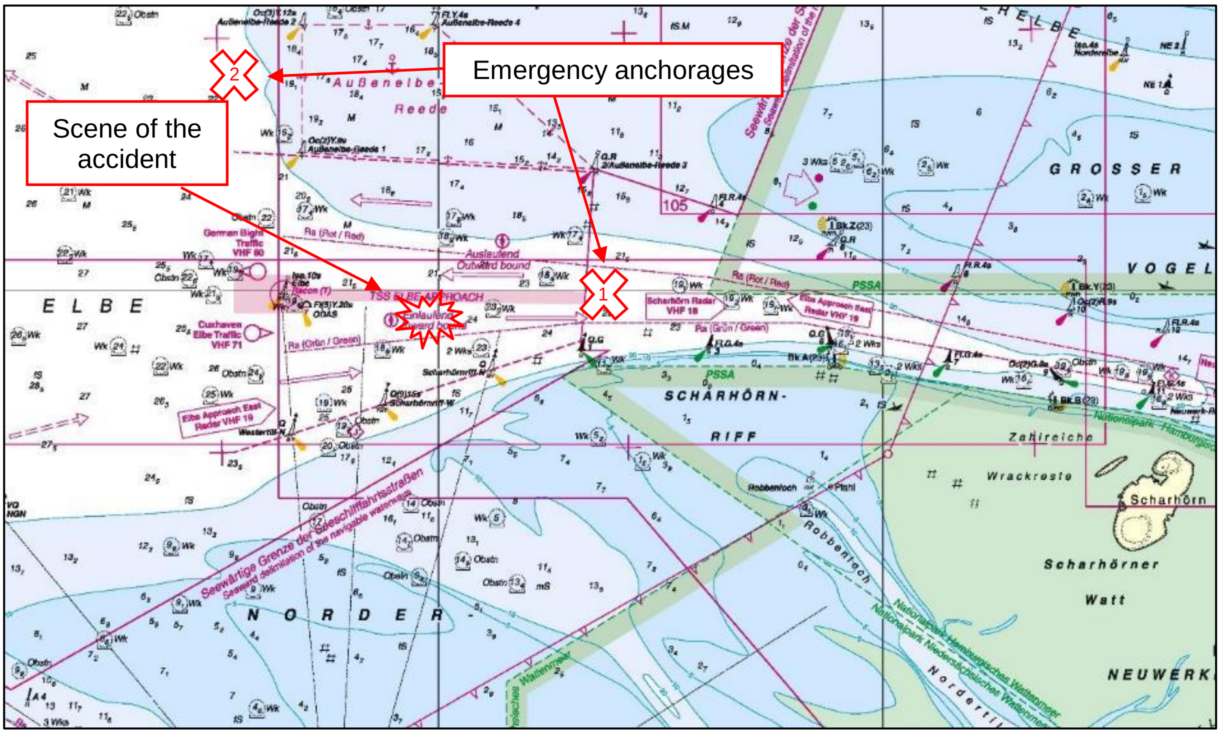

Figure 2: Scene of the accident and emergency anchorages[4]

2.5 Shore authority involvement and emergency response

Agencies involved:	– VTS Cuxhaven – Pilot on board for ship/shore communication
Resources used (external):	– Multi-purpose vessel NEUWERK on standby – Radar pilot for traffic control
Actions taken:	– Emergency anchoring manoeuvre in the Elbe fairway – Fire extinguished with permanently installed shipboard fire-extinguishing system – Repairs carried out on three ICUs[5] – Trial run in the German Bight – Extensive servicing work at the berth in Hamburg (scavenge air duct cleaned, other ICUs overhauled or replaced as a precaution; inspection of engine and scavenge air duct by an external service employee of the engine manufacturer)

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[4] Source: 'Mündungen der Jade, Weser und Elbe' navigational chart, BSH Chart 49 (INT 1463) (extract).

[5] ICU: Injection control unit, controls the cylinder injection in a common-rail engine. See also Chapter 3.2.4.3.

3 COURSE OF THE ACCIDENT AND INVESTIGATION

3.1 Course of the accident

3.1.1 Accident

On 29 July 2020, the EBBA MAERSK was en route from Felixstowe (UK) to Hamburg (Germany).

The ship uses open-loop scrubbers[6] on the high seas and has to change to a low-sulphur fuel for voyages in a SECA[7]. The amount of *heavy* low-sulphur fuel oil (ULSFO)[8] on board that day was not sufficient for the voyage segment up the River Elbe to the pier in Hamburg. The chief engineer had just joined the ship in Felixstowe and had not found the necessary quantities on board. Accordingly, the main engine was changed to a *light* low-sulphur fuel oil (LSMGO)[9], which was available in sufficient quantity.

When changing from heavy to light fuel, the entire machinery is brought to a significantly lower temperature (so that the viscosity[10] of the light fuel in the system is the same as that of the heavy fuel beforehand). While the engine is still at the right temperature for the heavy fuel, the viscosity of the light fuel would be far too low for a brief period. For this reason, the changeover takes place over a defined period in which the temperature is slowly reduced and an increasing percentage of light fuel is added to the heavy fuel at the same time, in order to always achieve the theoretical 'correct' viscosity for the prevailing component temperature. On the day of the accident, the changeover started at about 0150 in accordance with the company’s relevant procedural instructions[11] and a control unit that automatically adjusts the blending and cooling rate during the changeover process.

The main engine had not been run on a light fuel for several months. Normally, a low-sulphur heavy fuel oil had been used in order to speed up the changeover process, as these two kinds of fuel operate at the same temperature.

Shortly before the changeover process was completed at around 0415, increased liner temperatures were detected on two cylinders at 0327 (according to the alarm event log). Cylinder 10 was 'disengaged'[12] at about 0500, after it had also reported an increased cooling water temperature at about 0445 and an increased exhaust gas

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[6] For scrubbers, see Chapter 3.2.1.33.2.1.3.

[7] So-called 'sulphur emission control areas' according to MARPOL Annex VI, see also Chapter 3.2.1.1.

[8] 'Ultra-low-sulphur heavy fuel oil', ULSFO, see also Chapter 3.2.2.

[9] 'Low-sulphur marine gas oil', LSMGO, see also Chapter 3.2.2.

[10] Viscosity: a measure of a fluid’s thickness or its resistance to objects passing through it, changes with its temperature.

[11] Description of the procedure and rules for the performance of a task on board. Part of the ISM system (international safety management system, denotes measures for the documentation and organisation of safe ship operation).

[12] In the case of these modern engines, 'disengaging' means that the ICU is switched off in the engine's electronic monitoring system and no longer actuated (see Chapter 3.2.4.3). In contrast to the original meaning of 'disengaging' a cylinder, the piston continues to move up and down, i.e. it continues to compress up to ignition pressure but without injection.

temperature at 0455. The other, cylinder 5, was not disengaged during the course of the voyage.

An increased liner temperature manifests itself via the so-called ‘friction alarm’ (alarm indicating elevated friction between piston and liner, which can lead to dangerous damage and is triggered by temperature sensors). This can occur when using fuels with a high cat-fine content[13], for example, i.e. in the case of unwanted mechanical friction. The chief engineer had a sample of cylinder lubricating oil taken directly at the cylinder and had it examined straight away with a dedicated analysis device to determine whether it contained any metal abrasion. This was not the case. Accordingly, the alarm had not been caused by elevated friction, but rather by a temperature increase caused by something else.

The exhaust gas temperature of cylinder 10 started to rise again only half an hour after it had been disengaged (after initially dropping as expected), even though the ICU was not being actuated, meaning that no injection should have taken place.

Crewmembers whom the chief engineer had sent to the scene to gain an overview of the situation reported that pressure pulsations could still be felt on the forward injection line of cylinder 10, despite it being disengaged. These were described as having a high frequency – “like a machine gun.”

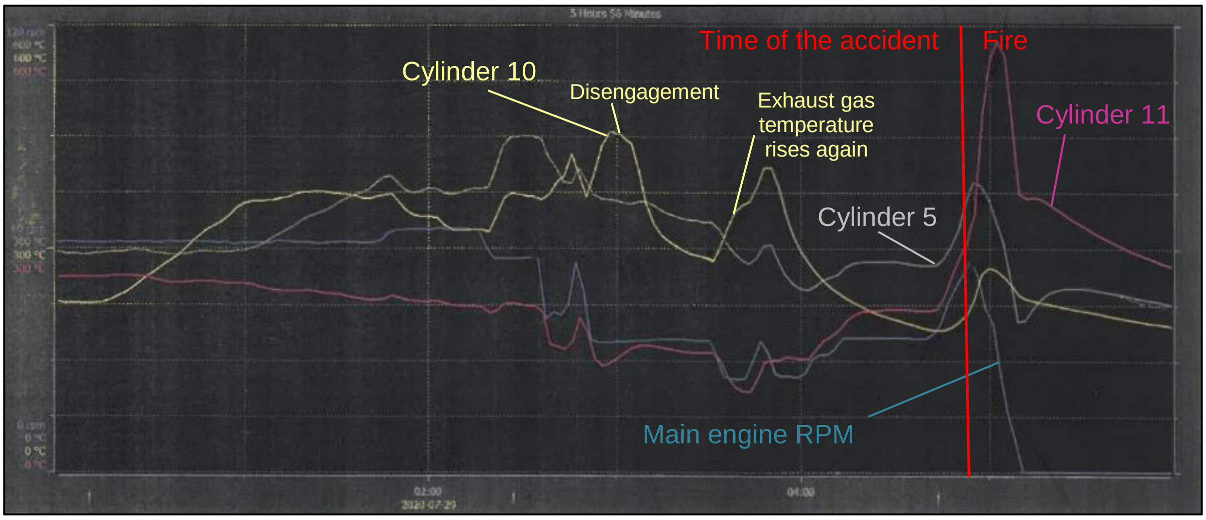

Figure 3: Development of individual exhaust gas temperatures and ME RPM[14] at between about 0200 and 0800 local time

At 0656, 'Fire in scavenge air duct' alarms sounded for cylinders 8 to 13. To verify that there was an actual fire (and not a sensor fault), the chief engineer sent a motorman[15]

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[13] 'Cat fines' are extremely small, extremely hard and sharp-edged aluminium and silicon oxide catalyst residues which originate from complex refining processes and can lead to significantly increased abrasive friction between the piston/piston rings and liner. Their presence in fuels can lead to the destruction of the entire cylinder unit (liner, piston, piston rings). Due to their size and hydrophilicity, they are difficult to separate from the heavy fuel oil.

[14] Source: Crew, WECS (Wärtsilä Engine Control System) printout. ME = main engine, RPM = rotations per minute = unit for rotational speed.

[15] Motorman: Ratings rank from the engine department.

to the engine room with an infrared thermometer, for contactless measurement of the temperature directly at the engine. He returned very quickly and reported that the paint on the scavenge air duct had turned black and was blistering. This dispelled any remaining doubts. At the same time, two of the temperature sensors in the cylinders failed completely (their displayed temperature suddenly dropped to obviously incorrect -200 °C). It later turned out that they had melted.

The chief engineer immediately communicated to the bridge that the engine needed to be shut down without delay, and that there was no time left to search for a safe anchoring position further away. At that point, the EBBA MAERSK was eastbound in the Elbe Approach traffic separation scheme (TSS) and already had a pilot on board. They anchored directly behind the exit of the TSS, east of its separating area, i.e. right between the traffic lanes (see also Figure 2). After the engine room had been evacuated, at the same time as the emergency was communicated to the bridge, the main engine was shut down as from 0710.

Once more with the help of Maersk's procedural instructions for such a case, the fire in the scavenge air duct was extinguished (reduction/shutdown of main engine RPM, deactivation of auxiliary blowers to minimise oxygen supply, shut-off of fuel supply, shut-off of lubricating oil supply, and 0725 activation of in-built scavenge air duct water-mist fire extinguishing system). At 0741, the pilot reported to Vessel Traffic Service Cuxhaven that the temperature in the scavenge air duct had dropped again.

A detailed inspection of the scavenge air duct, including pistons, liners, piston rings, ICUs etc., was carried out after the main engine had sufficiently cooled down. No damage to the cylinder units was found. However, the ICUs of cylinders 10 and 5 were clogged with a tar-like substance.
To enable the vessel to proceed quickly, the chief engineer planned to shut off the fuel pressure in one of the ICUs temporarily with a plug screw intended for this purpose (i.e. shut off the fuel supply and also take the ICU out of operation mechanically without having to dismount it). However, the screw's sealing surface was damaged. Accordingly, both ICUs had to be overhauled, using the last two overhaul kits on board, and then built in again. Meanwhile, the second engineer officer reworked the sealing surface of the plug screw.

Before the ship entered the River Elbe, the pilot demanded that a trial run be carried out to demonstrate that there was no longer any danger. However, the same phenomenon occurred again shortly after they weighed anchor, i.e. the exhaust gas temperature of a cylinder, this time cylinder 4, increased sharply. The ship anchored again at about 0330 on 30 July 2020 just west of the Outer Elbe anchorage.

This time the affected ICU was successfully taken out of operation, in addition to 'disengaging' it electronically, with the now refurbished plug screw.

The trial run was continued and proceeded without further incident. EBBA MAERSK entered the Elbe at about 0745 on 30 July 2020.

3.1.2 Subsequent events

A Wärtsilä service engineer came on board in Hamburg and confirmed the chief engineer's diagnosis that neither liners, pistons, nor piston rings had been damaged by the fire (see also Chapter 3.1.4). Apart from the clogged ICUs and slight traces of rust from the water-mist fire-extinguishing system, the melted temperature sensors were the only damage suffered. The classification society ABS was also present during the inspection and came to the same conclusion.

The shipping company's superintendent responsible for the ship sent several overhaul kits and a complete new ICU on board the EBBA MAERSK so as to be prepared for further incidents. ICU 4 was overhauled and reinstalled.

Fuel samples were taken immediately, and a comprehensive fuel analysis was ordered for the next port (Antwerp in Belgium). This included compatibility tests between the various fuels (see also Chapters 3.2.2.2 and 3.2.5.3).

The EBBA MAERSK was allowed to continue her voyage after the classification society and the Ship Safety Division (BG Verkehr) were satisfied that there was no permanent damage and the faulty ICUs had been replaced or overhauled. A similar incident did not reoccur on the ship.

3.1.3 Damage pattern

The traces of fire in and on the main engine were still clearly visible during the BSU inspection on 30 July 2020.

Figure 4: Stuffing box area of an affected cylinder[16]
with traces of rust from the extinguishing water

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[16] Source of Figure 4 to Figure 7: Crew.

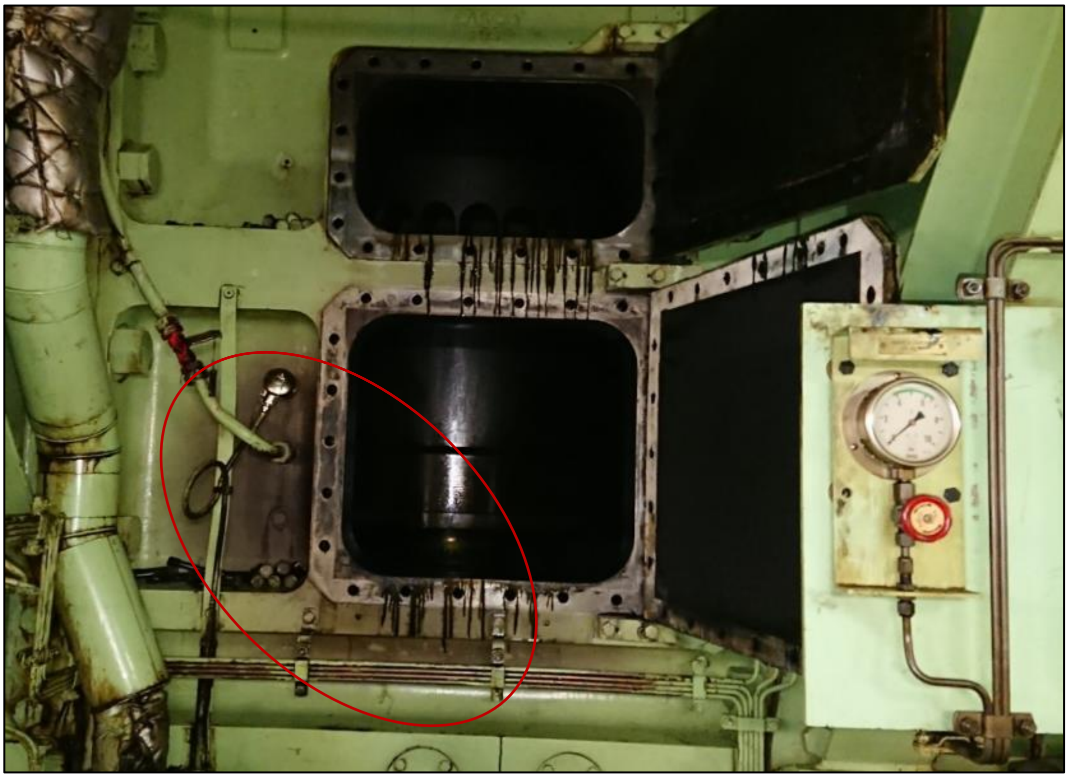

Figure 5: Paint on the main engine discoloured by high temperatures
next to the scavenge air duct inspection hatch of a cylinder affected by the fire

Cylinder 4's ICU was being overhauled on board and could be inspected in a disassembled state.

Figure 6: Removed and disassembled ICU
with the three injection control valves (left) and the fuel quantity piston (in hand)

The 'neutral spaces' between the 'rail valves' and the injection control valves were significantly clogged with a tar-like substance.[17]

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[17] Detailed explanations in Chapter 3.2.4.3. See also Figure 28.

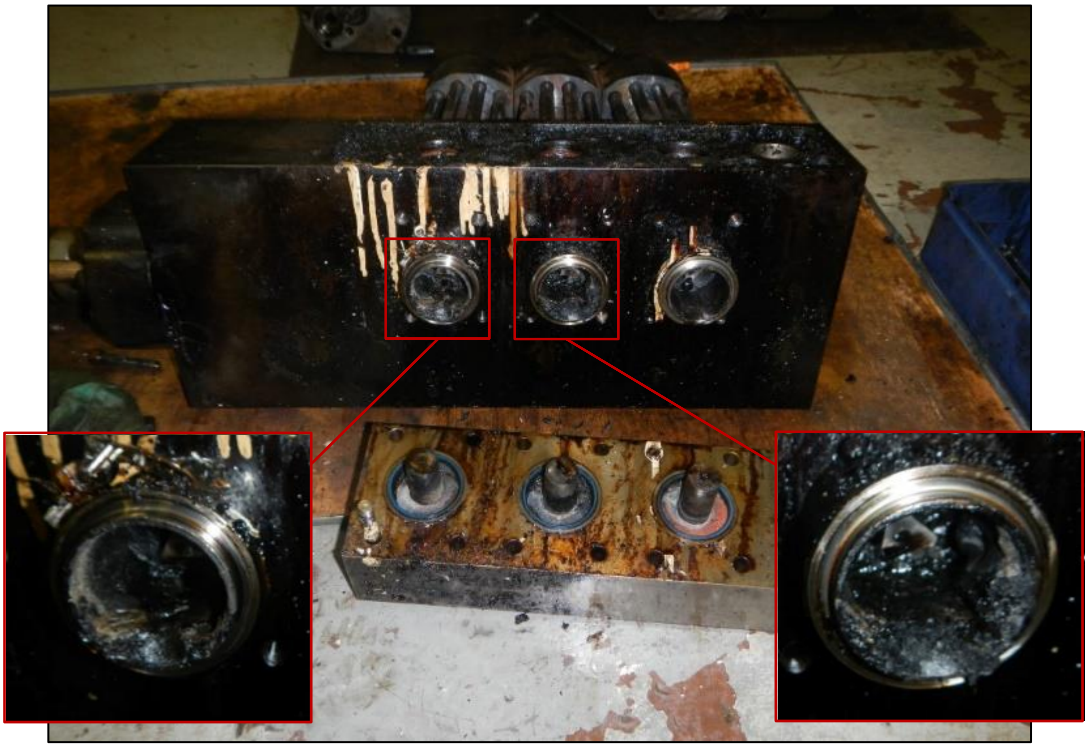

Figure 7: 'Neutral spaces' of an ICU clogged with a tar-like substance

The crew had a so-called technical bulletin[18] (Technical Bulletin RT-137) from Wärtsilä at its disposal as a guide for overhauling the ICUs as well as detailed repair instructions that were enclosed with the repair kits.

The BSU investigators also had samples taken of the two fuels involved in the fuel changeover (HFO and LSMGO), as well as from the low-sulphur heavy fuel oil (ULSFO) to which the ship had previously switched inside SECAs, for subsequent analyses. The chief engineer later sent them a sample of the tar-like substance with which parts of the ICUs had been clogged.

3.1.4 Wärtsilä service report

On 30 July 2020, a Wärtsilä service engineer came on board and inspected the main engine. A detailed inspection of the affected pistons, piston rings, liners, as well as the removed ICUs was carried out and documented with photos.

The engineer concluded that the ICU of the affected cylinder 10 must have continued to cause uncontrolled fuel injections even after it had been disengaged. This must have led to an accumulation of gas oil on the piston, which then must have spread with the piston movement and ultimately entered the scavenge air duct via the liner's scavenging ports (and thus not only onto, but also under the piston). The fuel would then have ignited over time (the engine was at operating temperature and, most importantly, the cylinder continued compressing).

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[18] 'Technical bulletin', also referred to as 'service bulletin': Document issued by an engine manufacturer such as Wärtsilä to its customers, providing details of technical modifications and/or updated procedural instructions.

As already established by the crew, Wärtsilä agreed that none of the cylinder units had sustained permanent damage. The only irregularity found were traces of cold corrosion on the liner of cylinder 1, which were however not directly related to the fire.

3.1.5 Recordings

3.1.5.1 Track

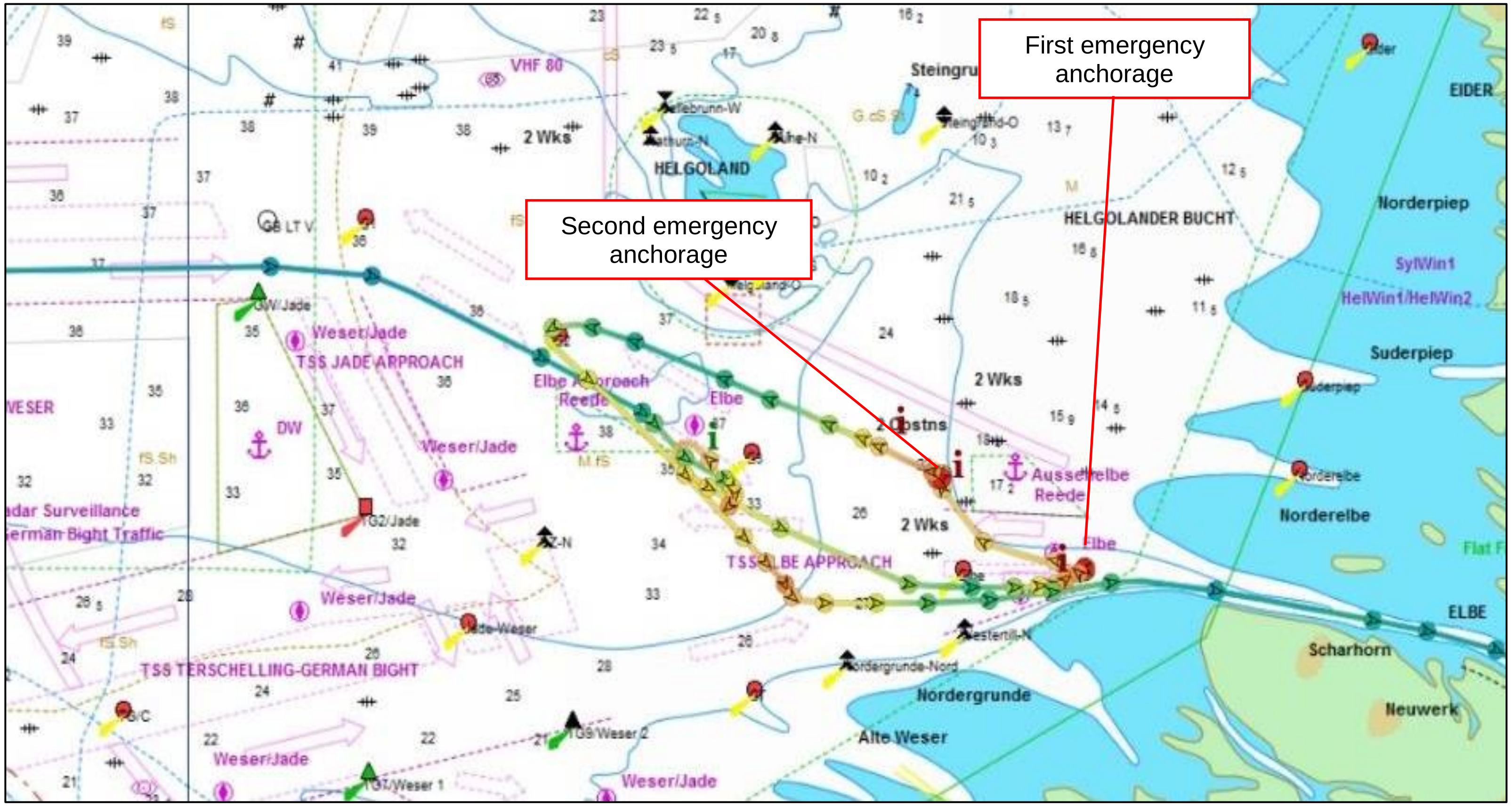

Figure 8: Track of the EBBA MAERSK, accident, emergency anchorages, trial run[19]

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[19] Source of Figure 8 and Figure 9: MarineTraffic (retrieved in 2020).

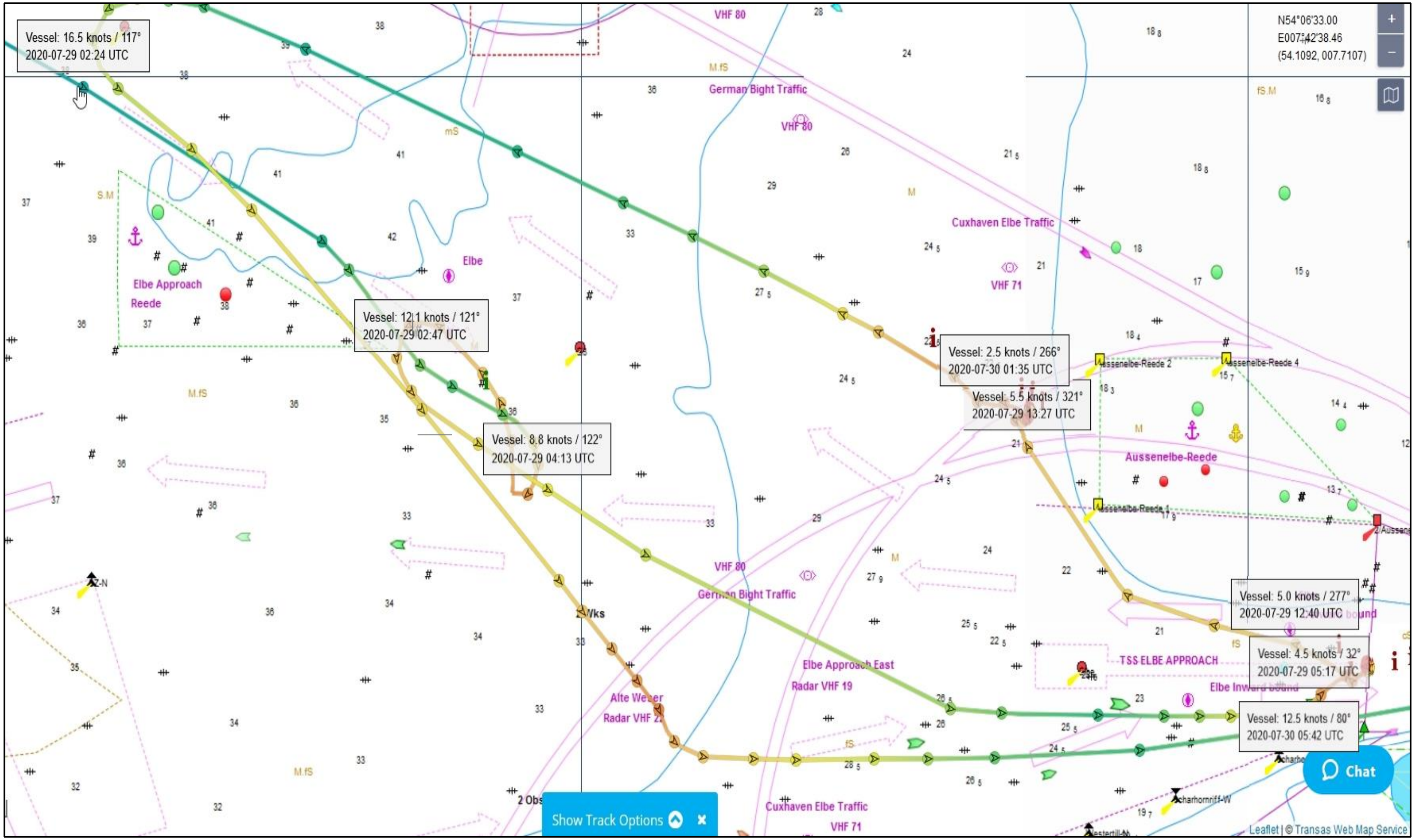

Figure 9: Track of the EBBA MAERSK, detail with timestamps (UTC)

3.1.5.2 Alarm recorder

The chief engineer's account of the course of the accident could be confirmed by the WECS (Wärtsilä Engine Control System) alarm recorder (available to the BSU for the time period covering the accident events). Some examples:

Firstly, a number of alarms indicate the fuel changeover (temperature change in the fuel changeover control unit, temperature change of the fuel entering the engine, etc.). The increased liner and cylinder cooling water temperatures show up in the described order, as do the scavenge air duct fire alarms for the individual cylinders.

The extinguishing operation is evident for the first time at 0725 from an alarm due to falling charge air pressure (the auxiliary blowers were switched off) and from several alarms that accompany the manual (i.e. fastest possible) shutdown of the main engine. Later on, an alarm for water in the engine room bilge indicates the draining of the extinguishing water (which could not remain in the engine, of course).

At 0728, the operation (probably the preparation) of the anchor windlass shows up for the first time, almost half an hour later the operation of the two thrusters, with which the anchor manoeuvre was evidently supported or completed.

At 0810, the activation of the main engine turning gear is the first indication of the scavenge air duct inspection.

3.2 Investigation

Two aspects played a role in the BSU's decision to investigate this accident. Firstly, the question was to be investigated whether the changes in heavy marine fuels since 2015 (see introductory chapters below) pose a risk of accident or fire in specific configurations, and if so, which risks exactly. Secondly, the consequences of the accident could have been far more severe. If the fire in the scavenge air duct had not been extinguished so quickly, it may have heated the crankcase lubricating oil in such a way that a crankcase explosion could have occurred as a worst-case scenario. The accident would then have caused far greater damage, possibly costing lives.

The BSU's investigation activities and their evaluation took place against the backdrop of specific basic legal and marine engineering facts and principles. The below description of the investigation activities is preceded by an outline of these basic principles in order to facilitate a better understanding.

3.2.1 Background: Limitation of sulphur in ship exhaust gases

The fire in EBBA MAERSK's scavenge air duct occurred during a period in which exhaust gas regulations were continuously being tightened (see Chapter 3.2.1.1 below) and had been tightened again in 2020.

3.2.1.1 MARPOL Annex VI[20]

The website of the German Federal Maritime and Hydrographic Agency briefly describes Annex VI to the MARPOL Convention in the following manner: *The International Convention for the Prevention of Pollution from Ships (MARPOL Convention) of 2 November 1973 is a convention designed to protect the marine environment. [...] Annex VI (entered into effect on 19 May 2005) is designed to prevent air pollution by seagoing vessels. Among other things, this Annex laid down emission limits for nitrogen oxides and sulphur oxides.*[21]

The MARPOL Convention was drawn up by the Member States of the International Maritime Organization (IMO) and is regularly amended and supplemented by the IMO's Marine Environment Protection Committee (MEPC), the Conference of the Parties to MARPOL.[22]

Among other things, Regulation 14 of Annex VI to the Convention defines the term 'ECA' (emission control area). These are sea areas designated as special zones in which specific environmental guidelines apply for emissions, e.g. from exhaust gases. ECAs in which limits are set for exhaust emissions specifically from sulphur are referred to as 'SECAs' (sulphur or SO_X emission control areas). For the purposes of the investigation, this report only deals with sulphur emissions and SECAs, as well as their practical relevance to shipping. Nitrogen oxide, sewage, noise, or other emission limitations are not considered here.

In Europe, the whole of the Baltic and North Seas including the English Channel, as well as all ports in these areas, have been SECAs since 2007. The Mediterranean Sea will also become a SECA from 1 May 2025. At the same time, the Convention also regulates sulphur emissions from ship exhaust globally (i.e. also on the high seas).[23] [24]

Figure 10 shows the progressive reduction in permitted sulphur limits in SECAs and globally since 2008. The percentages are based on the mass sulphur content in the combusted fuel. The limitation of the permitted fuel sulphur content is also referred to as 'sulphur cap'.[25] A global limit of 0.5% has been in force since 2020, in SECAs it has been 0.1% since 2015.

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[20] Source: NZ Ministry of Transport, *MARPOL Annex VI Treaty Text* (retrieved in 2022).
[21] Source: BSH, *Umwelt und Schifffahrt: MARPOL* (retrieved in 2022).
[22] Source: IMO, *Our work: Air pollution* (retrieved in 2022).
[23] Source: IMO, *Our work: Special MARPOL areas* (retrieved in 2022).
[24] Source: Täglicher Hafenbericht THB, *IMO macht Mittelmeer zur ECA-Schutzzone* (2022).
[25] Source: DNV, *Global Sulphur Cap* (retrieved in 2022).

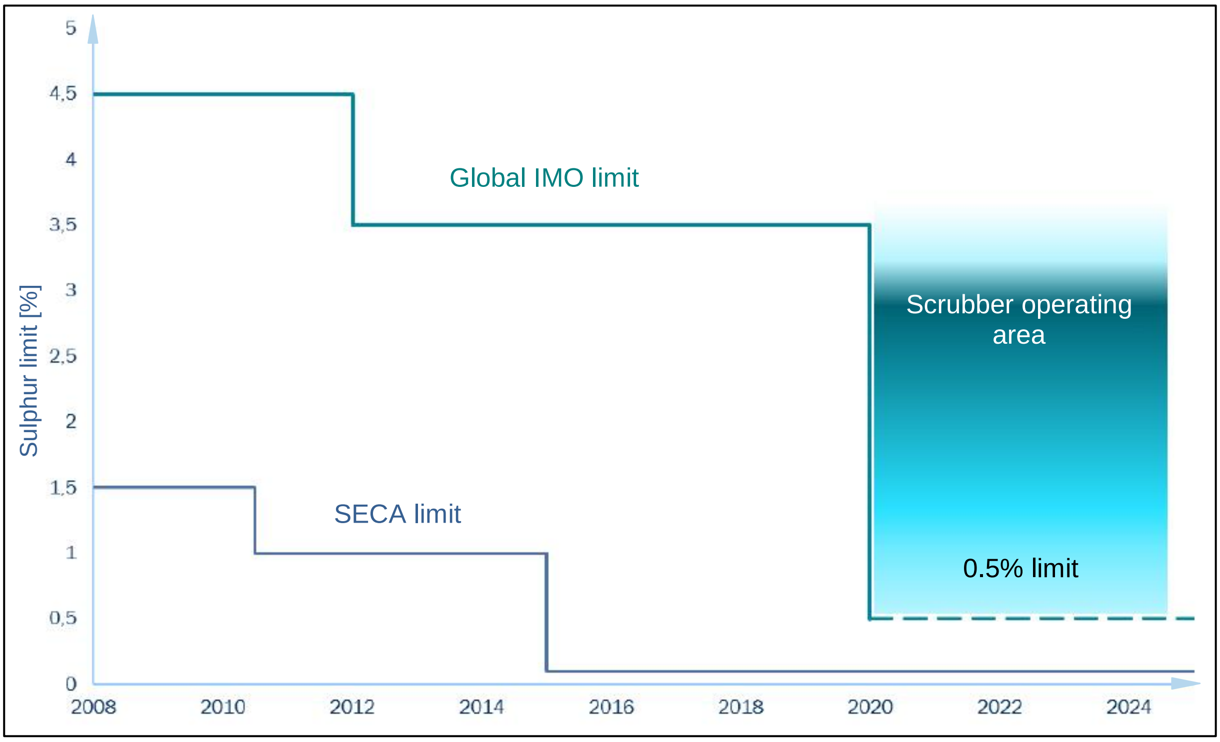

Figure 10: IMO sulphur limits[26]

The IMO estimates that these targets will result in a 77% reduction of global sulphur emissions from ships by 2025.[27]

3.2.1.2 Sulphur emissions from ship exhaust gases

Heavy fuel oils are basically refinery residues. Those parts of the crude oil that are not distilled out during the refining process remain in the heavy fuel oil. The sulphur, which is bound at a molecular level in the various types of crude oil, is one of these residual substances and is released during the combustion of heavy fuel oils (see also Chapter 3.2.2).

At the prevalent high combustion temperatures, molecular sulphur is highly reactive, initially oxidises with ambient oxygen to form sulphur dioxide, and in the next step possibly sulphur trioxide. These two substances then combine with the water vapour also contained in the exhaust gas to form sulphurous acid or sulphuric acid[28].

These water-soluble and extremely corrosive sulphur acids (as well as other acids produced during the combustion process), which enter the atmosphere with the exhaust gas, later rain back down to earth and oceans as so-called 'acid rain'. The lowering of the pH value[29] ('acidification') of soils and waters leads to a destruction of ecological balance. The growth of plants (including useful plants such as crops and

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[26] Source: *Wärtsilä Technical Bulletin RT-229: Operational Guidance to the Global Sulphur Cap 2020* (2019). Translation: BSU.

[27] Source: IMO, *Hot topics: Sulphur 2020* (2020).

[28] Source: EGCSA, *EGCSA Handbook 2012* (2012).

[29] pH value: '*Potentia hydrogenii*', Latin for 'potential of hydrogen', measure for the acidic or alkaline characteristics of an aqueous solution. The lower the figure, which ranges from 0-14, the more acidic the solution. The solution is neutral if the pH is 7 (e.g. pure water).

cereals) is disturbed or they die, nutrients are washed out of the soil and heavy metals are dissolved, marine biodiversity is reduced, buildings ashore are damaged, the oceans – which are normally slightly alkaline – lose their ability to bind acidic CO_2, and humans can suffer serious damage to their health.[30] Among other things, the provisions of Annex VI to the MARPOL Convention are designed to counteract such secondary damages.

3.2.1.3 Implementation of the sulphur emission targets

Seagoing ships have various options for complying with these targets.

1) Use of low-sulphur fuel

One option is to use low-sulphur marine fuels that are lighter than heavy fuel oil. The lighter refinery products are separated from the heavy base material during the refining process (see Chapter 3.2.2.1). Desulphurisation can be carried out at the same time. This does not always happen, but it is possible. Low-sulphur light fuels, however, are far more expensive than conventional heavy fuel oils.[31]

On the other hand, low-sulphur heavy fuel oils have been developed with which a ship operation mode is possible that does not necessitate a changeover from a heavy to a lighter fuel or vice versa every time a ship moves from one sea area to another (SECA or open sea). However, as explained in greater detail in Chapter 3.2.2.4, these are not simply desulphurised conventional heavy fuel oils, as this is technically not possible, but rather blends of heavy fuel oil, lighter low-sulphur fuels, and various other substances. These 'new' heavy fuel oils behave in a similar manner to conventional heavy fuel oils during operation and have a similar gross calorific value, but can still lead to problems that previously did not occur to this extent. They are also more expensive than conventional heavy fuel oils, but slightly cheaper than light fuels.

The increasingly common use of LNG (liquefied natural gas), which is inherently low in sulphur, is another example for the use of a low-sulphur fuel.[26]

2) Use of sulphurous fuel with subsequent desulphurisation of exhaust gas.[28] [32]

In accordance with Regulation 4.1 of Annex VI to the MARPOL Convention, contracting states (coastal states) may permit alternative emission-reduction methods, provided that their use is at least as effective as those provided for in Regulation 14. One such alternative method is the desulphurisation of the exhaust gases produced during the combustion of conventional fuels.

An exhaust gas desulphurisation system is also referred to as a ‘scrubber’. A scrubber dissolves the sulphurous components of the exhaust gas, either dry with alkaline granules or wet with seawater, which is naturally alkaline, or fresh water with an alkaline additive (both called 'wash water'). After the process, the sulphur is bound in the granules or wash water.

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[30] Source: KATALYSE Institute, *Umweltlexikon: Saurer Regen* (retrieved in 2022).
[31] Source: Energielexikon, *Schweröl* (retrieved in 2022).
[32] Source: EGCSA, *Rechtliche Vorgaben zum Umgang mit Schiffsabwasser* (retrieved in 2022).

In the simplest version, the wash water is discharged back outboard (referred to as 'scrubber water' when discharged into the corresponding body of water). Since this kind of wash water circuit is open towards outboards, this design is referred to as 'open loop'.

Some of the pollutants that are not meant to be released into the atmosphere because they would otherwise enter the oceans via the rain cycle, for example, are thus discharged directly into the oceans. Due to this open contradiction and the considerable pollution caused by scrubber water, which has been proven in a Swedish study, a blanket ban of open-loop scrubbers is being considered by Sweden, for example.[33] Germany, Singapore and China had already prohibited the use of open-loop scrubbers in their port and inland waters before 2020.[34] Nevertheless, of the 2,696 DNV GL[35]-certified scrubber systems that were ordered and already deployed in 2019, 2,130 (i.e. 79%) were open-loop systems.[34]

A scrubber system with a closed wash water circuit, accordingly referred to as 'closed loop', must be installed if the wash water is not meant to go outboard after the exhaust gas cleaning process. In this case, the wash water is collected in a holding tank and discharged ashore.

There are also hybrid scrubber systems which can be operated in both open and closed-loop mode. They contain all the system components needed for both modes of operation, which can be added or shut off as needed.

Figure 11: Simplified visualisations of the various types of scrubber[36]

At the time of the accident, the EBBA MAERSK was sailing with conventional, sulphurous heavy fuel oil and an open-loop scrubber system on the high seas, and with low-sulphur heavy fuel oil in territorial waters, if open-loop scrubbers were prohibited. In July 2020, the use of the scrubber was permitted in the previous seaport of Felixstowe, but not in German coastal waters. Since low-sulphur heavy fuel oil was not available on board in sufficient quantities, the systems had to be changed to light low-sulphur gas oil (see also Chapter 3.1.1).

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[33] Source: Chalmers University of Technology (Sweden), *Research reveals large emissions from ship scrubbers*. Study on the harmful effects of discharged scrubber water (retrieved in 2022).

[34] Source: Täglicher Hafenbericht THB, *Scrubber mit Fragezeichen* (2019).

[35] DNV GL: Classification society established in 2013 after the merger of Norway's Det Norske Veritas and Germany's Germanischer Lloyd, which has operated only under the name DNV since 1 March 2021. Source: DNV, *Namensänderung: DNV GL wird DNV* (retrieved in 2022).

[36] Source: VDL AEC Maritime, *'Why choose a scrubber?'* (retrieved in 2022).

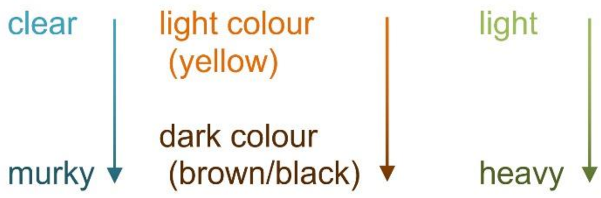
3.2.2 Background: Marine fuels[37] [38] [39] [40]

For an understanding of the properties of low-sulphur fuels in general and low-sulphur heavy fuel oils in particular, an overview of conventional fuels used on ships is provided below.

3.2.2.1 General remarks

During the refining process, the lighter components are removed from the crude oil in various processes that will not be discussed in greater detail here, such as distillation or 'catalytic cracking'. In addition to natural gas, this process produces the following light fuels, for example:

- Kerosene
- Petrol
- Diesel fuel
- Marine gas oil (MGO)
- Marine diesel oil (MDO)



The substance that remains when these light components have been extracted basically corresponds to the conventional heavy fuel oil with which large ship engines were, and still are, operated. It is essentially the waste product of the refinery process and is also referred to as 'residual marine fuel oil', 'bunker C' or 'RM' (residual marine), or as the abbreviation of its English name, HFO ('heavy fuel oil'). It is made up of liquid oil, solid suspended matter, and sediments in solution.

In addition to heavy fuel oil, the medium-heavy marine diesel oil (MDO) or the lighter marine gas oil (MGO) are also used on ships. Of the fuels listed above, marine diesel oil is the only one that is not a pure distillate marine fuel (DM), as it also contains a portion of heavy fuel oil.

The lighter the end product, the more refining steps are thus required. However, each refining step consumes energy and generates process costs, so that the general principle of 'the lighter, the more expensive' virtually always applies for fuels. Accordingly, conventional heavy fuel oil is by far the most cost-effective marine fuel because it is simply a residue.
Petroleum (or 'crude oil' in the refinery context) is found in many different variations and compositions, depending on the extraction site or type of deposit (oil well, oil sand, oil shale, or similar). In all crude oil types (‘grades’), sulphur is bound at a molecular level, in different concentrations and in complex, irregular molecules (see exemplification in Figure 12). The nature, structure, and concentration of these molecules and the total sulphur content of a crude oil are heavily dependent on the oil grade. Therefore, it is not possible to develop a uniform process for reliably extracting the molecularly bound sulphur (differently bound from grade to grade) from all types of

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[37] Source: ISO 8217:2017, *Fuel Standard for marine distillate fuels* and *Fuel Standard for marine residual fuels* (2017).

[38] Source: DIN-ISO 8217:2017, *Petroleum products – Fuels (class F) – Specifications of marine fuels* (2017).

[39] Source: Alfa Laval, *The Alfa Laval Adaptive Fuel Line BlueBook, Technical Reference Booklet – 2018 Edition* (2018).

[40] Source: Meier-Peter & Bernhardt, *Handbuch Schiffsbetriebstechnik* (2006).

crude oil. It is only possible to separate the lighter components from the base material during the refining process (see above). Accordingly, the residue, i.e. simple heavy fuel oil, is inherently sulphurous.

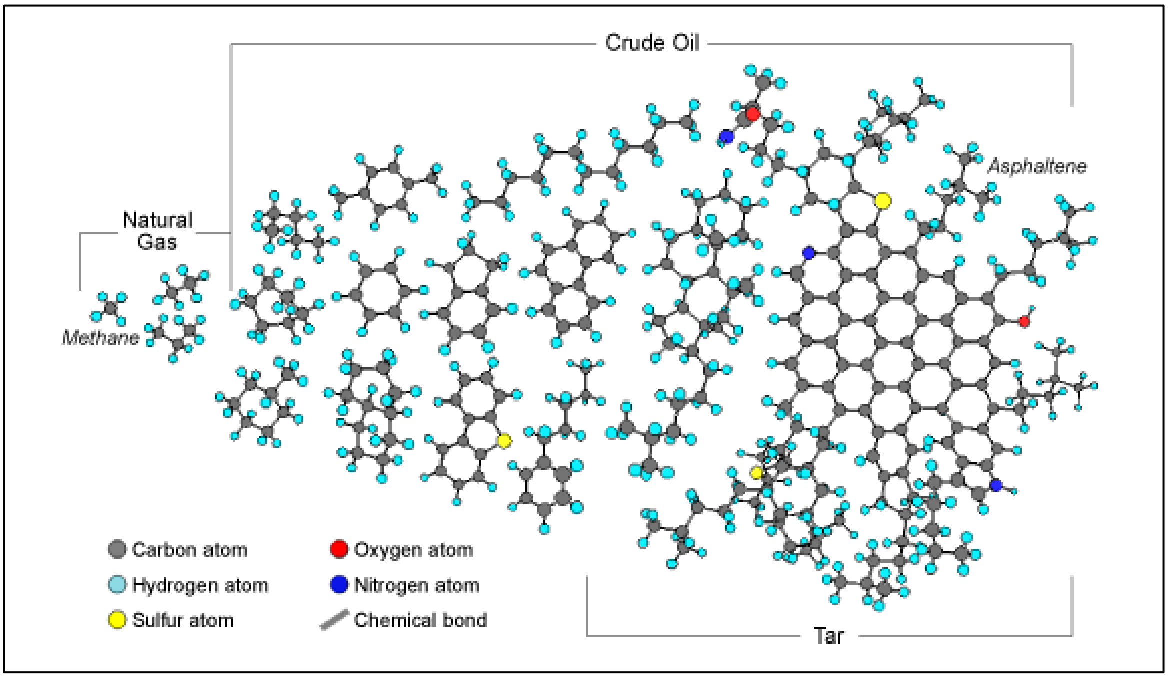

Figure 12: Structure of various petroleum molecules (exemplification)[41]
also showing isolated sulphur atoms (yellow)

Heavy fuel oil used as fuel on ships is different virtually every time it comes on board, not only because of the origin of its base material, but also because of the non-petroleum components or those originating from the refining process that it may contain. These can either be added intentionally for treatment or included for process reasons, for example. In some cases, illegally added components such as styrene or phenol (used in the production of plastics) or used engine lubricating oils are also present[42]. Components permitted in specified concentrations may include hydrogenated vegetable oils, catalyst residues from certain refining processes (so-called 'cat fines'[13]), fatty acid methyl ester (FAME[43]), ash, sediments, carbon, lubricating oil residues, sodium, or water.

Similarly, heavy fuels differ in their chemical and physical properties, such as viscosity, density, flashpoint, ignition quality, or pour point[44].

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[41] Source: United States Geological Survey USGS, *Examples of some organic compounds in petroleum* (retrieved in 2022).

[42] Source: Roslan Khasawneh (Reuters), *Contaminated marine fuels clog ship engines in Singapore hub – surveyor* (2018).

[43] FAMEs are compounds of a fatty acid and [...] methanol. [...] FAMEs produced with vegetable fats are liquid at ambient air temperature and some of their properties [...] are very close to diesel fuel (hence the name 'biodiesel'). These components are also solvents, however [...], which can lead to technical problems with sealing materials in engine systems. Source: German Wikipedia, *Fettsäuremethylester* (retrieved in 2022).

[44] The pour point is the lowest temperature at which an oil is flowable. Source: DIN EN ISO 3015:2019 (2019).

To ensure that marine fuels have a uniform quality, and in order to enable trouble-free, continuous operation of engines and boiler systems, the necessary values or limits are specified in the ISO 8217 standard. The values laid down there apply to heavy fuels (must be stored heated), which in turn are subdivided according to viscosity, as well as to distillate fuels (do not have to be stored heated).

However, even with the minimum standards of quality guaranteed by ISO 8217, a considerable amount of processing (sedimentation, purification, filtration) is still necessary on board in order to be able to combust heavy fuel oil, the refinery residue, as fuel.

3.2.2.2 Blending issues[45]

So-called 'asphaltenes' are found in all crude and heavy fuel oils. As their heaviest components, these aromatic hydrocarbons[46] make the oils viscous and given them a black or dark brown colour. In their molecular structure, they form microparticles that have a carbon core and a hydrogen outer layer (extremely simplified!) and are covered with maltene. Broadly speaking, asphaltene consists of the insoluble components of the heavy fuel oil, and resinous maltene consists of those that are soluble.

If a fuel with a high percentage of aromatic hydrocarbons is blended with one containing a high percentage of paraffinic hydrocarbons[47], with at least one of them being a heavy fuel oil, this may cause the maltene layer of the asphaltene particles to dissolve partially, leading to a polarity of these particles. When blended with a light fuel, the liquid oil phase of the heavy fuel oil is also diluted, causing its load-carrying capacity to drop.

While the asphaltene particles were previously isolated and suspended in the 'stable', i.e. homogeneous and flowable heavy fuel oil, the polarised particles now begin forming clusters. The result is that at least one of the heavy fuel oils breaks down into its lighter components on the one hand, and a thick, solid, tar-like mass, sometimes described as ‘clay-like’[48] (so-called ‘sludge’) on the other. This substance will settle in tanks and clog purifiers, filters, settling tanks, day tanks, and fuel lines. The heavy fuel oil has become 'unstable' (see Figure 13). In the worst case, this can lead to a seemingly sudden failure of the propulsion machinery.

If blending two heavy fuel oils leads to such an instability on at least one side, then this is referred to as 'incompatibility' of these two previously stable fuels. A blending ratio at equal parts (1:1) is considered the most critical, with the greatest risk of incompatibility, as is a blend between a conventional heavy fuel oil (rich in aromatics) and a light fuel oil (rich in paraffinic components).

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[45] Source: Claussen, S.: *Einführung in die Betriebsstofflehre für den Schiffsbetrieb* (2003).

[46] Aromatic hydrocarbons ('aromatics'): Double-bonded (reactive), cyclic hydrocarbons.

[47] Paraffinic hydrocarbons: Saturated (less reactive) aliphatic hydrocarbons, often in the form of very long-chain paraffin waxes.

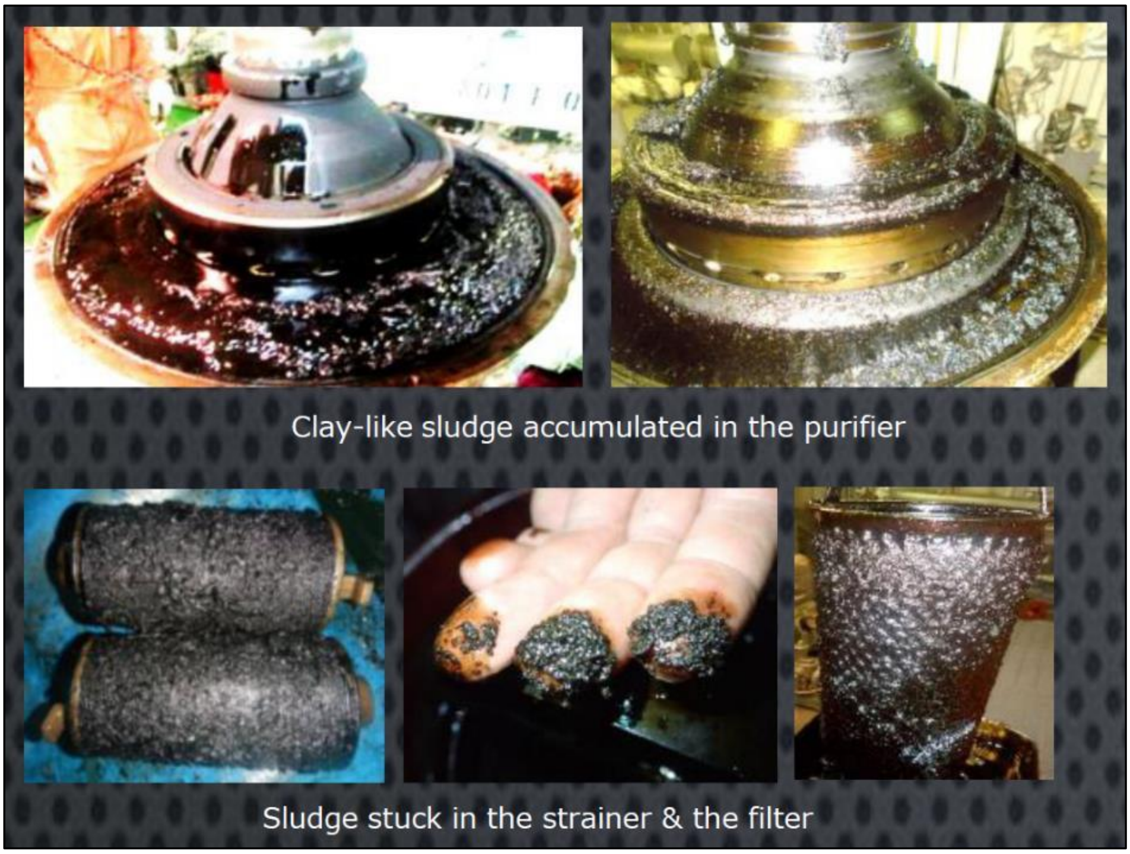

Figure 13: Oily sludge in purifiers and filters after fuel blending[48]
(precipitated asphaltenes)

It is important to ensure that two fuels come into contact with each other as little as possible when changing from a low-sulphur fuel to one containing sulphur (or back), and also generally when changing from one bunker batch[49] to another. New bunker batches, for example, are generally not added to old ones but rather filled into previously emptied tanks.

Only using equipment available on board, the so-called 'spot test' can be carried out to determine whether two heavy fuel oils bunkered at different locations, or a distillate fuel and a heavy fuel oil, are compatible with each other. This is a procedure standardised by CIMAC[50] with the official designation 'ASTM D4740'[51], in which a small quantity of each of the two fuels to be blended is mixed with the other in the planned blending ratio (e.g. to check whether incompatibilities could occur in the piping system during the changeover between two fuels). A drop of the mixture is placed on a special test paper (similar to filter or blotting paper), which is then heated to 100 °C in a special small oven. After an hour in the oven, the drop is examined for its appearance. If the fuels are compatible, a homogeneous spot has formed. If they are incompatible, an

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[48] Source: Class NK, *Issues after starting to use of* [sic] *VLSFO* (2021). Translation: BSU.

[49] 'Bunkering': The process of refuelling ships.
In this context, 'batch' refers to the amount of fuel taken on board during a single bunkering operation.

[50] CIMAC: Conseil International des Machines à Combustion (International Council on Combustion Engines). Registered international association that acts as an umbrella organisation for the large-engines industry.

[51] Source: CIMAC Guideline, *Marine fuel handling in connection to stability and compatibility* (2019).

additional inner ring has formed, which indicates a deposit of asphaltenes. ASTM D4740 distinguishes between five grades or categories, as shown in Figure 14 and Table 1:[51]

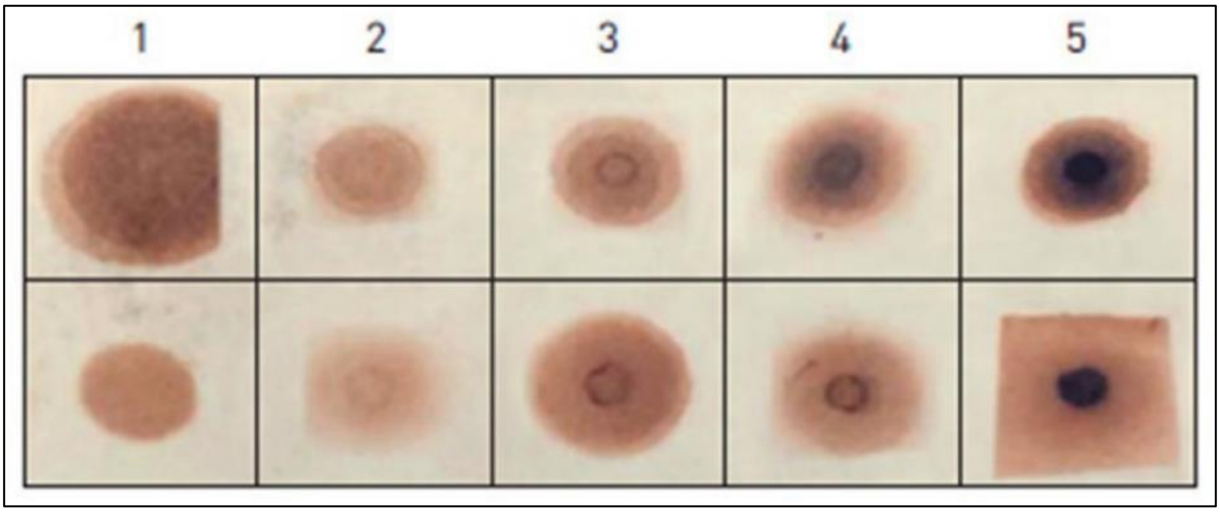

Figure 14: Five-stage evaluation of a spot test according to ASTM D4740
(always based on the blending ratio.)

Table 1: Five-stage evaluation of a spot test according to ASTM D4740

1	Homogeneous spot (no inner ring)	compatible
2	Faint or poorly defined inner ring	still compatible
3	Well-defined thin inner ring, only slightly darker than the background	avoid blending
4	Well-defined inner ring, thicker than the ring in reference spot No. 3 and somewhat darker than the background	incompatible
5	Very dark solid or nearly solid area in the centre. The central area is much darker than the background	incompatible

The stability (especially ageing stability) of a single heavy fuel oil can also be determined well with a spot test.

3.2.2.3 Fuel changeover during ship operation

In day-to-day operation (of the engine or boiler), a changeover from one fuel to another, where at least one is a heavy fuel oil, occurs regularly. Since the introduction of SECAs and the increased use of low-sulphur heavy fuel oils and/or lighter fuels, the frequency of these changeovers has significantly increased.[52] This is especially true following the introduction of the 0.1% sulphur limit value for SECAs in 2015.

The problem when switching between low-sulphur heavy fuel oils and those containing sulphur is that the latter tend to be rich in aromatic hydrocarbons, while low-sulphur

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[52] Source: Class NK, *Booklet for ship crew members: Precautions concerning change-over to 0.50 % sulphur compliant fuels*, information booklet (2019).

fuel oils are rich in paraffinic hydrocarbons (see also Table 2 on p. 33). As described in Chapter 3.2.2.2, this combination increases the probability of incompatibility when blending heavy fuel oils. Even though the possibility of two heavy fuel oils being incompatible has always existed, the probability of an incompatibility has significantly increased with the use of low-sulphur heavy fuel oils due to their composition.

When switching between a heavy fuel oil and lighter fuel, their different viscosities add to the problem. The light fuel must not be used in a hot engine (as its viscosity would then be too low) and the heavy fuel must not be used in a cold one (as the viscosity would be too high). A sudden change in temperature, however, leads to thermal stress in the components of the engine or boiler. Accordingly, the changeover must take place over an extended period, during which the operating temperature is slowly adjusted (and a temperature gradient of ± 2 K/min must not be exceeded in the process[52]). At the same time, an increasing percentage of light fuel is added to the heavy fuel oil (or vice versa) so as to theoretically always achieve the 'right' viscosity for the prevailing component temperature. When changing to a lighter fuel, it may even have to be cooled at the end to achieve the correct injection temperature. Of course, the aforementioned problems when blending two fuels must be taken into account and, ideally, a spot test carried out beforehand.

Due to the structural strain caused by the never completely avoidable thermal stress from many changeover operations (frequent expansion and contraction, possibly to varying degrees in adjacent components), fits may start leaking[53] or components may even fail completely[54]. At the same time, sulphur is a natural lubricant and its regular absence can be noticeable in increased friction, e.g. faster wear of fits and sealing surfaces.[52]

3.2.2.4 Low-sulphur heavy fuel oils

Low-sulphur heavy fuel oils and distillate fuels must also comply with the requirements of ISO 8217. It was explained in Chapter 3.2.2.1 that it is not possible to simply remove the sulphur from conventional heavy fuel oil. It follows that low-sulphur heavy fuel oils must be produced in a different manner than by simple desulphurisation of residual fuel oil. The chemical production of low-sulphur heavy fuel oils that behave like conventional heavy fuel oils within the specifications of ISO 8217 is a challenge, however.

Composition

To produce a low-sulphur heavy fuel oil in which e.g. the viscosity-temperature ratio, the calorific value, and the ignition quality remain within the required operating range stipulated in ISO 8217, a base of sulphurous heavy fuel oil is first blended with the required quantity of a low-sulphur lighter fuel that lowers the sulphur content to the

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[53] Source: Federal Bureau of Maritime Casualty Investigation, *Failure of the main engine with subsequent emergency anchor manoeuvre on the bulk carrier CAPE LEONIDAS on 17 January 2017 in the area of Kolmar on the River Elbe*, summary investigation report (2019).

[54] Source: Federal Bureau of Maritime Casualty Investigation, *Fire in the engine room of the passenger ship DEUTSCHLAND at 1230 on 23 May 2010 in the port of Eidfjord, Norway*, investigation report (2011).

desired level. Following that, the 'heavy properties' of this much lighter fuel blend are restored with various additives such as paraffin wax (extremely simplified!).

Table 2: Composition of conventional and low-sulphur heavy fuel oils[55]

Composition	HFO 3.5% S	VLSFO 0.5% S
Aromatic hydrocarbons	+/- 70%	+/- 30%
Naphthenic[56] and paraffinic hydrocarbons	+/- 30%	+/- 70%
Number of composition components	2-3	6-8 (dep. on production site)

Table 2 shows the composition of low-sulphur heavy fuel oils as compared to conventional ones in terms of the kinds of hydrocarbons they contain. Low-sulphur heavy fuel oils contain a far higher proportion of the less reactive naphthenic (saturated) hydrocarbons – and correspondingly a lower proportion of the more reactive non-saturated aromatic hydrocarbons. They also consist of more components, as described above.

Compatibility[39] [52]

This imbalance between aromatic hydrocarbons in conventional heavy fuel oils and paraffinic hydrocarbons in low-sulphur heavy fuel oils increases the likelihood of the asphaltene precipitation (instability) described in Chapter 3.2.2.2 when blended. Accordingly, low-sulphur fuels are generally less compatible with conventional heavy fuel oil than conventional heavy fuel oils are with each other. The use of low-sulphur fuels therefore carries an increased risk of the consequences of fuel instability, such as the contamination or even complete blockage of purifiers, filters, settling tanks, day tanks, and fuel lines.

In blends with low-sulphur heavy fuel oils, a faster and more sudden drop in stability over time has also been observed. This phenomenon is normal in itself and is caused by oxidative decomposition through contact with air in partly filled tanks, for example. However, a faster and, above all, sudden drop in stability can lead to sudden instability and precipitation of asphaltenes due to the temperature increase before injection, with all the aforementioned consequences, even after inconspicuously passing through the processing system (settling tanks, purifiers, filters). Additionally, the ageing stability of a low-sulphur heavy fuel oil often has a lower half-life than that of a conventional heavy fuel oil.

Cold flow properties[39] [52]

The addition of paraffin wax to low-sulphur heavy fuel oils (which is responsible for their high proportion of paraffinic hydrocarbons) to align their viscosity with that of heavy fuel oils gives rise to an entirely new set of problems. Paraffin wax starts crystallising at about 15 °C above the pour point of a fuel, giving a lighter fuel a cloudy

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[55] Source: Aderco, *Fuel Competence* (retrieved in 2022).

[56] Naphthenic hydrocarbons ('naphtenes', cycloalkanes) are saturated (= without double bonds) cyclic hydrocarbons.

appearance (i.e. well before the pour point is reached while cooling). This temperature is called the 'cloud point'. The slightly lower temperature at which a standardised filter is just permeable to this cloudy paraffinic fuel is called the 'cold filter plugging point'.

Figure 15: Filter clogged with solidified wax[57]

All these temperatures are related. They indicate the minimum temperature at which a fuel must be kept in storage tanks without wax forming. However, ISO 8217 does not require this information for residual fuels, under which the low-sulphur heavy fuel oils fall within this standard, but only for distillate fuels. The storage temperature for e.g. paraffinic heavy fuel oils can be higher than what would be sufficient for conventional heavy fuel oils to keep their viscosity above the pumpability limit (see above). Sometimes it is necessary to determine through trial and error the temperature at which a low-sulphur heavy fuel oil remains storable without wax crystallisation. Alternatively, the ship operator or a classification society can give a general recommendation on a storage temperature for these fuels, which is simply elevated by a fixed value.

Other properties

Paraffin wax also causes low-sulphur heavy fuel oils to change their viscosity in relation to temperature in a different manner to conventional heavy fuel oil. Their density is also lower. For example, a low-sulphur heavy fuel oil often has a lower viscosity at very high temperatures than a conventional heavy fuel oil at the same temperature, and it must therefore often be fed into the fuel system or injected at a lower temperature. Furthermore, increased injection pressures can occur, which may have to be adjusted via the WECS.[26]

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[57] Source: CIMAC, *Guideline 01 | 2015: Cold flow properties of marine fuels* (2015).

The purification temperature lies between these two poles (solidification point and injection temperature) and must sometimes also be determined through trial and error. “At least 15 °C above pour point” is the usual starting point.

ISO/PAS 23263[58]

In addition to ISO 8217, there is also the ISO/PAS 23263 standard, which was created specifically for low-sulphur heavy fuel oils. This standard deals more specifically with viscosity, cold flow properties, stability, ignition behaviour, cat fines content, as well as the general characteristics of these fuels. The limits of ISO 8217 remain applicable.

The standard also states that in addition to viscosity, which was sufficient for the classification of fuel quality in the past, further assessment criteria must be applied in the future (see above, different viscosity curve for low-sulphur heavy fuel oils). It is also assumed that the stability and compatibility problems of low-sulphur fuel oils will persist and become less and less predictable. That is why CIMAC recommends onshore laboratory testing in future, in addition to spot testing, for unambiguous predictions regarding the compatibility of two fuels.[51]

3.2.2.5 Lubricating oil compatibility

Due to the historically relatively high sulphur content of the combusted fuel, the associated cylinder lubricating oils are alkaline, i.e. neutralising, in order to prevent corrosion of the cylinder unit by sulphuric acid (‘cold corrosion’). This alkalinity of the lubricating oil is achieved by adding calcium hydroxide $Ca(OH)_2$ (slaked lime) and represented by its so-called 'total base number' (TBN[59]).

The aim is to 'use up' the calcium hydroxide, i.e. to convert all of it to calcium sulphate, the sulphate salt of calcium, in the neutralisation reaction. This salt is then discharged with the lubricating oil. If the calcium hydroxide is not used up, hard calcium residues can remain on the running surface between liner and piston or on the piston crown and cause abrasive damage. In addition to these residues, undesirable substances such as calcium carbonate (lime) are also produced due to the reaction with CO_2 in the exhaust gas.

Regular changeovers between fuels containing sulphur in scrubber operation on the high seas and low-sulphur fuels in territorial waters therefore mean that careful cylinder lubricating oil management is called for. In a conflict between cold corrosion due to excessively acidic heavy fuel oils and abrasive damage due to excessively alkaline lubricating oils, the right balance must be found.

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[58] Source: ISO/PAS 23263:2019, *Petroleum products – Fuels (class F) – Considerations for fuel suppliers and users regarding marine fuel quality in view of the implementation of maximum 0,50 % sulphur in 2020* (2019).

[59] The unit of the total base number is [mg KOH/g]. This means that 1 g of this lubricating oil has the same alkalinity as *[TBN]* milligrams of potassium hydroxide KOH – even if the alkalinity was not achieved with KOH but rather with $Ca(OH)_2$, for example. For marine diesel engines, the levels range from about TBN 15 to TBN 80 (lubricating oil has a maximum TBN of 100[60]). Source: Auto Motor Öl, *Gesamtbasenzahl TBN* (retrieved in 2022).

Some companies have already started to offer fully automatic total base number adjustments, ensuring a smooth changeover of lubricating oils according to the fuel in use at any given moment during operation.[60]

3.2.3 Container ship EBBA MAERSK

The EBBA MAERSK was built in 2007. She is the fifth of eight identical container ships. The series is also known as the 'E-class'[61] or 'EMMA MAERSK class'. The EMMA MAERSK was considered to be the first ULCS (ultra-large container ship)[62].

In 2016, the bridge deck of all E-class ships was raised and the lashing bridges were elevated accordingly. The ships could then carry another full tier of containers (about 1,300 TEU).[63] The figures in Chapter 2.2 refer to the increased capacity (i.e. that at the time of the accident).

Standard fuel for all engines (main and auxiliary) of the ship as well as her boiler is heavy fuel oil.

The ship was deployed in a liner service between East Asia and Europe at the time of the accident.

3.2.4 Main engine Wärtsilä 14RT-flex96C

3.2.4.1 The engine

The 14RT-flex96C is a low-speed, long-stroke[64], two-stroke diesel engine with common-rail injection control, produced by Wärtsilä.

The number '14' indicates the number of cylinders of the in-line engine. 'Flex' means that the engine has common-rail injection control (see Chapter 3.2.4.2), and '96' is its cylinder bore[65] in centimetres. The letter 'C' is part of the Wärtsilä type designations.

The engine has a stroke of 2.5 m, a height of 13.5 m, a length of 26.59 m and up to 80.08 MW rated power. This makes the 14RT-flex96C one of the most powerful and efficient internal combustion engines in the world to date. It is usually operated with four turbochargers. [66] [67]

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[60] Source: LUKOIL, *iCOlube®* (retrieved in 2022).

[61] EMMA MAERSK, ESTELLE MAERSK, ELEONORA MAERSK, EVELYN MAERSK, EBBA MAERSK, ELLY MAERSK, EDITH MAERSK, EUGEN MAERSK (in order of construction).

[62] ULCS: Large container vessel with a container carrying capacity upwards of ~10,000 TEU. Also known as a ULCV (ultra-large container vessel) or 'large container ship'.

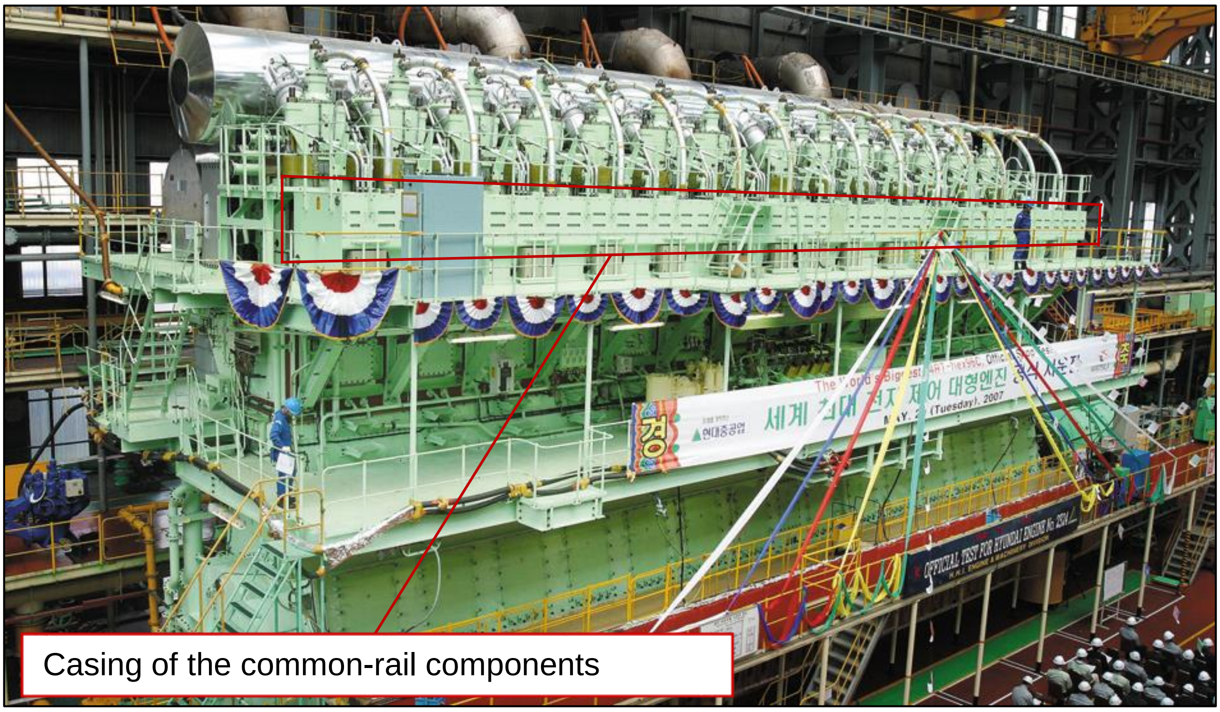
[63] Source: The Loadstar, *Maersk upgrades E-class containerships to bolster capacity* (2016).

[64] 'Long-stroke' refers to an internal combustion engine whose stroke is bigger than its bore.

[65] The 'bore' or 'cylinder bore' is the inner diameter of the cylinder liners of an internal combustion engine.

[66] Source: Wärtsilä Services Switzerland Ltd., *Wärtsilä RT-flex96C and Wärtsilä RTA96C Technology Review*, brochure (2008).

[67] Source: Wärtsilä Services Switzerland Ltd., *The world’s most powerful engine enters service* (2006).



Casing of the common-rail components

Figure 16: Hyundai Wärtsilä 14RT-flex96C (built under licence) during its test run[68]
(people for size comparison)

3.2.4.2 RT-flex common-rail injection control

During the injection cycle of a traditional internal combustion engine with camshaft, the injection period is static and unchangeable over the course of a cylinder stroke. Each cylinder has its own injection pump with pushrod, which triggers the injection process like a switch. The injection pattern is predetermined by the geometry of the cams. The same applies to the exhaust valves, which are also controlled via the camshaft, and whose opening times and periods are also rigidly predetermined by the cam geometry.

These components do not exist in a common-rail engine: no camshaft, no injection pumps, no pushrods. The injection pressure of about 700 bar is continuously applied in a *common rail*, i.e. a pipe for all cylinders which runs along the entire engine. Each cylinder’s injection is controlled by an injection control unit (ICU), also pressurised with injection pressure (see also Chapter 3.2.4.3 below). The ICUs are electronically controlled by the WECS. Fuel pressure is continuously maintained by up to eight high-pressure pumps.

The timing of the exhaust valves and the gas exchange[69] process are also controlled electronically.

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[68] Source: Hyundai Heavy Industries, *World's Most Powerful Marine Engine Runs Successful Trial,* report on the engine's test run on 29 May 2007 (2007).

[69] Charge or gas exchange means the introduction of fresh combustion air into the combustion chamber of an internal combustion engine's cylinder with simultaneous removal of the exhaust gases. In four-stroke and two-stroke engines, this is effected by the piston movement, possibly turbochargers and/or blowers increase the inlet air pressure (charge air).

A number of pipes run along the engine’s pump side (= one of its longitudinal sides), including the following:

- the described fuel line, the 'common rail' (700 bar);
- a line for control oil (lubricating oil, 200 bar), with which the exhaust valves in the cylinder head and the rail valves of the ICU are controlled (i.e. opened against a spring);
- a line for starting air (30 bar), and
- a return line for fuel.

Wärtsilä’s engine automation, control and alarm system as well as the associated secondary systems that also electronically control the injection is called 'WECS' (Wärtsilä Engine Control System).

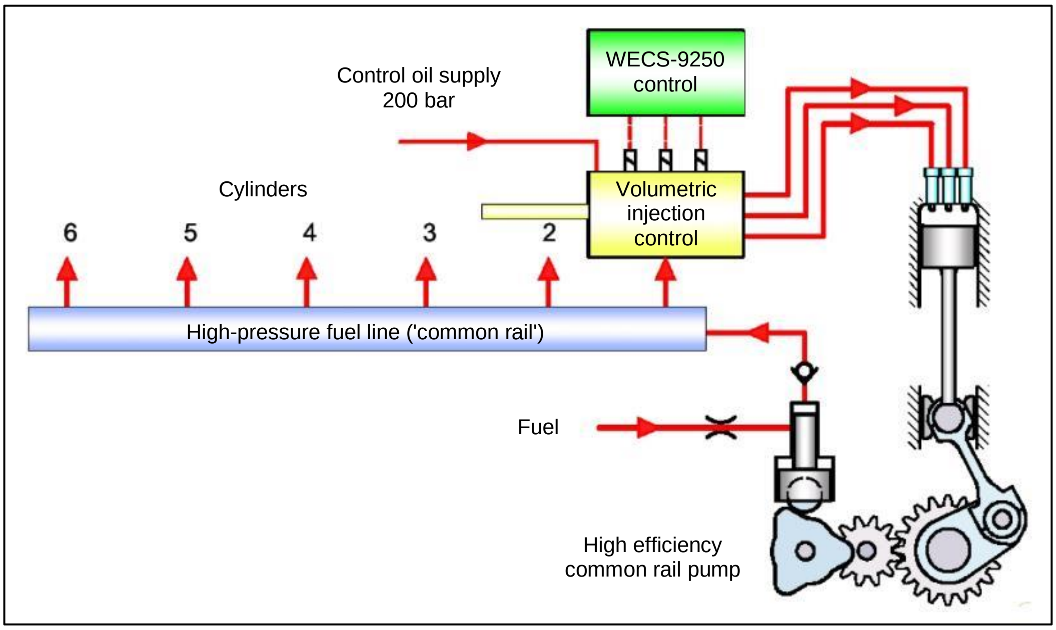

Figure 17: Schematic drawing of the common-rail principle[70]

3.2.4.3 Injection control unit ICU

Each cylinder has its own electronic ICU (the 'volumetric injection control' in Figure 17). It determines the injection profile as described in Chapter 3.2.4.2 above.

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[70] Source: Wärtsilä Sea and Land Academy, *RT-flex Control Elements* (2009).

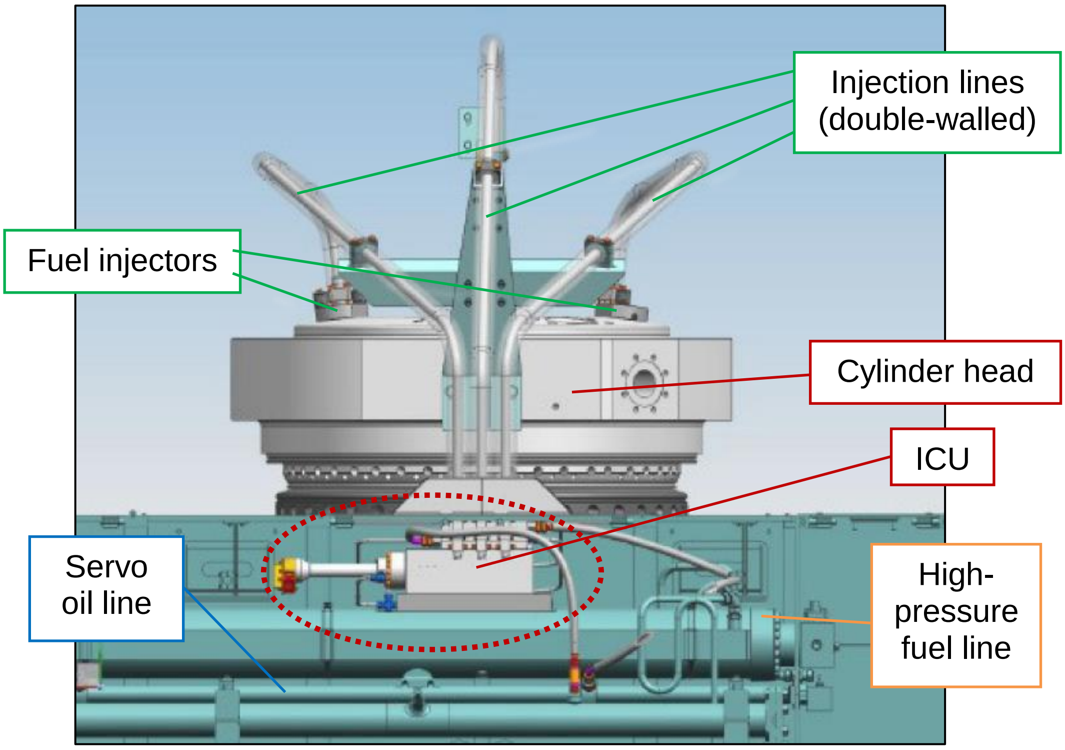

Figure 18: ICU in front of cylinder head, injection lines[71]

The following functional description is limited to the first-generation ICUs. Developed in 2003, these were in use on the EBBA MAERSK at the time of the accident. Although developments have since been made, the functionality is basically still the same.

Each ICU has one input via the high-pressure fuel line and three[72] outputs via the three injection control valves (ICV) into the injection lines. These three lines lead to the cylinder's three fuel injectors (see Figure 18). The injection control valves are activated by the so-called 'rail valves' (see Figure 19).

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[71] Source: Wärtsilä Services Switzerland Ltd., *Upgrading of Wärtsilä FuelFlex Injection Control Unit enables reliable operation with low-sulphur fuel oils,* press release (2020). Labels: BSU.

[72] Two-stage versions with two rail valves, two injection control valves per ICU, and two injectors on the cylinder are also available.

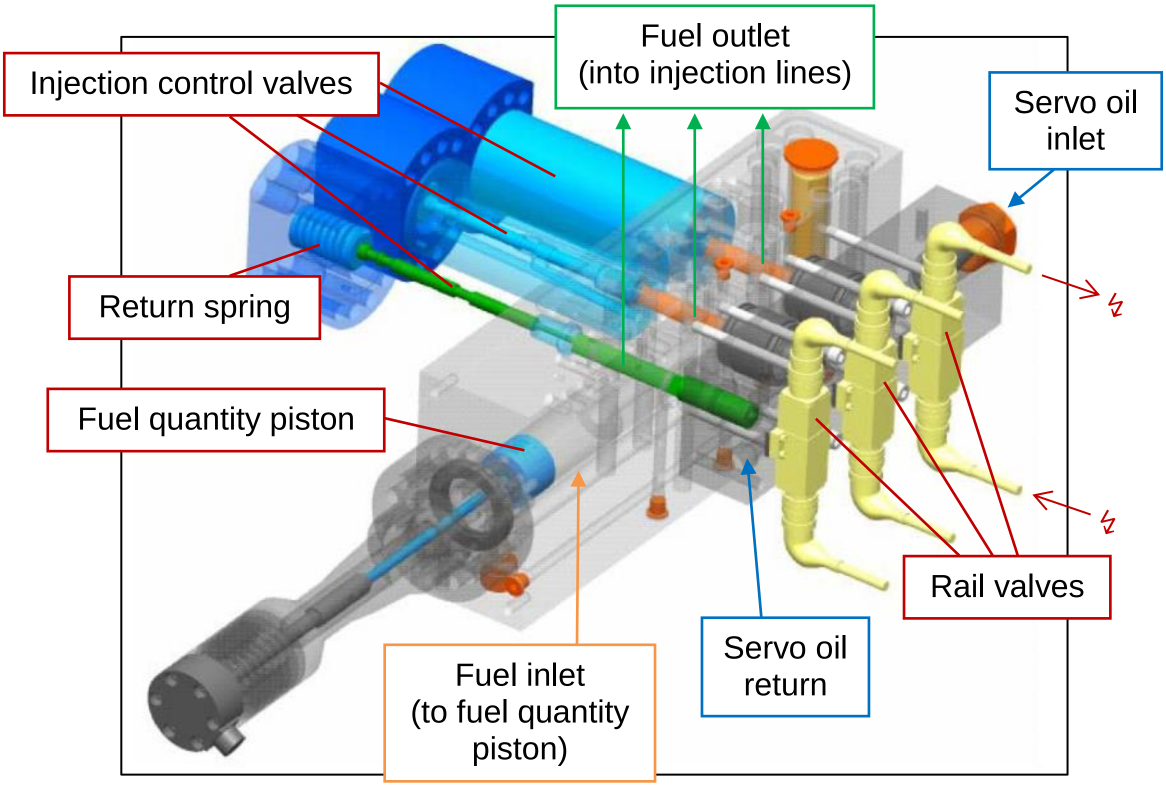

Figure 19: 3D representation of an ICU[73]

The rail valves are activated electronically via the WECS and control the flow of the control oil (blue), which in turn opens and closes the spring-loaded injection control valve hydraulically. The injection control valves receive the fuel (orange) at 700 bar from the fuel quantity piston and deliver it on (green) into the injection lines and to the fuel injectors in the cylinder. In each case, one injection control valve actuates one injector.

Basically, if a rail valve is actuated, then injection takes place via the corresponding injection valve. No injection without actuation.

The fuel quantity piston never moves to its end position during operation in order to have a reserve at all times. Full engine load corresponds to an 80% stroke of the fuel quantity piston.

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[73] Source: Wärtsilä Sea and Land Academy, *RT-flex Control Elements* (2009). Labels: BSU.

Figure 20: Photograph of an ICU[74]
(during installation; various openings still covered with yellow plastic caps.)

A more detailed description of an ICU's injection cycle is given below with the help of a hydraulic circuit diagram.

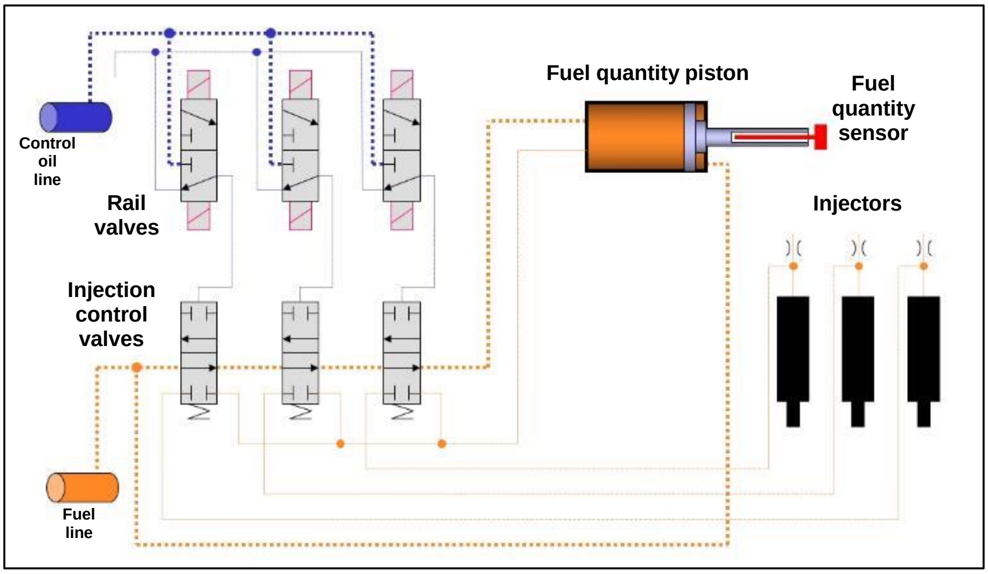

Figure 21: Operating principle of the ICU: Idle state

In their idle state, the injection control valves are open for the transverse fuel flow (orange). The fuel quantity piston is pressurised from both sides with fuel under 700 bar. Due to the piston rod on its rear side, the impact surface there is smaller, meaning that the surface pressure on the piston is greater from the front side. Thus, it is pushed to its rear end when idle, filling itself with fuel. The rail valves are also in their idle state and block the flow of control oil (blue). (Figure 21)

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[74] Source: Figure 20 to Figure 27: Wärtsilä Sea and Land Academy, *RT-flex Control Elements* (2009).

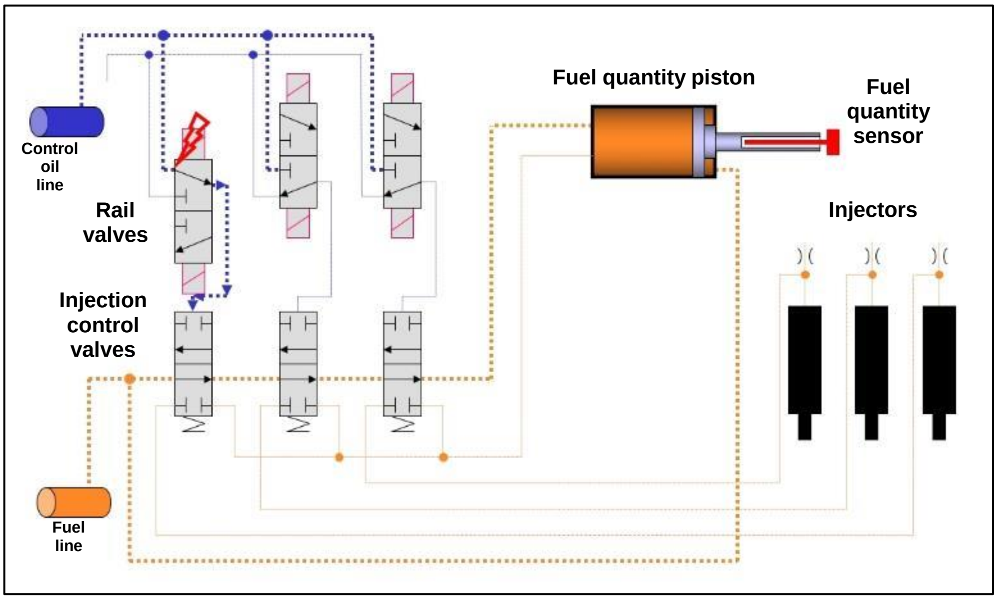

Figure 22: Operating principle of the ICU: Rail valve is activated by the WECS

A rail valve is electronically activated via the WECS. It opens the flow channel for control oil (blue), which then exerts hydraulic pressure on the corresponding injection control valve. (Figure 22)

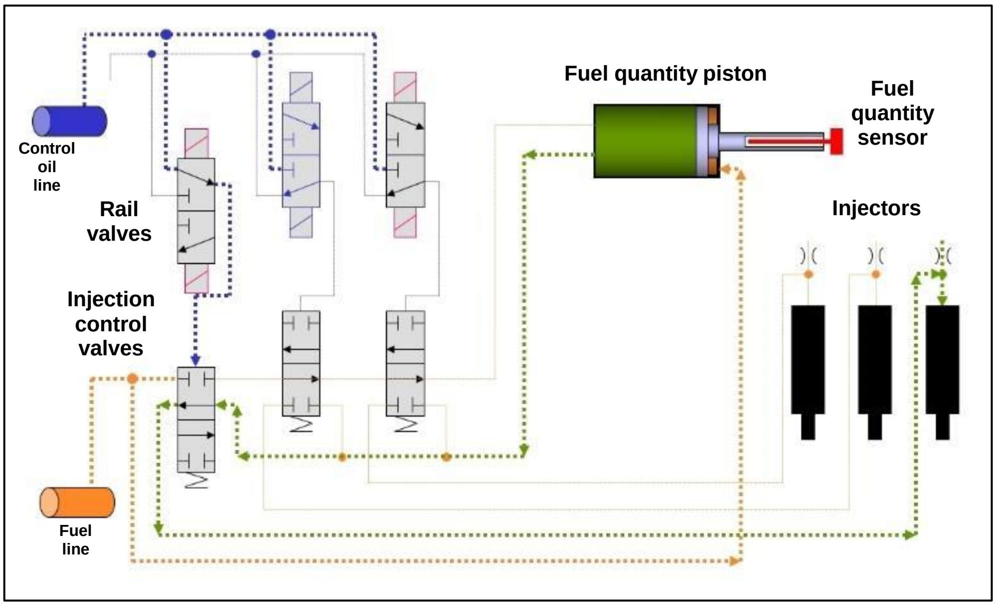

Figure 23: Operating principle of the ICU: Servo oil activates fuel quantity piston

The control oil (blue) hydraulically opens the injection control valve, i.e. pushes it into the open position against its return spring. It closes the channel through which the front side of the filled fuel quantity piston was pressurised with fuel. The rear side is always pressurised (orange). The channel between the piston and the injection line (green) is opened at the same time. (Figure 23)

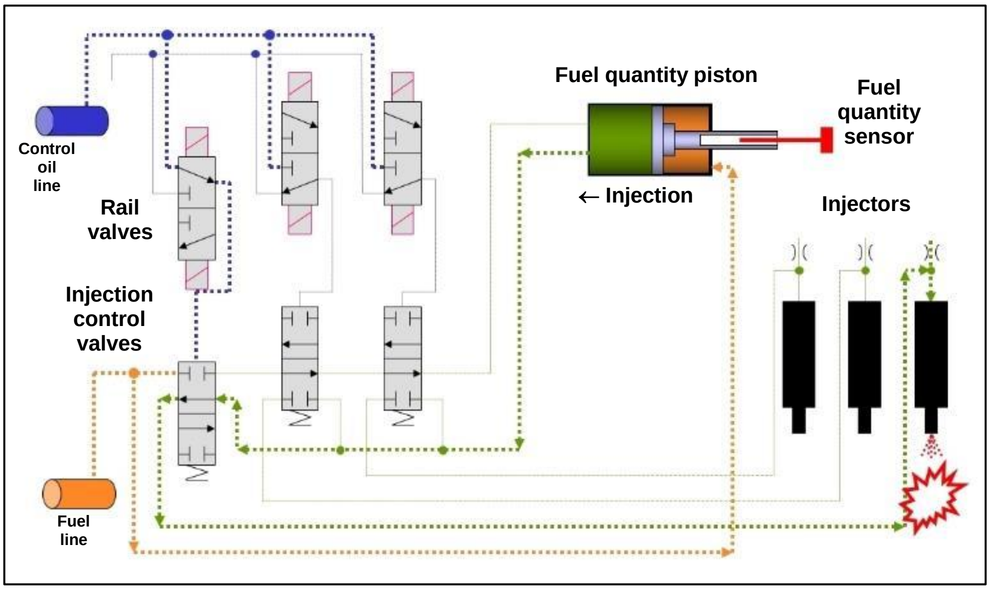

Figure 24: Operating principle of the ICU: Fuel is injected

Due to the changed pressure difference between the front and rear sides of the fuel quantity piston (now the pressure on the rear side is higher), it moves to its forward position and empties into the injection line (green). Injection occurs as soon as 700 bar is reached at the injector and the needle element opens. (Figure 24)

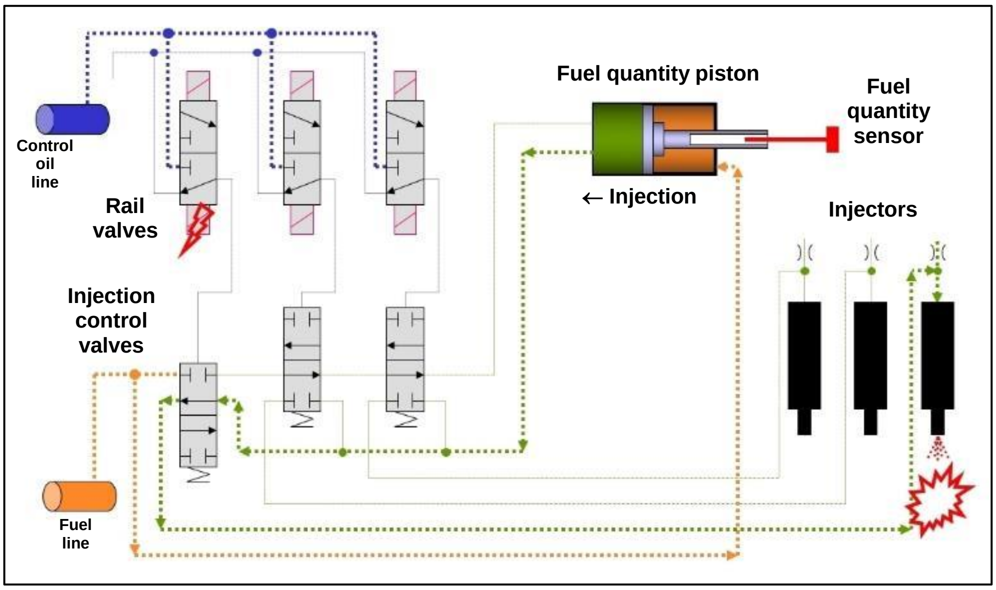

Figure 25: Operating principle of the ICU: Rail valve moves to original position

The WECS moves the rail valve back to its original position even before the injection process has finished, and it closes for control oil (blue). (Figure 25)

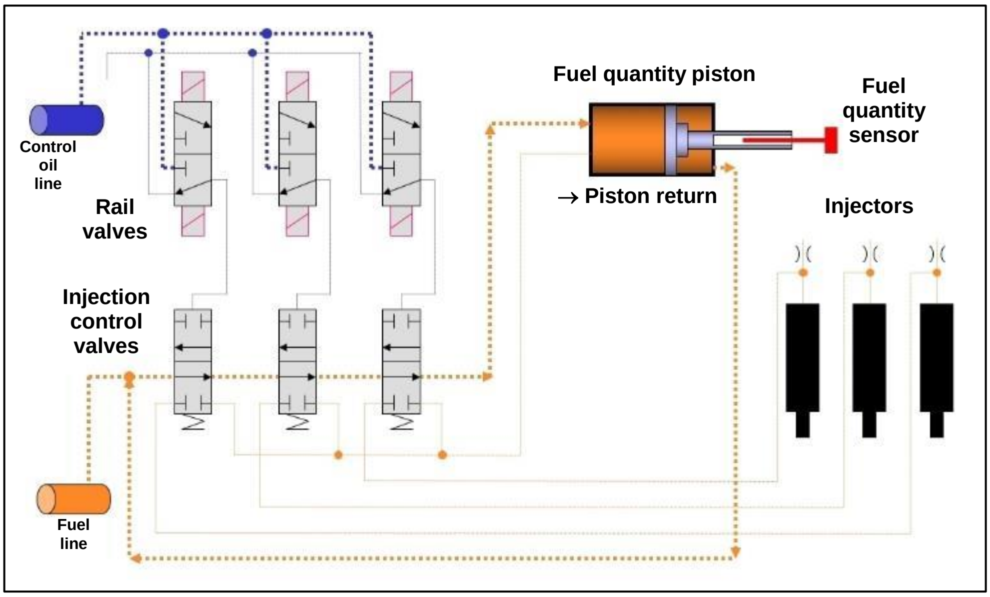

Figure 26: Operating principle of the ICU: Fuel quantity piston refills

Without the hydraulic pressure of the control oil (blue), the injection control valve is also moved back to its original position by its return spring. The channel that pressurises the front side of the fuel quantity piston with 700 bar via the transverse fuel flow (orange) is opened again. The piston moves back to its original rear position, as described above, refilling itself in the process. The fuel supply to the injector is interrupted and injection ends. (Figure 26)

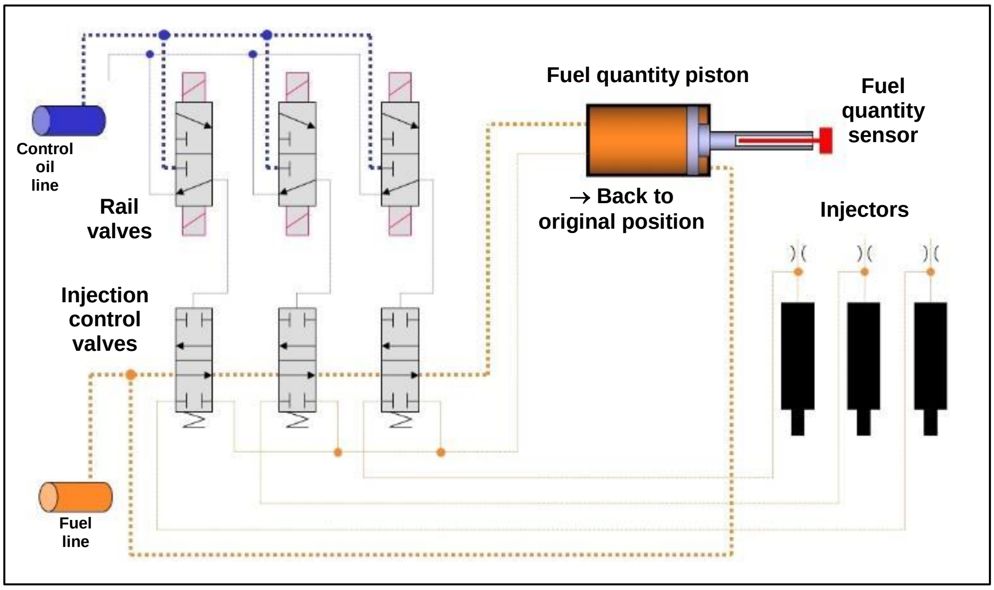

Figure 27: Operating principle of the ICU: Idle state

The ICU is now in its idle state again (Figure 27). The described process usually takes place simultaneously for all three injection valves (and all three rail valves and all three injection control valves). At partial load, only two or – as in the preceding figures – one injection valve might be activated.

The distance that the piston travels during one injection is proportional to the injected fuel volume. This is reported back to the WECS. The injection volume can be adjusted by changing the piston end position.

3.2.4.4 Leakage flows in the ICU

At extremely high pressures and/or temperatures, such as those present in the fuel injection system and the ICU, leak-tightness is achieved by precisely machined metal-to-metal fits and a minimal leakage flow of the transported fuel, hydraulic oil, or lubricant through the remaining gap (and not with rubber seals or similar). This means that the small gaps in the ICU needed for two components to move against each other are kept tight by small amounts of fuel or control oil flowing through them. This leakage rate is intentional and normal. Leaking fuel, for example, is discharged via leakage lines into a leakage tank. The tank’s level is monitored, and the fuel finally fed back into the fuel system.

Minor leakage flows in the direction of the injector, due to an injection control valve that is no longer completely tight (continuous transverse fuel flow, see above), can be discharged via a leakage line near the nozzle. However, this discharge stops working in a useful way once the fuel flow becomes too strong. At some point, the fuel will even be able to raise the injector's needle element outside the regular injection times, meaning that uncontrolled injection is possible in the combustion chamber of the affected cylinder.

According to Wärtsilä's Technical Bulletin RT-82[75], the fuel-side sealing gaps in the ICU are designed for HFO operation. In continuous MGO operation, the leakage rate at these points will increase about fivefold, and as much as tenfold for a short period during an HFO-to-MGO changeover, due to the increased component temperature that cannot be completely avoided.

Natural component wear apparently also increases the leakage rate over the years (possibly exacerbated by the lower lubricity of the low-sulphur fuels already mentioned in Chapter 3.2.2.4, which can lead to increased friction). There is something of a vicious circle at this point because the heavier the component wear, the greater the leakage rate – which in turn also increases the component wear, as a liquid flow always also means a small degree of material abrasion or erosion and can lead to such effects as cavitation[76].

A so-called 'neutral space' borders on the hydraulic impact surface of the injection control valves by the control oil. The only purpose of this space is to allow the valve to move. It is not normally filled with fluid. However, there can be a small and undesired leakage rate of control oil (i.e. lubricating oil) into the neutral space via the adjacent

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[75] Source: Wärtsilä Services Switzerland Ltd., *Technical Bulletin RT-82: Operation on distillate fuels* (2015).

[76] Cavitation is the formation of vapour bubbles in a liquid when local pressure rapidly drops below the vapour pressure of the liquid (e.g. due to a sudden local increase in flow velocity). These vapour bubbles usually only remain intact for a brief period before collapsing back into the liquid phase. A popping sound is heard during this process and high pressure and temperature peaks, capable of damaging nearby surfaces, are reached. Small craters around propeller fluke tips are a typical symptom of cavitation, for example.

sealing surfaces (Figure 28, marked in blue), which is nevertheless ‘acceptable’ under normal circumstances, according to WinGD.

Similarly, if the sealing gaps are worn (i.e. enlarged), there will be a certain amount of fuel leakage through the seats (guides) of the so-called 'valve sliders'[77] into the neutral spaces (shown in green, leakage flow 1). This is intended and desired because fuel lubricates and cools (even at the prevailing fuel temperatures). Deposits can occur when control oil is exposed to much hotter fuel here and is then thermally decomposed, especially if the drain for discharging the leakage is clogged.[78]

Another unintentional fuel leakage flow originates at the valve slider seats into the so-called 'spring space' in which the return spring is located (leakage flow 2). A further unwanted leakage flow occurs in the area of the 'transverse flow', which originates from the fuel quantity piston and flows in the direction of the injection valve (leakage flow 3, see also Figure 21 to Figure 27). This leakage is evidently 'highly dependent on viscosity', i.e. especially prevalent when using light fuels, and can reach the injection valves.[78]

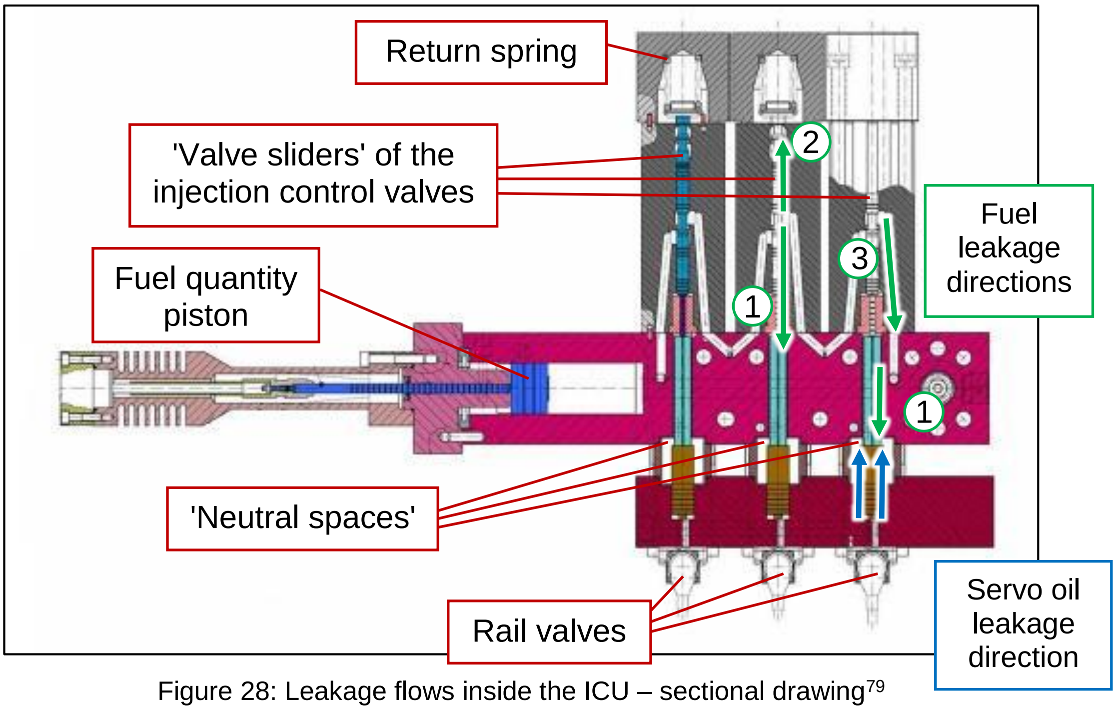

Figure 28: Leakage flows inside the ICU – sectional drawing[79]

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[77] The 'valve sliders' of the injection control valves are the vertical 'rods' in Figure 28, which the rail valves move up against the return spring, and that open or close the fuel flow openings in the process.
[78] Source: Grote, N. (WinGD), email correspondence (2020) and videoconference (2023).
[79] Source: Wärtsilä Sea and Land Academy, *RT-flex Control Elements* (image detail) (2009).

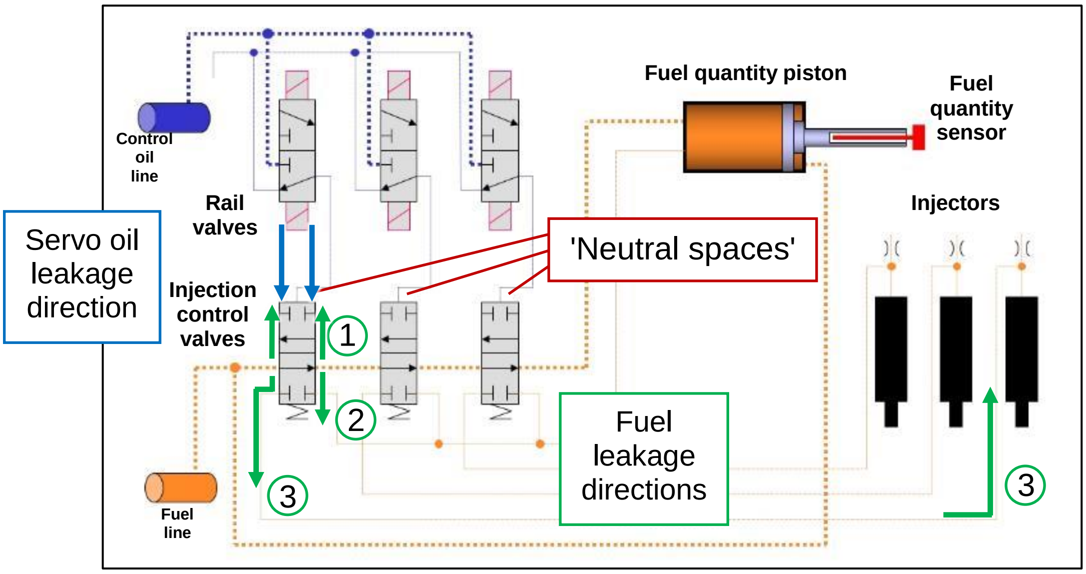

Figure 29: Leakage flows inside the ICU – hydraulic diagram

3.2.4.5 Wärtsilä Technical Bulletins

In addition to the aforementioned Technical Bulletin RT-82, Wärtsilä has supplied its customers with a number of further bulletins that address the impact of sulphur limitation in fuel on engine operation. RT-82, issued in 2015, shows that many findings were apparent before 2020. In some cases, such as with the increased leakage rate when operating on lighter fuels, these basic phenomena were known beforehand. However, when it became necessary to switch to low-sulphur, i.e. often light fuels, far more frequently due to the lowering of the SECA sulphur limit from 1% to 0.1% in 2015 (see Figure 10 on p. 24), these phenomena began to occur far more frequently.

Technical Bulletin RT-82 specifically points to the fact that ICUs can experience increased fuel leakage, and advises that the most affected units be identified and overhauled sooner than recommended, or replaced altogether if necessary.[75] For RT-flex engines with a bore of 84 or 96 cm (the latter applies to EBBA MAERSK), whose ICUs belong to the first generation produced before 2010 (also applies), Technical Bulletin RT-123 of 2016 specifies a 'lifetime' reduced by one third for these ICUs (24,000 instead of 36,000 running hours).[80]

Technical Bulletin RT-126 of 2018 states that ULSFO operation falls under the full responsibility of the operator of the machinery.[81]

Technical Bulletin RT-229, published in 2019, provides basic guidance for the operation of two-stroke large diesel engines with low-sulphur fuel oils.[82] For example, it says that the ICUs' injection control valves have been subject to more wear since 2015 due to the increase in heavy-to-light changeovers. At and above a fuel leakage

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[80] Source: Wärtsilä Services Switzerland Ltd., *Wärtsilä Technical Bulletin RT-123: Inspection and overhaul intervals* (2016).

[81] Source: Wärtsilä Services Switzerland Ltd., *Wärtsilä Technical Bulletin RT-126: Diesel Engine Fuels* (2018).

[82] Source: Wärtsilä Services Switzerland Ltd., *Wärtsilä Technical Bulletin RT-229: Operation Guidance to the Global Sulphur Cap 2020* (2019).

rate of 200 ml/min an ICU is assumed to be worn. According to the bulletin, long-term operation with light fuels can lead to prematurely worn valve seats (i.e. sealing surfaces, see above) of the injection control valves (see Figure 30), which in turn could lead to increased exhaust gas temperatures on large RT-flex models such as the RT-flex96C.

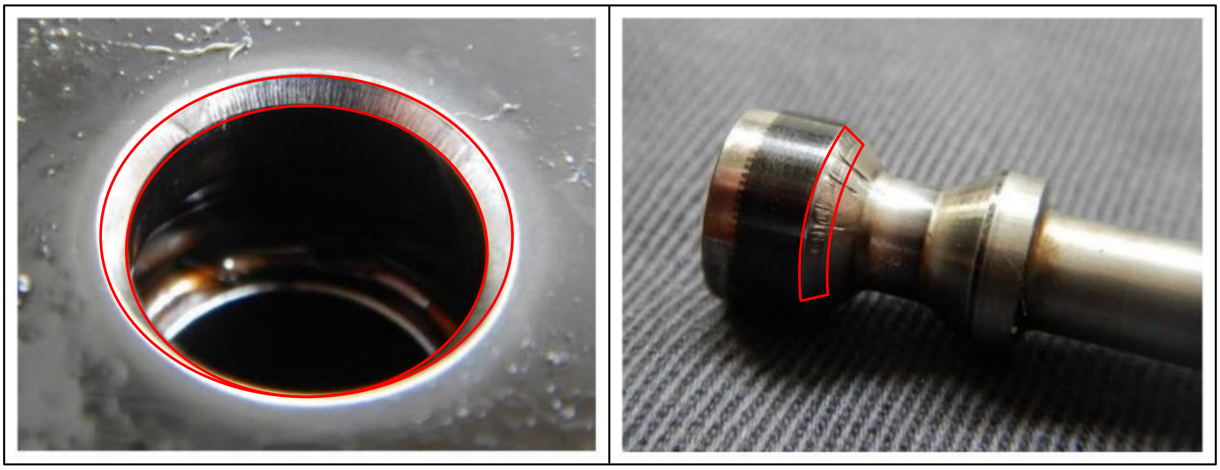


Figure 30: Traces of wear (e.g. grooves) on the valve seat and slider of an injection control valve belonging to an ICU of a RT-flex large diesel engine (sealing surfaces outlined in red)[82]

This is based on the fact that even if the affected ICU is not actuated, fuel is transported in small but steady quantities through leaking sealing surfaces towards the injector and then possibly injected there in an uncontrolled (even continuous) way (see Chapter 3.2.4.4).

This effect was apparently already known, but had only occurred sporadically, namely in ICUs used in HFO operation for periods up to the limits of the maintenance interval or beyond. Due to the increased changeover frequency to lighter fuels, this effect now occurs much more often. Accordingly, the bulletin also recommends a reduction in the maintenance interval by one third for first-generation ICUs.

Reference is also made to several retrofitting options for components of the injection system elements, including the ICU. These elements are said to be more suitable for frequent operation with lighter fuels afterwards. Proper lubricating oil management in the event of many changeovers between fuel containing sulphur and low-sulphur fuel is also referred to (as explained in Chapter 3.2.2.5).

It was noticeable that Technical Bulletins RT-82 and RT-229 only make a recommendation to reduce the ICU maintenance interval from 36,000 to 24,000 hours, while RT-123 specifically refers to an estimated ‘lifetime’ of 24,000 running hours, rather than only recommending them. This refers to first-generation ICUs (manufactured before 2010) that have not yet been remanufactured, i.e. upgraded or refurbished accordingly.

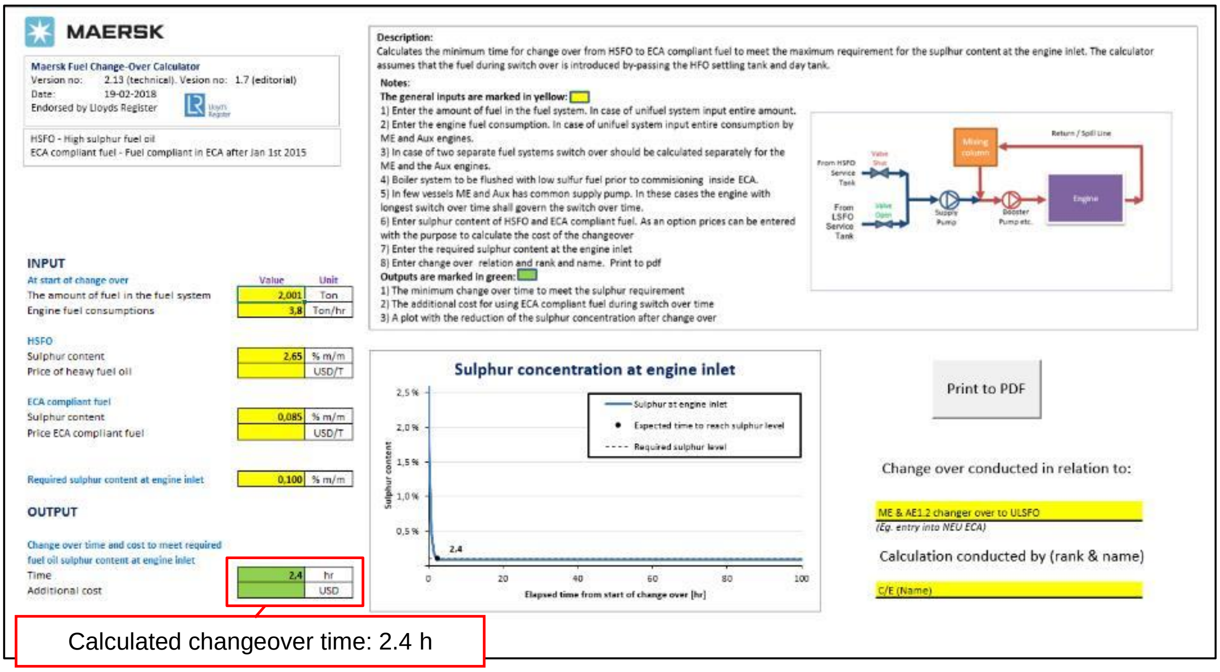
It is assumed that the term 'lifetime' in this publication is incorrect or a remainder from older versions, as the term precludes e.g. condition-based maintenance[83]. A recommended value is therefore assumed here, too.

The ICUs of the affected cylinders 4, 5, 10 and 11 on board the EBBA MAERSK had 26,312 running hours[84] on the day of the accident.

3.2.5 Further investigations

3.2.5.1 Fuel changeover process

The changeover time from HFO to VLSGO was calculated using a simple but effective Excel spreadsheet. This also contained the text of the associated ISM procedural instruction (see Figure 31). The sulphur content of the two fuels is entered (and optionally also their cost in US dollars per ton to calculate any additional costs caused by the changeover). Taking into account the thermal necessities, the changeover time (and optionally the additional costs) is calculated with these values.



Maersk Fuel Change-Over Calculator
Version no: 2.13 (technical). Vesion no: 1.7 (editorial)
Date: 19-02-2018
Endorsed by Lloyds Register

HSFO - High sulphur fuel oil
ECA compliant fuel - Fuel compliant in ECA after Jan 1st 2015

Description:
Calculates the minimum time for change over from HSFO to ECA compliant fuel to meet the maximum requirement for the suplhur content at the engine inlet. The calculator assumes that the fuel during switch over is introduced by-passing the HFO settling tank and day tank.

Notes:
The general inputs are marked in yellow: 🟨
1) Enter the amount of fuel in the fuel system. In case of unifuel system input entire amount.
2) Enter the engine fuel consumption. In case of unifuel system input entire consumption by ME and Aux engines.
3) In case of two separate fuel systems switch over should be calculated separately for the ME and the Aux engines.
4) Boiler system to be flushed with low sulfur fuel prior to commisioning inside ECA.
5) In few vessels ME and Aux has common supply pump. In these cases the engine with longest switch over time shall govern the switch over time.
6) Enter sulphur content of HSFO and ECA compliant fuel. As an option prices can be entered with the purpose to calculate the cost of the changeover
7) Enter the required sulphur content at the engine inlet
8) Enter change over relation and rank and name. Print to pdf
Outputs are marked in green: 🟩
1) The minimum change over time to meet the sulphur requirement
2) The additional cost for using ECA compliant fuel during switch over time
3) A plot with the reduction of the sulphur concentration after change over

INPUT

At start of change over	Value	Unit
The amount of fuel in the fuel system	2,001	Ton
Engine fuel consumptions	3,8	Ton/hr
HSFO		
Sulphur content	2,65	% m/m
Price of heavy fuel oil		USD/T
ECA compliant fuel		
Sulphur content	0,085	% m/m
Price ECA compliant fuel		USD/T
Required sulphur content at engine inlet	0,100	% m/m

OUTPUT

Change over time and cost to meet required fuel oil sulphur content at engine inlet		
Time	2,4	hr
Additional cost		USD

Change over conducted in relation to:
ME & AE1.2 changer over to ULSFO
(Eg. entry into NEU ECA)

Calculation conducted by (rank & name)
C/E (Name)

Calculated changeover time: 2.4 h

Figure 31: EBBA MAERSK fuel changeover spreadsheet[84]

The calculated changeover time of 2.4 h (2 hours and 24 minutes, see Figure 31) was adhered to and even slightly exceeded on the day of the accident. A longer time is favourable here (see course of the accident, Chapter 3.1.1: the changeover operation started at about 0150 and finished at 0327, corresponding to 2 hours and 37 minutes, i.e. 2.62 h).

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[83] Condition-based maintenance is a maintenance strategy in which the actual condition of a system is monitored in order to decide which maintenance operations must be carried out, instead of applying rigid time intervals.

[84] Source: Chief engineer of the EBBA MAERSK, *Maersk Fuel Changeover Calculator* (printed on the day of the accident, 29 July 2020).

3.2.5.2 Condition-based maintenance[85] [86] [87]

The term "Condition-Based Maintenance" (CBM) refers to a maintenance strategy in which a component is not replaced or overhauled until it has reached its maximum safe level of wear, instead of after a fixed and always identical time between overhauls (TBO).

An agreement exists between Wärtsilä and A. P. Møller-Mærsk A/S (APMM) concerning the condition-based maintenance of the different components of the RT-flex engines. In a Letter of No Objection (LONO), Wärtsilä certifies that they have no objections to an extension of the time between overhauls for ICUs and other components of the injection system on the ships of the APMM fleet, provided that the following conditions are met:

- regular checks of the entire fuel system (procedure according to a checklist that was not made available to the BSU);

- continuous monitoring of all ICU leakage rates in normal operation (i.e. HFO operation): above a specified hourly leakage rate, an ICU is to be monitored more closely; above a specified, higher leakage rate, it is considered to be worn and requires overhaul or replacement;

- accounting for the operating profile of the main engine: High load ranges are weighted more heavily when determining after how many operating hours a component must be replaced at the latest. Low load ranges are weighted less heavily. (A long operation time at partial load means fewer load changes, and thus a higher number of operating hours before the same degree of wear is reached than through shorter periods at full load).

If the fuel system check does not identify any irregularities, the overhaul of an ICU may be postponed by a further 6,000 hours once the original limit of 36,000 operating hours has been reached.

The reduced TBO of 24,000 operating hours given in the bulletins is not assumed as a minimum here, but rather – with Wärtsilä's approval and under the aforementioned conditions – 36,000 operating hours. These may be further extended up to a maximum of 42,000 hours. According to a paper provided by Maersk, the EBBA MAERSK operated on a medium load profile between the years 2015 and 2017, for example. Based on this profile, an expansion of the ICUs' maximum operating hours to 39,000 is permitted.

Continuous leakage rate monitoring is carried out in any case.

For this LONO, WinGD is the legal successor of Wärtsilä.

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[85] Source: Wärtsilä Services Switzerland Ltd., *Letter of No Objection (LONO) for TBO Extension of Flex Components on APMM Fleet* (2015).

[86] Source: Wärtsilä Services Switzerland Ltd., *Flex Agreement, Appendix 3* (2015).

[87] Source: Wärtsilä Services Switzerland Ltd., *Maintenance scheme RTFlex96 Injection Control Unit (ICU)* (2018).

3.2.5.3 Laboratory analyses

Problems with the injection system occurred shortly before the changeover process was completed. Those ICUs from which the fire in the scavenge air duct presumably originated were clogged in one area with a tar-like mass. These facts pointed to a possible involvement of a fuel incompatibility in the accident. Accordingly, this possibility was investigated by both Maersk and the BSU.

After the accident, in Antwerp (Belgium), the shipping company arranged for the Veritas Petroleum Services[88] fuel-testing laboratory in Brussels (Belgium) to carry out an analysis of the two fuels involved in the changeover. Routine laboratory analyses had also been carried out after the bunkering of each of these fuels.

The BSU later also arranged for the fuel samples that had been taken during the inspection, as well as for the sample of the tar-like substance, to be analysed comprehensively by the fuel laboratory of the Hamburg University of Technology (TUHH). The findings of these investigations are compared below.

a) Conventional laboratory analyses

Heavy fuel oil

The sulphurous heavy fuel oil was bunkered in Hamburg on 5 and 6 February 2020.

On 14 May in Antwerp, a sample was submitted for analysis to the aforementioned Brussels laboratory. The sample was taken at the bunkering manifold[89] on deck. It had a sulphur content of 2.42%. Its other values were also within the stipulated range, only density and viscosity were slightly too high, while ignition quality was slightly too low. Cat fines were detected in the fuel. For operation, it was recommended that the percentage of cat fines be reduced by at least 67% by parallel operation of two purifiers, although the increased fuel density might make purification more difficult (a large density difference to water is desirable here). To compensate for the reduced ignition quality, it was recommended that partial loads be avoided and higher charge air temperatures used.

After the accident, a sample of the same bunker batch was given to the same laboratory again on 8 August 2020. This time, the sampling point was at the day tank (i.e. after the purifiers). The values had hardly changed, only the proportion of cat fines was reduced by about one third (not by two thirds as desired) from 42 to 30 mg/kg.

The TUHH fuel laboratory carried out an automated, i.e. very precise and reproducible spot test on the sulphurous heavy fuel oil. This revealed that it was stable (see Figure 32).

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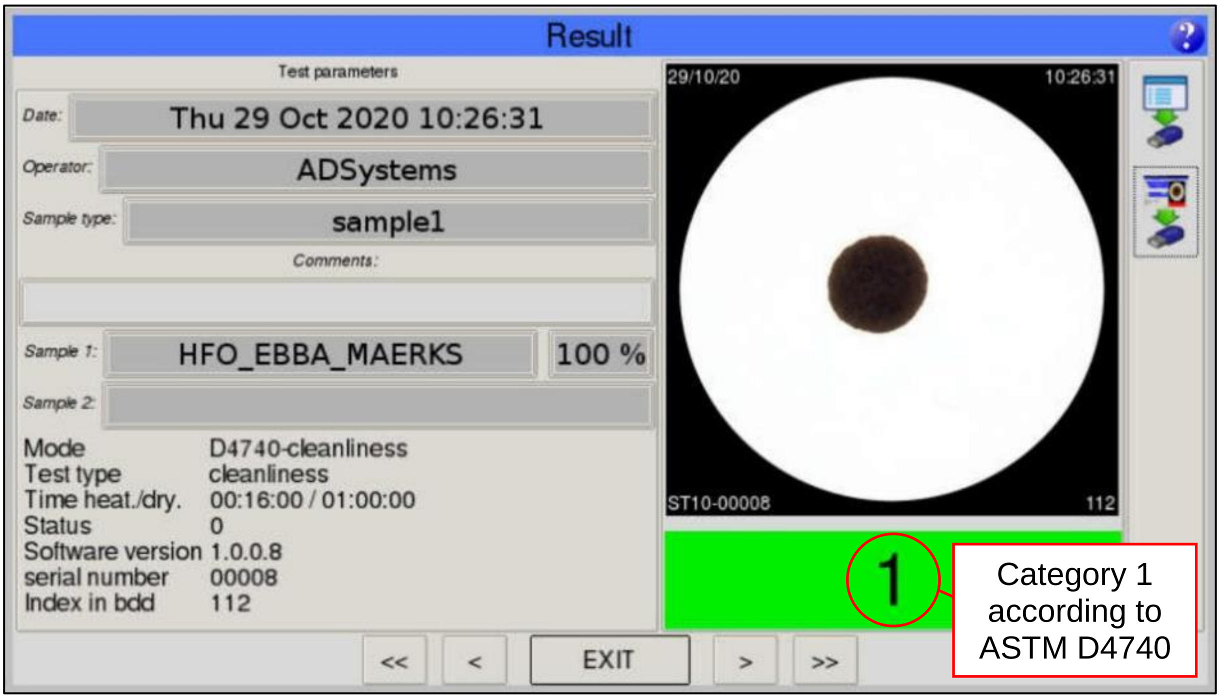
[88] Veritas Petroleum Services BV (VPS), established in 1981 by DNV in Oslo, is now an independent company specialising in marine fuel analysis and related consulting. Source: VPS BV, *About* (retrieved in 2022).

[89] 'Manifold': Hose connection station for transferring bunker goods – liquid cargo in the case of tankers – into the ship.



Date: Thu 29 Oct 2020 10:26:31

Operator: ADSystems

Sample type: sample1

Comments:

Sample 1: HFO_EBBA_MAERKS 100 %

Sample 2:

Mode D4740-cleanliness
Test type cleanliness
Time heat./dry. 00:16:00 / 01:00:00
Status 0
Software version 1.0.0.8
serial number 00008
Index in bdd 112

Category 1 according to ASTM D4740

Figure 32: Spot test of the HFO used before the changeover[90]

Gas oil

The low-sulphur gas oil was bunkered in Tanjung Pelepas (Malaysia) on 4 July 2020.

A sample of it was sent to the same laboratory after bunkering, arriving there on 8 July. The sample was taken at the bunkering manifold on deck. The analysis revealed no anomalies whatsoever. The sulphur content of 0.093% was within the stipulated limits.

After the accident, a sample of the same batch was also analysed in the laboratory on 8 August. The sampling point was also at the day tank. There were only two noticeable changes in the values: The gas oil was no longer light and clear, but dark and cloudy. This was consistent with the fact that the 'micro carbon residue' (MCR) was more than three times as high as allowed according to Maersk Specification DMA01, and almost ten times as high as when it was bunkered.

According to the laboratory, it is conceivable that the light fuel oil was stored in a tank that had previously contained a heavy fuel oil (perhaps the day tank from which it was taken). This evidently had no influence on the sulphur content, which had remained within the permissible limits.

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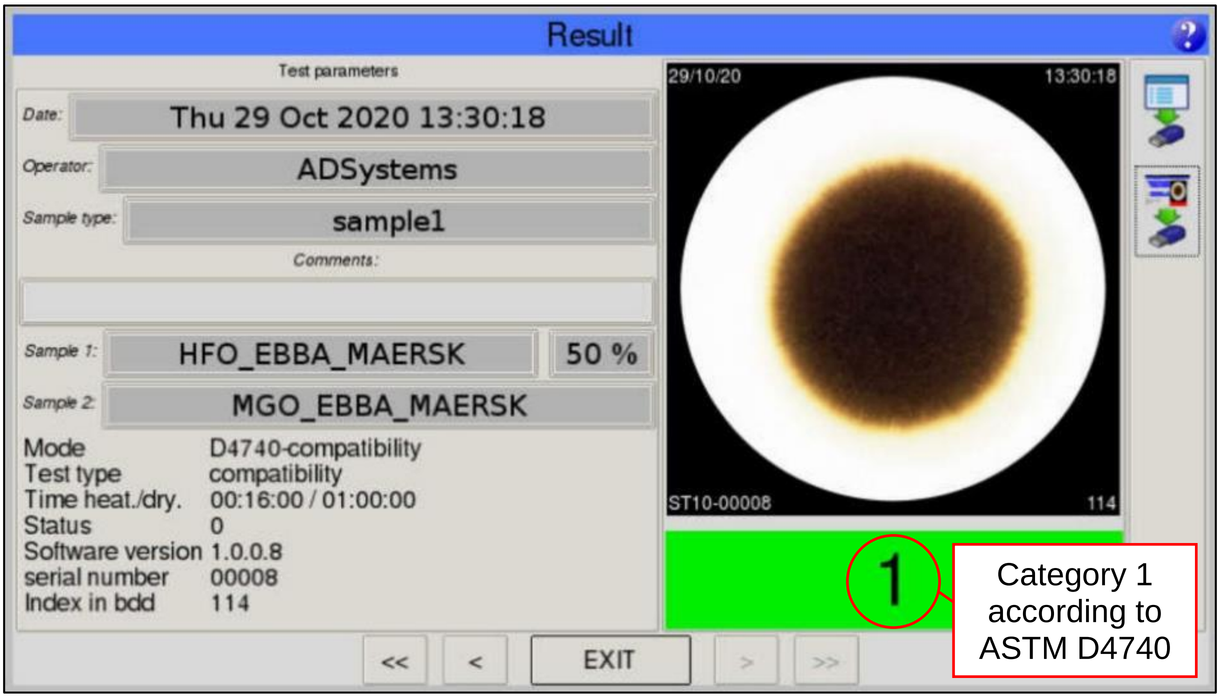
[90] Source of Figure 32 and Figure 33: Dr. rer. nat. J. Bullermann, Hamburg University of Technology Fuel Laboratory, Department of Marine Engineering (2020).
For an explanation of the ASTM D4740 categories, see Figure 14 and Table 1 on p. 31.

Blend of both fuels

Another automated spot test was carried out in the TUHH fuel laboratory. This time the two fuels were blended at a ratio of 1:1. The test revealed that the blend was stable, i.e. the two fuels were compatible with each other (see Figure 33). Accordingly, the possible storage of the gas oil in a tank previously used for heavy fuel oil had had no influence on its stability.



Result

Test parameters

Date: Thu 29 Oct 2020 13:30:18
Operator: ADSystems
Sample type: sample1
Comments:
Sample 1: HFO_EBBA_MAERSK 50 %
Sample 2: MGO_EBBA_MAERSK

Mode	D4740-compatibility
Test type	compatibility
Time heat./dry.	00:16:00 / 01:00:00
Status	0
Software version	1.0.0.8
serial number	00008
Index in bdd	114

Category 1 according to ASTM D4740

Figure 33: Spot test of the two fuels involved in the changeover

ULSFO

During the inspection, the BSU also took a sample of the low-sulphur heavy fuel oil (ULSFO) that had been in use most recently. Here, too, the spot test showed that the fuel was a stable category 1 (no figure).

<u>b) Further analyses by the TUHH fuel laboratory</u>[91]

Analyses of commercial fuel laboratories only assess properties and components covered by ISO 8217. The TUHH fuel laboratory has more advanced methods at its disposal and is able to identify foreign components that may additionally – possibly illegally – be contained in the fuels.

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[91] Source: Dr Bullermann, J., *Analysenbericht Unfall EBBA MAERSK* (2021).

Dr Jasmin Bullermann, head of the TUHH fuel laboratory, conducted an X-ray fluorescence analysis (XRF)[92] and an ATR infrared spectroscopy[93] for this accident. Since the laboratory was still being set up immediately after the accident, these analyses were carried out in July 2021.

None of the fuels exhibited anomalies during the measurements. All the determined components were within the limits specified by ISO 8217. Accordingly, the results of the conventional laboratory fuel analyses could be confirmed. No foreign components were identified.

However, the tar-like deposit exhibited several anomalies. In addition to a conspicuous appearance (also contained solid lumps, see Figure 34), the XRF measurement revealed the presence of prominently high levels of phosphorus, molybdenum, zinc, iron, and calcium. Moreover, the vanadium level corresponded to that of the heavy fuel oil, and the sulphur content was increased (see Table 3).

Figure 34: Tar-like residue
in the weighing bowl of the TUHH fuel laboratory

According to Dr Bullermann, these results permit the following conclusions:

- phosphorus, molybdenum, zinc, iron and calcium indicate a contamination with lubricating oil;
- the vanadium and sulphur levels indicate that conventional heavy fuel oil is also present in the sample.

To confirm the levels, the measurement was repeated. This produced the same results within the measurement tolerances of this method.

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[92] X-ray fluorescence analysis is a method of determining the elemental composition of a sample in terms of quality and quantity using X-rays (put very simply).

[93] Infrared spectroscopy uses infrared radiation to determine the quantity of the substances contained in a sample. ATR (attenuated total reflection) infrared spectroscopy draws conclusions from the reflectivity of the respective substance (put very simply).

Table 3: Results of the XRF measurements

Element	**Residue**	**HFO**	**MGO**	**ULSFO**	**Residue rep.**
	[ppm]	**[ppm]**	**[ppm]**	**[ppm]**	**[ppm]**
P	2.125,00				2.218,00
Mo	71,90				83,20
Zn	9.337,00				9.753,00
Ni	25,40	43,20		31,20	13,00
Fe	130,70	18,40		12,40	187,70
Mn	18,40				21,40
V	147,00	149,60			120,00
Ba	36,60	16,50			43,60
Ca	48.062,00			48,50	62.130,00
Si	42,40	11,40	9,30	0,10	38,10
Al	28,30	9,10	10,20	10,40	20,10
S	1,38	2,37	0,06	0,09	1,36

The image of the ATR spectrum revealed an initially unknown peak at 875 cm^{-1}, which, after a comprehensive library comparison, turned out to be calcium carbonate. This was consistent with the unusually high calcium levels in the XRF measurements.

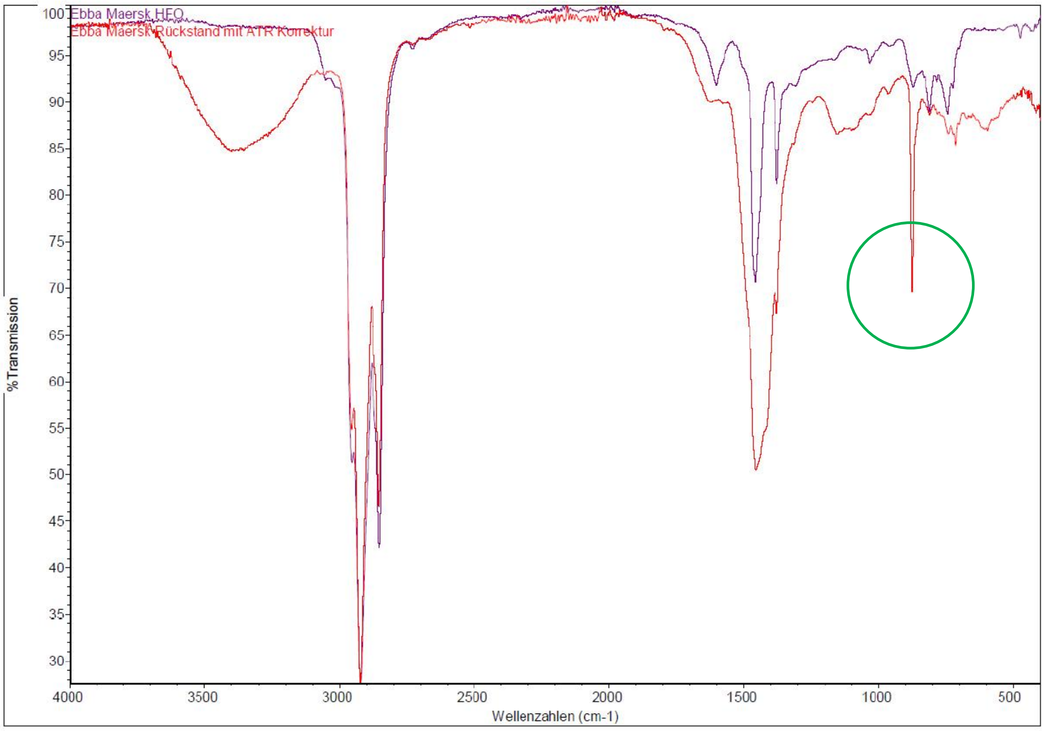

Figure 35: ATR spectrum of the tar-like deposit
(calcium carbonate band marked)

Dr Bullermann requested a sample of lubricating oil from the EBBA MAERSK, which was sent accordingly. However, no calcium components were found in this.

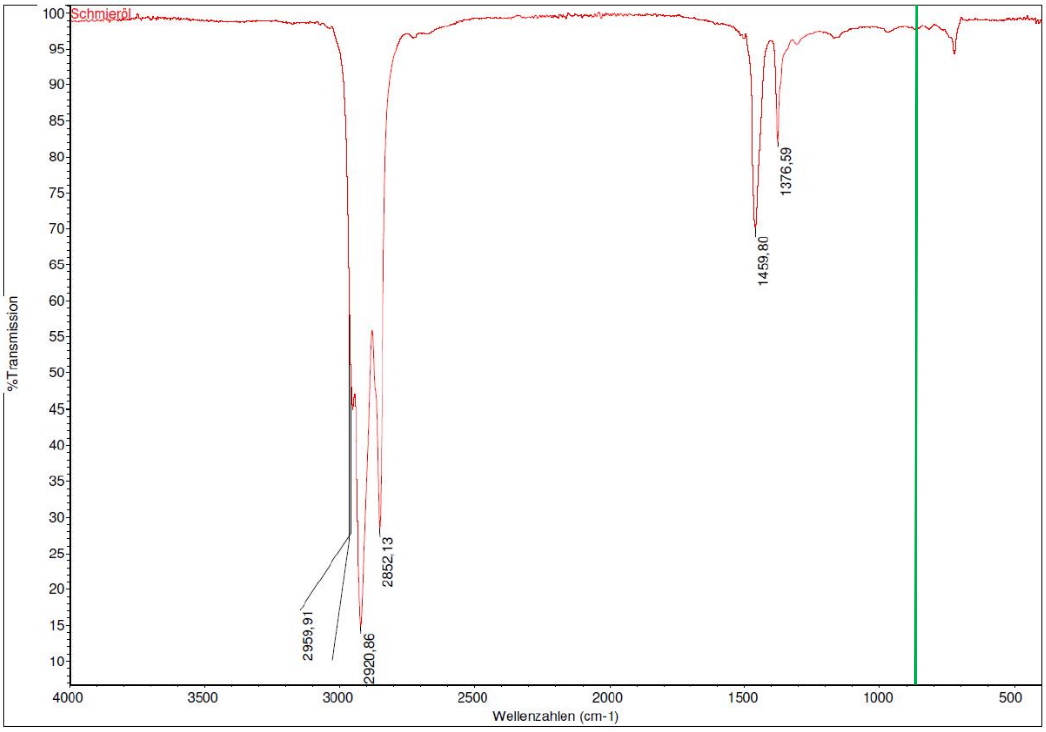

Figure 36: ATR spectrum of the subsequently delivered lubricating oil
(875 cm^{-1} marked)

3.2.5.4 Bachelor thesis[94]

Shortly after the accident and in cooperation with the Flensburg University of Applied Sciences, a student of marine engineering, focus ship operation engineering, was tasked with investigating the possible cause of the fire in the scavenge air duct. As part of his bachelor thesis, he conducted a failure analysis in accordance with VDI 3822 (a VDI, Association of German Engineers, guideline).

The results of the work were influential in the preparation of this investigation report and delivered important impetus at several points.

After a detailed description of the damage, he put forward two damage hypotheses. Firstly, he investigated a possible incompatibility of the fuels as the cause of the damage, and secondly, the question whether a malfunction of the affected ICUs could have led to the fire.

Detailed research was conducted for both hypotheses. He finally concluded that fuel incompatibility could be ruled out in this case, and that there must have been a problem with the ICUs.

He also tried to compile statistics on the frequency of comparable accidents since the introduction of low-sulphur fuels. Since the first sulphur limit was stipulated in 2010 (see Figure 10 on p. 24) and the complexity of fuels has steadily increased since then,

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[94] Source: Koeplin, E. L., *Schadensanalyse nach VDI 3822 – Brand in einem Spülluftkanal* (bachelor thesis) (2020).

he hoped to receive corresponding feedback from ship underwriters and classification societies.

In response to his emails to underwriters, he received only one reply from the *Verein Hanseatischer Transportversicherer e.V.* [Association of Hanseatic Marine Underwriters], which stated that minor damages, which include fires in the scavenge air duct, are often below the excess and therefore not reported to underwriters. On the other hand, underwriters do not specify engine damages, but rather summarise them under generic terms, such as 'damage to main engine'. Accordingly, such cases could not be 'filtered out' for the compilation of statistics even if they had been reported.

A few more replies were received in response to his emails to the classification societies (he does not give any numbers). Although a 'partial' increase in comparable claims was indeed reported, it appears that no society had usable data in the form of statistics.

3.2.5.5 Exchanges with WinGD[95]

To clarify basic questions of understanding, in particular in connection with the functionality of the ICUs and possible known problems with them, WinGD was contacted. The questions compiled by the student and the BSU investigators were answered in detail in an email exchange and in a video conference with the BSU investigators and TUHH representatives.

The images of the neutral spaces of the injection control valves clogged with the tar-like substance led to an explanation of the leakage flows and the possibility of fuel and lubricating oil (control oil) being exposed to each other in these areas. Wärtsilä and WinGD have apparently known about this type of contamination of the neutral spaces for some time.

Accordingly, an upgrade is recommended on Wärtsilä's website. The reasons for this are explained in a film. [96] Product brochures are also available for download.

The film begins by explaining what this investigation report has already set out, i.e. that the increased use of light fuels in SECAs since 2015 due to the lowering of the sulphur limit causes accelerated wear on the metallic sealing surfaces of ICUs. The film states that the introduction of a significantly stricter limit also outside the SECAs in 2020 is expected to cause the problem to worsen dramatically, up to uncontrolled injection in isolated cases.

WinGD confirmed that the new ICU generation has fewer operational problems with light fuel oils, but emphasised that safe operation is also possible with the first generation at any time if the recommendations in the bulletins are adhered to, especially with regard to maintenance intervals.

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[95] WinGD: Winterthur Gas & Diesel Ltd, joint venture between Wärtsilä and the Chinese state-owned shipbuilding group CSSC, responsible for engineering, i.e. development and R&D in the field of diesel engines distributed by Wärtsilä. Source: WinGD, *Our History* (retrieved in 2022).

[96] Source: Park J. Y., *Wärtsilä FuelFlex injection control unit upgrade for RT-flex engines* (2020; retrieved in 2022).

4 ANALYSIS

The analysis section of this investigation report begins with a classification of the actions and reactions of the parties involved in the accident, both generally and in relation to the ISM procedural instructions available to them.

The latter part of this analysis section adopts the damage assessment sequence proposed in the bachelor thesis. Accordingly, a possible incompatibility of the fuels involved in the changeover process will be examined first, followed by possible problems with the ICUs.

4.1 Crisis management and handling of the accident

4.1.1 General assessment

In the opinion of the BSU, the chief engineer and the engine department, as well as the ship’s command and the pilot, responded with the necessary calmness, prudence, and speed first to the irregular exhaust gas temperatures, later to the fire, and finally to the emergency repairs. These were carried out against the clock at the emergency anchorage.

The changeover from heavy fuel oil with 3.5% sulphur content to gas oil with 0.1% sulphur was carried out according to the associated procedural instructions and in the pre-calculated time (using the Excel spreadsheet provided for this purpose). There was no alternative to changing to a light fuel oil in these pilotage waters because of the insufficient quantity of low-sulphur heavy fuel oil on board. The chief engineer, who had just joined the ship, was not responsible for the amount of fuel that was ordered and available.

After the significant increase in exhaust gas levels, especially from cylinder 10, the obvious suspicion of increased friction between liner and piston due to cat fines was investigated first. When this was not confirmed, the chief engineer decided not to interrupt the approach to Hamburg, but rather to look for the cause of the problem later at berth, and to disengage the cylinder until then. Since the EBBA MAERSK's engine can compensate for this loss of power easily and fully automatically with the other cylinders while sailing slowly in pilotage waters – this is not even noticeable on the bridge – this was the most sensible course of action.

When the alarm for a fire in the scavenge air duct went off, he had this confirmed by measuring the temperature directly on the engine before instantly taking countermeasures. He immediately communicated with the bridge and evacuated the engine room. Then he referred to the shipping company's ISM procedural instructions and extinguished the fire by working through them.

After the engine had cooled down as necessary, the integrity of the main engine was immediately checked and any damage recorded.

When it became clear that the electronically disengaged cylinder had also had injection problems, the chief engineer wanted to shut it down physically, so that only the other ICU would need to be overhauled there at the emergency anchorage. This would have made it possible to have the main engine operational again and leave the emergency anchorage more quickly. Only when this was not possible due to the tool at hand, both affected ICUs were overhauled and built back in again, using the 'overhaul kits' provided for this.

The first emergency anchorage was located just east of the Elbe Approach TSS entrance/exit. It was therefore not an ideal position to spend several hours carrying out emergency repairs. This is of course an intrinsic characteristic of emergency anchorages, however, and as such cannot be considered negative. On the contrary, the ship's command and pilot selected the best possible position between the two traffic lanes in the available time (minutes!). Thanks to the good communication between ship, Vessel Traffic Service, and surrounding traffic, the traffic did not come to a standstill and there were no secondary accidents.

The fact that the pilot only allowed the vessel to enter the Elbe after a trial run was prudent and appropriate to the accident. When the exhaust gas temperature of another cylinder increased during the trial run, the affected ICU could this time be shut off physically, because the necessary tool had been reworked in the meantime. The second emergency anchorage was unproblematic.

All further necessary measures, in particular the overhaul of cylinder 4 ICU, could later be carried out without unnecessary pressure at berth in Hamburg.

4.1.2 Maersk procedural instructions: Fire in the scavenge air duct

The ISM system for the EBBA MAERSK contains two documents for dealing with a fire in the scavenge air duct. One is in text form and describes the problem in a very basic manner, as well as the associated measures, possible ensuing hazards (e.g. crankcase explosion, turbocharger pumping, turbocharger explosion) and the necessary safety-related behaviour.[97] The other procedural instruction is a checklist that must be worked through in order to extinguish the fire.[98]

The BSU cannot identify any inconsistencies between the two procedural instructions and the chief engineer’s behaviour. In particular, the engine room was evacuated immediately, communication was established with the bridge promptly, the main engine was shut down quickly, the supply of air and fuel was cut off, and the extinguishing system was activated as soon as possible, but at the correct point in the sequence. Engine inspection was only carried out once it had cooled down sufficiently.

4.2 Compatibility of fuels

The changeover from a heavy fuel oil to a light fuel oil directly preceded the accident, which began with the increased exhaust temperatures. Consequently, the BSU investigators initially suspected that the fundamental problem of a potential fuel incompatibility, which has been known for decades, existed. They also suspected the possibility of a connection with low-sulphur heavy fuel oils, with which incompatibilities occur more frequently. The tar-like residue found in the neutral spaces of the injection

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[97] Source: Maersk ISM system, *Scavenging air receivers – fire precautions* (2018).
[98] Source: Maersk ISM system, *Flowchart – Fire (Scavenge Space)* (2021).

control valves of the affected ICUs was initially also considered indicative of fuel instability (possibly precipitated asphaltene).

The reason why there was not enough heavy low-sulphur fuel oil on board in the first place could not be determined in retrospect. It is a fact that ships now have to carry a wider range of different fuels than before SECAs were introduced: As much conventional heavy fuel oil as possible is still used for economic reasons, but additional fuels also have to be carried. Of course, this means that there are smaller amounts of each type of fuel on board, especially on a ship built before the introduction of these rules and not optimally adapted to today's fuel situation, e.g. with regard to the available number of tanks. A single short-notice change in schedule can completely disrupt fuel management.

The possibility that the 'new' fuels might have facilitated such a serious incident was to be investigated, even after it was clear that no low-sulphur heavy fuel oil was involved in the changeover operation. Especially in the case of deposits or contamination, there may have been a long run-up.

The two spot tests carried out by the TUHH fuel laboratory prove on the one hand that the sulphurous heavy fuel oil was stable, and on the other hand that it was compatible with the low-sulphur gas oil that was changed over to. Both formed a stable 1:1 blend.

The laboratory tests carried out on the two fuels after the bunkering operation and immediately after the accident also show no anomalies associated with incompatibility. Even the extremely thorough analyses of the TUHH fuel laboratory did not reveal any anomalies. It is true that the increased MCR levels in the gas oil suggest that it must have been blended with small quantities of a heavy fuel oil. However, the spot test still did not reveal any incompatibility between the gas oil and the heavy fuel oil that had been in the fuel system before the changeover. This suggests that there was no incompatibility problem inside the fuel lines, ICUs, or injectors after the changeover process that resulted from the blending of the two fuels.

The TUHH analysis of the tar-like substance from the neutral spaces of the ICUs revealed that this was not precipitated asphaltene but rather that it contained high proportions of lubricating oil residues in addition to parts of heavy fuel oil (see following section). These findings also opposed the theory that the substance may have formed due to fuel incompatibility.

4.3 ICUs

4.3.1 Laboratory analyses

The laboratory analyses by Dr Bullermann from the TUHH fuel laboratory showed that the secured tar-like residue contained proportions of lubricating oil and sulphurous heavy fuel oil.

As already mentioned, calcium carbonate is a lubricating oil residue that forms from the neutralisation reserve of a lubricating oil, which is present in the form of calcium hydroxide. A large diesel engine has two lubricating oil circuits. One is the so-called 'circulating oil', which lubricates the drive, and the other is the 'cylinder oil', which lubricates the pistons and seals them in the direction of the exhaust gases. In the circulating oil, the alkaline components are low, usually about TBN 5, compared to the cylinder lubricating oil, which has about TBN 80 or higher due to direct contact with the exhaust gases, which may contain sulphuric acid. Control oil is circulating oil, which forms a closed circuit, is cheaper due to the low TBN, and does not have to be constantly adapted for the fuel in use. Nevertheless, circulating oil also contains small amounts of calcium hydroxide. Moreover, there can be a leakage flow of control oil into the neutral space of the ICU's injection control valves, as described (see Chapter 3.2.4.4, in particular Figure 28).

The calcium carbonate thus indicates that control oil actually did enter the neutral space. Furthermore, a reaction (e.g. coking) with the hot fuel must have occurred here.

The fact that the comparative analysis with the subsequently delivered lubricating oil that was actually used did not reveal any calcium carbonate may mean that the quantities of lubricating oil entering the neutral space were continuously low but constant, meaning that certain components were able to accumulate over the operating time. For example, it is conceivable that the MGO flushed out other residues, leaving only the comparatively hard components such as calcium, which were then present in a growing concentration. However, the quantities of calcium carbonate in a single lubricating oil sample were possibly below the detection limit.

The question of the origin of the calcium in the neutral spaces could not be answered conclusively.

4.3.2 Evaluation

It is known from the Wärtsilä technical bulletins that increased operation with light fuels results in accelerated wear of the sealing surfaces in first-generation ICUs developed for heavy fuel oil operation. The result of this wear are unintentionally strong fuel leakage flows, e.g. via the transverse flow between the injection control valves towards the injection valves, coming from the fuel quantity piston. Similarly, it is known that the introduction of stricter sulphur guidelines in 2015 resulted in exactly this industry-wide increased operation with light fuels.

Furthermore, several bulletins and a Wärtsilä video warn quite specifically that this phenomenon might lead to continuous injection. Even though the BSU has no images of the injection control valves of the affected ICUs and their valve seats, it can be assumed with a high degree of probability that this was the case with the EBBA MAERSK.

If the wear is so advanced that the fuel that leaks towards the injection valve in unwanted quantities can build up sufficient pressure to lift the injection valve's needle element, continuous injection occurs with the ‘machine-gun-like’ injection pulses observed by the engine department: Pressure is built up, the needle element is raised, the triggered injection pulse causes the pressure to decrease, the needle element drops, then pressure quickly builds up again, etc. Since the worn sealing surfaces obviously also cause this effect when the ICU would ordinarily be 'closed' from the fuel side (not actuated), electronic 'disengaging' is insufficient, as this does not shut off the fuel pressure of 700 bar physically. On the contrary, the pressure inside the ICU would normally drop regularly due to the likewise regular injections. This is never the case with an ICU that has only been electronically 'disengaged'. In that case, the pressure is continuous and is therefore, as a worst-case scenario, capable of exacerbating the unwanted leaks.[78]

WinGD recommended that the rail valves be shut down by disconnecting their power supply instead of 'disengaging' them. To this end, the lower plug on one of the rail valves must be removed. The fuel quantity piston will then move to its end position. In this manner, the fuel would drain completely from the ICU and the leakages could no longer be fed. However, this is not knowledge that WinGD or Wärtsilä has spread in any way, e.g. via bulletins, meaning that it could not be known to the crew.

In addition to the increased leakage, the contamination of the neutral spaces of the injection control valves was so heavy that their freedom to move was possibly restricted. There is photographic evidence of this, yet no reference to it was found in the bulletins. WinGD was aware of this phenomenon.

EBBA MAERSK's main engine had not been operated with a light fuel oil for a long time before the accident. Low-sulphur heavy fuel oil had always been used during that period. The exact duration of this period could not be specified. Overall, however, this ship has also increasingly changed to light fuels since 2015.

According to the laboratory analysis, the tar-like residues partly consisted of lubricating oil, i.e. control oil, as described. A proportion of heavy fuel oil was also detected.

The BSU therefore suspects that the changeover from heavy fuel oil to gas oil on the day of the accident was 'the final straw', as it were. Due to the age of the ICUs, it is reasonable to assume that the wear on their sealing surfaces was already advanced, but still operable with heavy fuels. During the changeover process, the leakage rate of the lighter fuel suddenly increased five to tenfold for a short period. On the one hand, this will have been sufficient to build up the pressure at which the needle elements of the injectors could be lifted (through the worn sealing surfaces of the injection control valve seats).

On the other hand, the hot fuel that suddenly entered the neutral spaces at an increased leakage rate may then have reacted more intensively with the lubricating oil that was already present. The servo oil might well have made its unintentional way there and formed the decisive part of the deposits beforehand. As already discussed, it is also conceivable that parts of the residues already present were washed out and only the harder components stayed behind, i.e. that the tar-like substance suddenly became significantly more viscous. The heavy fuel oil content of the residue, especially its sulphur content, shows that some of the deposits must have formed beforehand in reaction with sulphurous heavy fuel oil. However, the fact that the described problems only occurred after the changeover process on that day suggests that also in this case, the changeover process ‘took the final straw’.

The BSU takes the view that the permanent injection due to the wear of the sealing surfaces was possibly aggravated by a sudden mobility impairment of the injection control valves due to the deposits.

The BSU assumes that it was this unfortunate combination that enabled the unregulated injection of such large amounts of fuel that it could spread over a large area and even ignite. The increased wear due to the frequent changeover to light fuels, with the aforementioned consequences, is however considered to be the main cause.

5 CONCLUSIONS

5.1 Fuel incompatibility during the changeover process

The BSU concludes that the two fuels involved in the changeover were not incompatible.

5.2 Malfunction of the affected ICUs

The BSU concludes that a combination of

- worn and therefore leaking sealing surfaces inside the ICUs, on the one hand, and
- to a lesser extent, contaminated neutral spaces of the injection control valves, on the other hand,

led to the accident.

According to the Wärtsilä technical bulletins, the wear-down of the sealing surfaces was due to the increased changeovers to light low-sulphur fuels since the SECA sulphur limits were lowered to 0.1% in 2015. According to WinGD, the contamination of the neutral spaces was due to increased control oil and fuel leakage flows within the ICUs into the neutral spaces.

The fact that wear and deposits were not initially noticeable due to the temporary but prolonged operation with heavy fuel oil explains the timing of the accident. When a change was made back to a light fuel oil for the first time, both problems became apparent simultaneously due to the briefly greatly increased leakage rates, although the associated damage or contamination must have been present, but possibly not as severe, beforehand.

Within the condition-based maintenance scheme, the leakage rates of the affected ICUs had not been critical before the fuel changeover. Therefore, the BSU concludes that the leakage rates that determine whether an ICU is to be considered worn or not must be based on operation with light fuel, if the engine is to be changed over to a light fuel. The affected ICUs, after all, had not even reached the minimum value of 36,000 operating hours that serve as the basis for the CBM assessment.

The leakage rates in HFO operation do not indicate whether they would also be uncritical in MGO operation. The affected ICUs on the EBBA MAERSK may well have remained inconspicuous for some time in continued HFO operation.

6 ACTIONS TAKEN

Wärtsilä took immediate action when the intensified wear due to increased operation with light fuels became apparent after 2015. Customers were informed via the technical bulletins and a new generation of ICUs was developed that could cope better with the many changeovers.

After the accident, the superintendent responsible for the EBBA MAERSK sent further ICU overhaul kits on board, as well as one complete new unit.

Maersk had the fuels analysed in a laboratory immediately in order to detect possible problems with them.

7 SAFETY RECOMMENDATION

The following safety recommendations do not constitute a presumption of blame or liability.

7.1 Maersk Line

Assessment of ICU wear condition based on leakage rate

The BSU recommends that Maersk Line, as operator of the EBBA MAERSK, assess the condition of an ICU, especially with regard to increased monitoring and complete replacement or overhaul, on the basis of the leakage rates in MGO operation.

When switching from a heavy fuel to a light fuel, the changing leakage rate must be closely monitored, at least until it and the component temperature have stabilised. Based on this leakage rate, a decision must be made as to whether continued operation on light fuel is safe or not.

7.2 WinGD

Re-evaluation of the Letter of No Objection regarding the TBO extension for flex components of the APMM fleet

The BSU recommends that WinGD, as Wärtsilä’s legal successor for this type of agreement, re-evaluate the Letter of No Objection with A. P. Møller-Mærsk A/S, taking into account the different deterioration and leakage rates on light fuel operation.

8 SOURCES

Aderco. *Fuel Competence* (video). Retrieved on 26 Oct 2022 from https://aderco.com/en/Expertise

Alfa Laval. (2018). *The Alfa Laval Adaptive Fuel Line BlueBook*, Technical Reference Booklet – 2018 Edition

Auto Motor Öl. *Gesamtbasenzahl TBN*. Retrieved on 21 Oct 2022 from https://www.auto-motor-oel.de/ratgeber/motoroel-gesamt-basenzahl-tbn/2367/

Bullermann, Dr J. (Jul 2021). *Analysenbericht Unfall EBBA MAERSK.* (K. TUHH, (publ.)

Chalmers Sweden. *Research reveals large emissions from ship scrubbers*. Retrieved on 28 Oct 2022 from https://www.chalmers.se/en/departments/m2/news/Pages/Research-reveals-large-emissions-from-ship-scrubbers.aspx

Class NK. (2019). *Booklet for ship crew members: Precautions concerning change-over to 0.50 % sulphur compliant fuels*

Class NK. (2021). *Issues after starting to use of VLSFO [sic]*

Claussen, S. (2003). *Einführung in die Betriebsstofflehre für den Schiffsbetrieb* (lecture notes). Hamburg

Conseil International des Machines à Combustion (CIMAC). (Jan 2015). CIMAC Guideline 01 | 2015: *Cold flow properties of marine fuels*

Conseil International des Machines à Combustion (CIMAC). (Jan 2019). *Marine fuel handling in connection to stability and compatibility*

Det Norske Veritas (DNV). (13 January 2021). *Namensänderung: DNV GL wird DNV*. Retrieved on 10 Nov 2022 from https://www.dnv.de/news/namensanderung-dnv-gl-wird-dnv-194340

Det Norske Veritas (DNV). *Global Sulphur Cap*. Retrieved from https://www.dnv.com/maritime/global-sulphur-cap/index.html

German Standards Institution (DIN). (2017). DIN ISO 8217:2017. *Petroleum products – Fuels (class F) – Specifications of marine fuels*

German Standards Institution (DIN). (2019). DIN EN ISO 3015:2019

Energielexikon. *Schweröl*. Retrieved on 18 Oct 2022 from https://www.energie-lexikon.info/schweroel.html

Exhaust Gas Cleaning Systems Association (EGCSA). (2012). *EGCSA Handbook 2012.* Retrieved on 14 Oct 2022 from https://www.egcsa.com/wp-content/uploads/EGCSA-Handbook-2012-A5-size-.pdf

Exhaust Gas Cleaning Systems Association (EGCSA). *Rechtliche Vorgaben zum Umgang mit Schiffsabwasser*. Retrieved on 20 Oct 2022 from https://www.egcsa.com/wp-content/uploads/2019-02-18_texte_09-2019_rechtsgutachten_schiffsabwasser_fin.pdf

Federal Bureau of Maritime Casualty Investigation (BSU). (2011). *Fire in the engine room of the passenger ship DEUTSCHLAND at 1230 on 23 May 2010 in the port of Eidfjord, Norway* (investigation report). Retrieved from https://www.bsu-bund.de/SharedDocs/pdf/DE/Unfallberichte/2011/UBericht_216_10.pdf?__blob=publicationFile&v=1

Federal Bureau of Maritime Casualty Investigation (BSU). (2019). *Failure of the main engine with subsequent emergency anchor manoeuvre on the bulk carrier CAPE LEONIDAS on 17 January 2017 in the area of Kolmar on the River Elbe* (summary investigation report). Retrieved from https://www.bsu-bund.de/SharedDocs/pdf/EN/Investigation_Report/2019/Investigation_Report_20_17.pdf?__blob=publicationFile&v=1

Federal Maritime and Hydrographic Agency (BSH). *Umwelt und Schifffahrt: MARPOL*. Retrieved on 12 Oct 2022 from https://www.bsh.de/DE/THEMEN/Schifffahrt/Umwelt_und_Schifffahrt/MARPOL

Grote, Norbert, WinGD. (2020). Email correspondence

Grote, Norbert, WinGD. (2023). Video conference

Hyundai Heavy Industries. (Jun 2006). *World's Most Powerful Marine Engine Runs Successful Trial,* report on the engine's test run on 29 May 2007. *HHI-EMD News, Issue 16*

International Maritime Organization (IMO). (2020). *Hot topics: Sulphur 2020*. Retrieved on 14 Oct 2022 from https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx

International Maritime Organization (IMO). *Our work: Air pollution*. Retrieved on 12 Oct 2022 from https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx

International Maritime Organization (IMO). *Our work: Special MARPOL areas*. Retrieved on 12 October 2022 from https://www.imo.org/en/OurWork/Environment/Pages/Special-Areas-Marpol.aspx

International Organization for Standardization (ISO). (2017). ISO 8217:2017. *Fuel Standard for marine distillate fuels and marine residual fuels*

International Organization for Standardization (ISO). (2019). ISO/PAS 23263:2019. *Petroleum products — Fuels (class F) — Considerations for fuel suppliers and users regarding marine fuel quality in view of the implementation of maximum 0,50 % [sic] sulphur in 2020*

KATALYSE Institute. *Saurer Regen*. Retrieved on 12 Oct 2022 from http://umweltlexikon.katalyse.de/?p=5203

Khasawneh, R. (2018). *Contaminated marine fuels clog ship engines in Singapore hub – surveyor*. Retrieved on 17 November 2022 from Reuters News Agency: https://www.reuters.com/article/singapore-bunker-shipping/contaminated-marine-fuels-clog-ship-engines-in-singapore-hub-surveyor-idINKBN1KH172

Koeplin, E. L. (2020). *Schadensanalyse nach VDI 3822 – Brand in einem Spülluftkanal (bachelor thesis).* Flensburg

LUKOIL. *iCOlube®*. Retrieved on 26 Oct 2022 from https://marine-test.lukoil.com/en/iCOlube/AboutiCOlube

Maersk ISM system. (1 Feb 2018). *Scavenging air receivers – Fire precautions*

Maersk ISM system. (22 Mar 2021). *Flowchart – Fire (Scavenge Space)*

MarineTraffic. *Past Track EBBA MAERSK*. Retrieved on 31 Jul 2020 from https://www.marinetraffic.com/

Meier-Peter, H., & Bernhardt, F. (2006). *Handbuch Schiffsbetriebstechnik.* Hamburg: Deutscher Verkehrs-Verlag GmbH | Seehafen Verlag

Ministry of Transport of New Zealand. *MARPOL Annex VI treaty text*. Retrieved on 20 Oct 2022 from https://www.transport.govt.nz/assets/Uploads/Policy/OC05343-MARPOL-Annex-VI-treaty-text.pdf

Park, J. Y. (2020). Retrieved on 12 October 2022 from https://www.wartsila.com/services-catalogue/engine-services-2-stroke/fuelflex-injection-control-unit-upgrade/

Täglicher Hafenbericht (THB). (18 Jan 2019). *Scrubber mit Fragezeichen*

Täglicher Hafenbericht (THB). (2022). *IMO macht Mittelmeer zur ECA-Schutzzone*

The Loadstar. (4 Aug 2016). *Maersk upgrades E-class containerships to bolster capacity*. Retrieved on 17 November 2022 from https://theloadstar.com/maersk-upgrades-e-class-containerships-bolster-capacity/

United States Geological Survey (USGS). *Examples of some organic compounds in petroleum*. Retrieved on 20 Oct 2022 from https://energy.usgs.gov/geochemistrygeophysics/geochemistryresearch/organicoriginsofpetroleum.aspx

VDI (Association of German Engineers). (Aug 2020). *Failure analysis – Fundamentals and performance of failure analysis (VDI Guideline 3822).*

VDL AEC Maritime. *Why choose a scrubber?* Retrieved on 12 Oct 2022 from https://www.vdlaecmaritime.com/sox-scrubbing/why-a-scrubber.

Wärtsilä Services Switzerland Ltd. (12 Sep 2006). *The world's most powerful engine enters service*. Retrieved on 11 Jan 2022 from https://www.wartsila.com/media/news/12-09-2006-the-world's-most-powerful-engine-enters-service.

Wärtsilä Services Switzerland Ltd. (2015). *Flex Agreement, Appendix 3.*

Wärtsilä Services Switzerland Ltd. (2008). *Wärtsilä RT-flex96C and Wärtsilä RTA96C Technology Review.*

Wärtsilä Services Switzerland Ltd. (4 May 2015). Technical Bulletin RT-82: *Operation on distillate fuels.*

Wärtsila Services Switzerland Ltd. (4 Sep 2015). *Letter of No Objection (LONO) for TBO Extension of Flex Components on APMM Fleet*.

Wärtsilä Services Switzerland Ltd. (29 Nov 2016). Wärtsilä Technical Bulletin RT-123: *Inspection and overhaul intervals.*

Wärtsilä Services Switzerland Ltd. (20 Jul 2018). *Maintenance scheme RTFlex96 Injection Control Unit (ICU).*

Wärtsilä Services Switzerland Ltd. (27 Nov 2018). Wärtsilä Technical Bulletin RT-126: *Diesel Engine Fuels.*

Wärtsilä Services Switzerland Ltd. (12 Aug 2019). Wärtsilä Technical Bulletin RT-229: *Operation Guidance to the Global Sulphur Cap 2020*

Wärtsilä Services Switzerland Ltd. (25 May 2020). *Upgrading of Wärtsilä FuelFlex Injection Control Unit enables reliable operation with low-sulphur fuel oils* (press release)

Wärtsilä Sea and Land Academy. (2009). *RT-flex Control Elements*

Wikipedia (German). *Fettsäuremethylester*. Retrieved on 20 Oct 2022 from Wikipedia (German): https://de.wikipedia.org/wiki/Fettsäuremethylester