The Alfa Laval Adaptive Fuel Line Blue Book

Technical reference book – 2026 edition

A guide to fuel oils and modern fuel oil treatment, examining emission regulations, catalytic fines, compatibility issues and strategies to meet these and other challenges

The Alfa Laval **Adaptive Fuel Line**

This book provides an overview of the Alfa Laval Adaptive Fuel Line concept, beginning with the issues and rationale behind its development. In a clear and understandable way, it presents the diversity of today's marine fuel choices and the regulatory issues that influence them. Further, it serves as an introduction to fuel oil handling and treatment, providing a technical reference for those interested in the fuels involved and the function of relevant equipment. Finally, it offers guidance for designing the entire fuel oil treatment chain, aimed at improving engine protection, operational safety, energy efficiency and operating costs.

Introduction

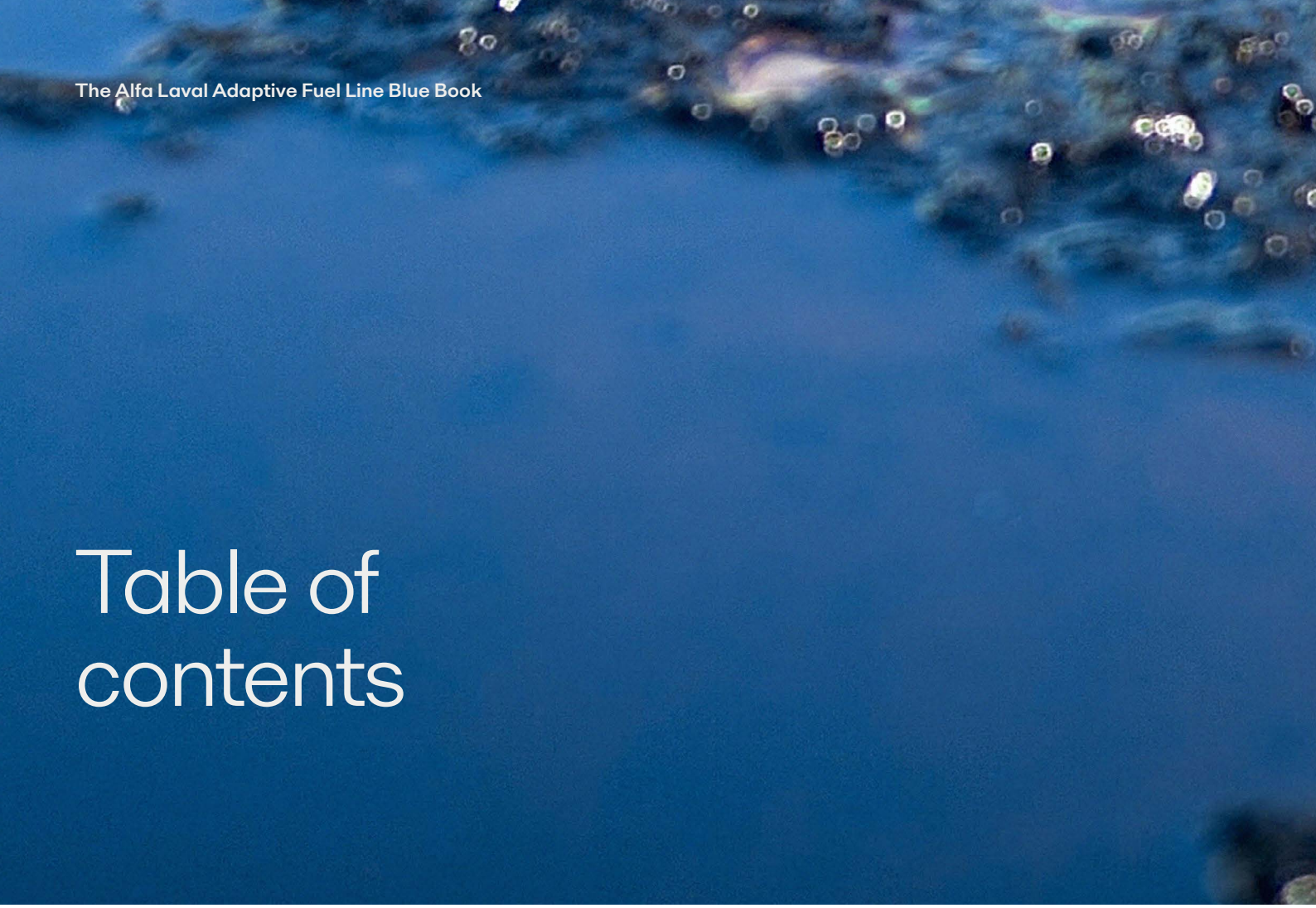
The shipping industry today faces many challenges – both familiar and unfamiliar. Recent years have brought unprecedented changes, intended to reduce the industry's environmental impact. The changes are necessary, and they will continue. But they increase the challenges and uncertainties for shipowners and vessel operators, especially when it comes to fuel oils and their use on board. This book examines the fuel oil issues in detail, arriving at a complete solution in the Alfa Laval Adaptive Fuel Line.

What is the Alfa Laval Adaptive Fuel Line?
The Alfa Laval Adaptive Fuel Line is a concept for meeting complex fuel oil handling and treatment needs, even as the fuels themselves are evolving. It builds on established principles and best practices, but it introduces cutting-edge thinking and equipment solutions that address the growing range of fuel-related issues. At the same time, it creates significant opportunities to save energy and costs.

Above all, the Alfa Laval Adaptive Fuel Line is a comprehensive solution, bringing together all aspects of the fuel oil treatment chain – from onboard storage to engine injection.

What exactly does this book cover?
This book addresses all major aspects of fuel oil handling and treatment. It begins with definitions and important background information, then progresses through the key challenges and the optimal ways of dealing with them. The book is divided into five chapters, which can be read in order or referenced individually:

- **Marine fuels and biofuels**
  This chapter describes the fuel oils used the marine industry today, which are defined by the ISO 8217 marine fuel standard. Both the fuel oil types and the variations within them have expanded significantly as a result of emission regulations. The chapter highlights characteristics that impact fuel treatment and, where relevant, the production processes leading to them.
- **The regulations driving fuel choices and change**
  This chapter explains the regulatory developments behind the shifts in the marine fuel market. It looks first at sulphur emission regulations, which have driven the move from traditional high-sulphur residual fuels to low-sulphur blends and distillates. It then explores greenhouse gas regulations and the push for decarbonization, which are driving the implementation of biofuels.
- **Operational challenges in working with today's fuels**
  This chapter dives into the major issues associated with fuel oil treatment today. It begins with the problem of cat fines, which are tiny, abrasive particles that pose a significant danger to marine engines. It then details the complex issues related to storage and processing of multiple fuels on board, such as incompatibility and fuel changeover. Finally, it explores issues related to energy efficiency.
- **Fuel oil treatment and engine performance**
  This chapter lays out the basics of a fuel oil treatment setup, focusing on its key aspects: fuel cleaning and fuel conditioning. It explains the main equipment types and their purpose, showing how they contribute to protecting the engine and its performance. It also points out principles that can be leveraged for more effective fuel treatment, which are incorporated into the Alfa Laval Adaptive Fuel Line.
- **Cutting-edge fuel oil treatment – the Alfa Laval Adaptive Fuel Line**
  The final chapter builds on everything discussed previously, showing how the knowledge and principles are applied in the Alfa Laval Adaptive Fuel Line. It presents a complete and optimized approach to fuel oil treatment, illustrating how innovative thinking and advanced equipment can make a vital difference. The ideas and connections described can be applied universally, but Alfa Laval equipment supporting the concept is also presented.



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1 Marine fuels and biofuels

When using marine fuel oils, onboard fuel treatment – comprising fuel cleaning and fuel conditioning – is critical for efficient vessel operation. This has not changed with the introduction of biofuels. This chapter explores the many marine fuel oils in use today, emphasizing the complexity of modern fuel oil treatment.

1.1 Marine fuel oils and their use

Marine fuel is used on vessels by the main engines, which generate propeller thrust, and by the auxiliary engines, which provide electrical energy for onboard systems. Additionally, it is used by the oil-fired boiler systems to produce heat for vessel services and cargo management. Modern shipping operations necessitate the use of different types of fuel, most of which fall into the category of fuel oils.

Because marine engines are flexible machines, they are capable of consuming everything from heavy fuel oil to lighter distillates, provided that an efficient fuel cleaning system is in place and that the temperature and viscosity are within the recommended limits of the engine. The broad range of fuel oils for marine use are defined in the internationally recognized ISO 8217 fuel standard.

ISO 8217 – the international marine fuel standard
Seagoing vessels have traditionally relied on diesel/gas oil or residual fuel oil as their energy source. The characteristics of these fuels are agreed on by all parties – shipowners, engine makers and fuel suppliers – in an international fuel standard, ISO 8217. The standard is defined through the International Organization for Standardization (ISO).

ISO 8217 describes the physical properties of the various oil grades. It covers, and puts limits on, the properties that are important when a fuel is used in an engine. These include not only the ignition properties but also contaminants that have an impact on engine performance. Some contaminants, such as water and cat fines, can be removed by the fuel cleaning system. Others, such as vanadium, cannot.

To be covered by the respective classification society, vessels must buy their fuels according to ISO 8217 – and check the supplied fuel accordingly for compliance.

The standard is periodically updated with new learnings and fuel developments, most recently in 2024. The current revision (ISO 8217:2024) includes learnings from the low-sulphur era by introducing a table for very-low-sulphur fuel oil (VLSFO). Additionally, it allows vessels to use fatty acid methyl ester (FAME) biofuel according to specifications in any concentration. The use of hydrogenated vegetable oil (HVO), another biofuel, was already approved in an earlier revision.

1.2 The broadening range of fuels on board

Fuel bunkers have changed drastically in recent years as the result of additions to MARPOL Annex VI – Regulations for the Prevention of Air Pollution from Ships (IMO, 2023). New regulations introduced to the annex have had a major impact on fuel properties. The regulations include:

- **Regulation 14 – Sulphur Oxides (SOx) and Particulate Matter**, which introduced a global fuel sulphur cap in 2020 that led to the introduction of a wide variety of low-sulphur fuel blends
- **Chapter 4 – Energy Efficiency Regulations,** which is currently forcing vessels to minimize their carbon footprint in response to Carbon Intensity Indicator (CII) requirements, for example by using biofuels.
- **The developing Chapter 5 – Net-Zero Framework,** which will demand the introduction of renewable fuels and effectively force the implementation of biofuels

The use of biofuels is further incentivized by local legislation, for example within the European Union (EU) by FuelEU Maritime and the EU Emissions Trading System (EU ETS).

The new regulations are explored in detail in Chapter 2. In combination, they have shifted the marine fuel demand towards the following fuels:

- **Very-low-sulphur fuel oil (VLSFO)**
  VLSFO has a maximum sulphur content of 0.50%. Successfully introduced in 2020, it is expected to dominate the market well into the 2030s.
- **Ultra-low-sulphur fuel oil (ULSFO)**
  ULSFO has a maximum sulphur content of 0.10%, which is the fuel sulphur limit in the Emission Control Areas (ECAs) that began appearing in 2015. New ECAs are still being introduced by IMO. Today, the majority of ULSFO grades are based on marine gas oil (MGO).
- **High-sulphur fuel oil (HSFO)**
  HSFO, which has a sulphur content between 0.50% and 3.50%, can be used in combination with an exhaust gas cleaning system (scrubber). By installing a scrubber, vessels can secure fuel sulphur compliance while continuing to use fuel with a relatively low cost.
- **Liquefied natural gas (LNG)**
  LNG as a fuel for vessels other than LNG carriers has seen significant growth in the early 2020s. The trend is expected to continue, driven by two significant factors: very low non-CO_2 emissions, which make LNG ideal for use in port, and the classification of LNG as a low-CO_2 fuel in the MARPOL legislation, which makes it a viable compliance option.
- **Renewable fuel oils (biofuels)**
  Renewable fuel oils are fast becoming part of the fuel mix as a result of greenhouse gas (GHG) regulations. They comprise well-known biofuel options like fatty acid methyl ester (FAME) and hydrotreated vegetable oil (HVO), but also less defined options that require deeper knowledge and significant caution.
- **Other biological and non-biological renewable fuels**
  A range of other renewable fuels, including bioethanol (a non-oil biofuel), methanol and e-ammonia, are also emerging as marine fuel alternatives. As with renewable fuel oils, decarbonization is the driving force between these options.

This book focuses solely on the marine fuel oils in today's fuel mix: VLSFO, ULSFO, HSFO and renewable fuel oils. Other fuels, including LNG, bioethanol, e-ammonia and methanol are outside its scope and will not be covered.

1.3 Increased blending of marine fuel oils

The supply of the various sulphur-graded fuels – VLSFO, ULSFO and HSFO – is now well established. However, today's fuel market is complicated by measures intended to promote decarbonization. These include measures decided during MEPC 83 in 2025, as well as national and regional measures, e.g. in Indonesia and the EU.

In the European Union, for example, FuelEU Maritime and the EU ETS (see Chapter 2) are meant to promote the use of sustainable fuels in shipping. Specifically, they penalize GHG emissions, making it more expensive to operate solely on fossil fuels. Each year, the emission limits are tightened. A similar mechanism was introduced by the International Maritime Organization (IMO) in 2025.

In practice, such measures force the blending of familiar sulphur-graded fuels with less familiar biofuels. The vast majority of the world fleet cannot convert its energy supply to fuels other than marine fuel oils. So most vessels must rely on petroleum-based or renewable oils, i.e. fuels that can be used with their existing equipment for fuel handling and treatment.

As the emission limits tighten, the proportion of biofuel needed to avoid penalties will steadily increase. Consequently, shipowners and charterers that target the most cost-effective means of fuel management will need an ever-increasing amount of biofuel in their bunkers. The biofuel used will need to conform to the sustainability and GHG reduction requirements of the regulations, but it should also be the most cost-effective biofuel available. An on-spec, automotive-ready biofuel is not necessarily the most cost-effective biofuel for shipping, especially as the demand may be much larger than the supply.

This book will not offer guidance on choosing fuels in response to the various regulations. As a technical document, it provides insight into how to specify marine fuel oils and use them on board. The remaining sections of this chapter elaborate on the different types of marine fuel oils, along with their methods of production. This includes the automotive-ready biofuels FAME and HVO, as well as biofuels that are unsuitable for the automotive industry but which can be processed by fuel oil installations on board – even though they are not approved in the current ISO 8217 standard.

1.4 Fossil fuel oils

Fossil fuel oils are derived from petroleum by means of refining. The refining process (see fact spread on following pages) produces fuels in a range of quality grades, including the residual grades that have been used on vessels for decades. Residual fuels are well established and remain popular due to their low cost in comparison to other fuels, but they pose significant challenges for fuel treatment. The most notable is the presence of cat fines, which are discussed at length in Section 3.1.

1.4.1 Residual fuel oil (VLSFO and HSFO)

Residual fuel oil, or heavy fuel oil (HFO), is essentially a refinery by-product. The main production drivers in the refining industry are the light and middle distillate grades, which are used to formulate petrol (gasoline), jet fuel, automotive diesel fuel and chemical feedstock. HFO, by contrast, is blended to satisfy market demand for a relatively cheap source of energy.

Since the implementation of a global fuel sulphur cap in 2020 (see Section 2.3.1), the terms very-low-sulphur fuel oil (VLSFO) and high-sulphur fuel oil (HSFO) are in common use. These are further divisions of HFO, although the only formal chemical distinction is the maximum sulphur content, which is 0.50% by mass for VLSFO and 3.50% by mass for HSFO.

1.4.2 Distillate fuel

The use of distillates has grown more common within shipping due to the 0.10% sulphur cap in ECAs that entered into force in 2015. (See Section 2.3.1.) Vessels can generally be assumed to run on VLSFO, but they switch to distillates whenever they enter ECAs.

The distillate fuel used in the marine industry is commonly divided into marine gas oil (MGO), which is a pure distillate, and marine diesel oil (MDO), which is a blend comprising both distillates and residuals (up to 10%). Because distillate fuel is often used in areas with a fuel sulphur limit of 0.10%, the term ultra-low-sulphur fuel oil (ULSFO) is frequently used as a synonym. This is not formally correct, however, as ULSFO is only defined by its maximum sulphur content.

Refining processes and fuel production

Crude oil is the source of the most common fuels, which are produced through refining. Some of the basic refining processes are described below. Special emphasis is placed on catalytic cracking, a secondary conversion process that leads to catalytic fines (cat fines) in residual fuel. More on cat fines and the significant operational challenges they pose can be found in Section 3.1.

Crude oil
Crude oil is a complex mixture of hydrocarbons. It is recovered from geological pockets through drilling, then refined into various petroleum products. Due to significant variations in density, viscosity, sulphur content, vanadium content and other properties, no two crude oil deposits are alike. As a result, the end products can also vary from one refinery to another.

Distillation
Refineries use distillation to separate the crude oil into fractions, creating the components of fuels. In the early days of refining, only atmospheric distillation was used to obtain the required grades in the required quantity. Since then, vacuum distillation has enabled further refinement of atmospheric residue.

Atmospheric distillation
Atmospheric distillation is the first step in refining the crude oil. The process leverages the fact that the diverse hydrocarbons in the crude oil mixture have different boiling points. The lightest and most volatile hydrocarbons boil off as vapours first, while the heaviest and least volatile boil off last (Figure 1).

The non-boiling fraction collects at the base of the fractionating tower. This fraction, referred to as atmospheric residue, may be used as a blending component in residual fuel oil.

Atmospheric distillation is a relatively simple physical process where the type of crude determines the percentage of each product that can be obtained through boiling. To increase refining margins, many refineries make use of additional vacuum distillation and other refining processes. The aim is to reduce the amount of residue and increase the amount of distillate fuel produced.

Vacuum distillation
Vacuum distillation follows the same principle as atmospheric distillation, but the process takes place under vacuum conditions. Due to the correlation between pressure and the boiling point of a liquid, a higher proportion of light distillate fractions can be drawn off without reaching temperatures that cause thermal decomposition.

As in atmospheric distillation, not all the liquid vaporizes. The fraction collected at the bottom of the vacuum distillation tower, referred to as vacuum residue, may be used as a component of marine residual fuels.

On their own, atmospheric and vacuum distillation do not produce enough distillate products to meet increasing global demand. Subsequent and more complex refinery processes, known as secondary conversion processes, are frequently required.

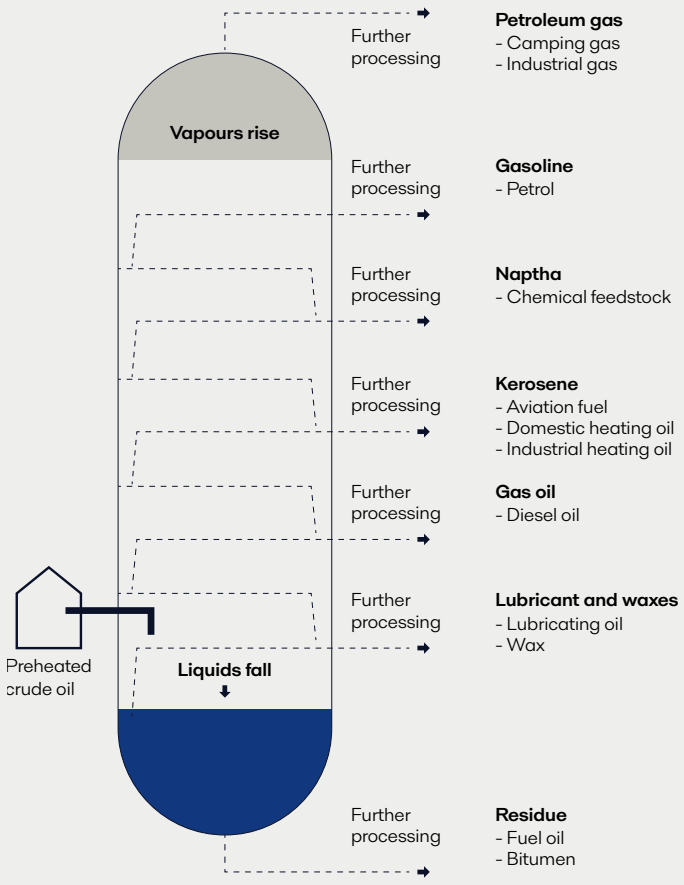


Figure 1: Distillation of crude oil into different fractions
Distillation is carried out as a continuous process in a fractionating tower.

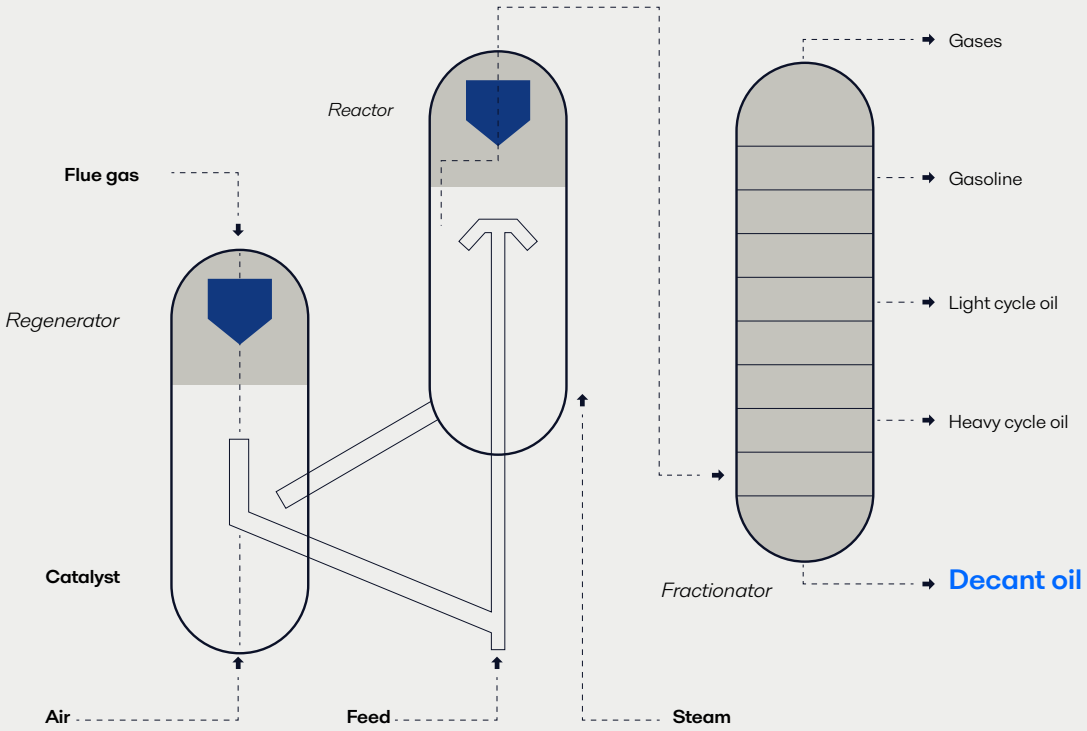


Figure 2: The catalytic cracking process
Hard chemical catalysts are used to break down complex hydrocarbons. These catalysts are the origin of catalytic fines.

Secondary conversion processes

Secondary conversion processes allow refineries to extract a higher proportion of light distillate fuel from the crude oil. Whereas distillation separates fractions of crude oil according to their volatility, these processes alter the chemical structure of the fractions themselves.Secondary conversion processes include 'cracking' the long hydrocarbon chains of heavy fuel fractions into shorter molecules, which can then be more easily processed into required fuel oil products. There are two basic types of cracking processes: thermal and catalytic.

Thermal cracking

Thermal cracking uses temperature and pressure to provoke a chemical reaction that alters the structure of the oil. It can be performed on both distillate and residual fuels. One typical thermal cracking process is visbreaking, which significantly lowers the viscosity of heavy residue to enable blending with other fuel oils. Another is coking, a very severe form of thermal cracking that converts the heaviest low-value residue into valuable distillates and coke.

Catalytic cracking

Catalytic cracking uses chemical catalysts, rather than high pressure, to break down complex hydrocarbons into simpler molecules. Catalysts are substances that stimulate a chemical reaction without being changed in the reaction itself. Their chemical properties remain constant throughout the process.

The most common cracking process is fluid catalytic cracking (FCC), which is used to convert gas oil and residual oil into high-octane petrol (gasoline) and diesel fuel. Figure 2 shows how the catalysts, in the form of fine particles with a diameter of approximately 20–100 µm, are circulated between a reactor and a regenerator in a fluidized bed process. The catalysts used in the process are generally expensive, and large cracker units typically contain around 500 tonnes of catalyst.

Hot catalyst from the regenerator mixes with the feedstock before entering the reactor, causing the feedstock to vaporize. The vaporized hydrocarbons then undergo catalytic cracking reactions on the surface of the catalyst, breaking into smaller molecules to achieve the desired product quality. During this process, some carbon is deposited on the catalyst particles. The catalyst and vapours are then separated in the reactor, where the vapours rise and flow into a fractionating tower for further processing. The catalyst flows back into the regenerator, where heat is applied to burn off the carbon deposits before the catalyst is returned to the reactor to be mixed anew with the feedstock.

Continuous recycling of the catalyst causes it to break up into smaller particles, primarily due to attrition. Some of these particles, commonly referred to as cat fines, are carried over into the fractionating tower. Although refiners use cyclones to minimize the loss of catalyst from the catalytic cracking process, some carryover of cat fines is inevitable.

The product drawn off at the bottom of the fractionating tower is called slurry oil, decant oil or FCC bottoms. It has a high density of around 1000 kg/m^3 at 15°C and a low viscosity of approximately 30–60 cSt at 50°C. It is an ideal blending component for residual fuels due to its high aromaticity, conferring stability to the end fuel product. However, it is through this bottom fraction of catalytic refining that cat fines enter marine residual fuel. Cat fines can cause severe or even catastrophic damage to the engines in which the fuel is combusted, as discussed in detail in Section 3.1.

1.5 Renewable fuel oils (biofuels)

Renewable fuel oils are fast becoming part of the marine fuel mix as a result of decarbonization and greenhouse gas regulations (see Section 2.4). In most cases these oils are biofuels, derived from vegetable oils and fats. But there are also oils that comprise recovered carbon from non-biological waste products such as tyres (tyre pyrolysis oils).

Vegetable oils and fats are sulphur-free and can be converted into fuel suitable for combustion in diesel engines. The oil must be processed to reduce its viscosity and improve its cold flow properties (see Section 3.2.4), with the specific processing method determining the final oil characteristics. An extensive explanation of biofuels for shipping can be found in the Alfa Laval white paper Marine biofuels: What to expect in the coming decades.

1.5.1 Fatty acid methyl ester (FAME)

FAME is a so-called biodiesel. Biodiesels are derived exclusively from fats and oils such as animal fats (e.g. tallow oil), vegetable oils (e.g. palm oil, soybean oil or rapeseed oil) and used cooking oil. They are produced through a transesterification process with methanol in the presence of a catalyst.

As a biodiesel, FAME can replace MDO and MGO in low- to medium-speed diesel engines. However, it is more commonly used as a blending component, and it can be blended with residual oil as well. Depending on its chemical composition, FAME in neat form can be compromised by cold weather, thereby causing problems in engine systems.

FAME is internationally specified in EN 14214 and ASTM 6751, but national standards exist that vary on minor details. Marine FAME specifications, which are currently in development, will be based on the Dutch standard NEN 7427-1. They will specify where FAME can deviate from automotive grade FAME but still be suitable for use on board.

1.5.2 Hydrotreated vegetable oil (HVO)

HVO, or renewable diesel, is derived through hydrogenation. It is also known as hydrotreated esters and fatty acids (HEFA) or hydrotreated renewable oil (HRO). HVO can be produced from the same biomass as FAME, but it may also be produced from residual crops and industrial waste like wood spill.

HVO is specified in EN 15940:2016 Class A and is considered a drop-in fuel for the automotive industry. The major factor impacting fuel treatment on marine vessels is its low density of 770–790 kg/m^3, which needs to be understood and mitigated in the fuel supply system.

The biofuels above, FAME and HVO, are very well defined and derived through well-known production processes. The fuels themselves – if tested and within specification – can be utilized on board if the equipment is up to date and prepared to handle biofuel.

There are other renewable fuels in development that do not fulfil the requirements of the automotive industry. They may, however, be utilized on vessels with proper knowledge and understanding. Engineers who work with these emerging alternatives must have additional training to ensure correct fuel handling and proper treatment with onboard equipment before the fuel is supplied to the engine.

Some examples of renewable fuel oils that have reached the point of lab trials or field tests can be found below.

1.5.3 FAME distillate residues (FDR)

FAME is a distillate derived from fats and vegetable oils, just as MGO is a distillate of crude oil. Similarly, just as residual oils like VLSFO and HSFO are the residues of crude oil, FDR is a residual, leftover product taken from the bottom of the distillate column. FDR can be used in the same way as HFO on seagoing vessels– especially on those that already have HFO equipment on board to heat and clean it.

Of course, FDR contains many undesirable residual components, and these must be specified to some degree for the FDR to be used on board. The same Dutch working group that established the NEN 7427-1 standard for FAME (see Section 1.5.1) is now working towards NEN 7427-2, a standard to cover FDR. The development of NEN 7427-2 is being monitored closely by the ISO 8217 working group, which will use it as the basis for a later international standard.

1.5.4 Cashew nutshell liquid (CNSL)

In 2023, the world produced 4,000,000 tonnes of cashew nuts (Our World in Data, 2026), the shells of which contain a high-value liquid that can be pressed out and combusted. This liquid, CNSL, has many disadvantages. But investigations are underway to ready it for use as fuel, looking into more favourable extraction methods, the use of additives and post-processing.

CNSL is a caustic, viscous oil that is extracted from cashew shells after the nuts have been harvested. The chemical composition of the oil may vary, depending on the source of the cashew tree and the extraction method. The main component making it suitable for fuel use is cardanol, which is extracted by roasting the nutshells to produce technical CNSL.

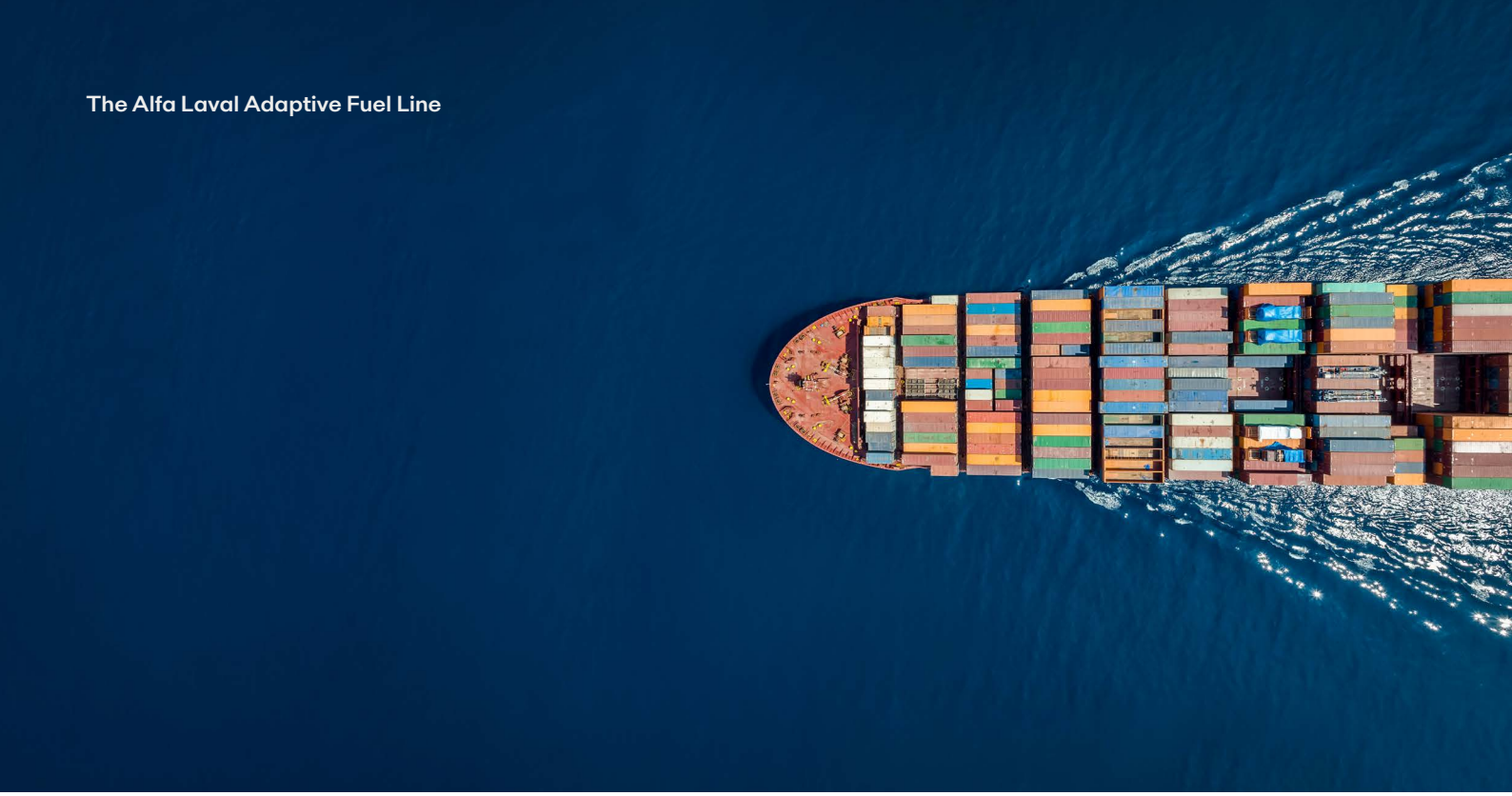
Cardanol, along with other derivatives that may be present in CNSL, can polymerize at temperatures of 200–250°C. Such behaviour is not typically seen in marine fuel line equipment, where the critical temperature of around 200°C is not reached. However, it can occur in the engine fuel injectors following the fuel line, causing the injectors to block up with lacquer.

CNSL can be blended into residual fuel oil and diesel oil to a level of up to 30%. When CNSL is used as a blending component, the stability of the blend is an important parameter for use on board. As with all fuels, CNSL must be handled safely – especially due to its potential acidity, which may be higher or lower depending on the production process and blending composition. As an example, a blend of 30% CNSL and 70% MGO can remove all paint from the components it is spilled on.

1.5.5 Pyrolysis oil from cashew shell press cake (POCC)

After CNSL has been extracted from cashew nutshells, the remaining press cake can be put through a pyrolysis process. The resulting oil, POCC, is a residual product created from another residual product, which means its sustainability value is very high. However, its harsh properties mean that it can only be used in marine fuel applications.

At sea, POCC can be used as a fuel blending component. Its chemical properties make it a good candidate for blending with VLSFO, and field tests on board show very good results in both usability and performance. Having been an advisor in the tests (FVTR, 2024), Alfa Laval can confirm the results and the fact that POCC blends fulfil the property requirements of ISO 8217:2024 for onboard use.



2 The regulations driving fuel choices and change

The complexity of today's marine fuel market, which comprises a growing number of fuel oil types, is driven largely by regulations. Through various measures, international and national bodies are incentivizing the move to cleaner fuels. This chapter explains the key regulations and their targets: sulphur emissions and greenhouse gas (GHG) emissions.

2.1 Global maritime legislation

Shipping is regulated globally by the International Maritime Organization (IMO). IMO is a United Nations (UN) body where member states, trade organizations and non-governmental organizations (NGOs) meet, discuss and conclude everything to do with international shipping – where vessels move between one state and the next. Agreements made within IMO are then implemented in the national law of the member states.

One of IMO's main responsibilities is protecting the environment from adverse effects of shipping, such as pollution. The Marine Environment Protection Committee (MEPC) is an IMO council that meets biannually to discuss environmental legislation. Its decisions on pollution prevention are incorporated into the International Convention for the Prevention of Pollution from Ships, commonly referred to as MARPOL.

Adopted in 1973 and modified by the 1978 Protocol, MARPOL covers pollution by oil, noxious liquid substances, harmful substances in packaged form, sewage, garbage and air pollution. Accepted into law by the IMO member states, it dictates pollution limits through six technical annexes, each of which addresses a specific type of pollution.

Sulphur emissions and GHG emissions, both the result of fuel combustion, fall under MARPOL Annex VI – Regulations for the Prevention of Air Pollution from Ships.

2.2 Regional maritime legislation

The global regulatory framework is supplemented by regional regulations. Individual nations or groups of nations can establish their own policies and mechanisms. These may be aimed at speeding up local implementation of global goals, but they may also introduce additional or stricter requirements.

In addition to exploring relevant sections of MARPOL Annex VI, this chapter presents related regulations introduced by the European Union (EU).

2.3 Sulphur emission regulations

The sulphur content in exhaust gas, comprised mainly of sulphur oxides (SOx), has long been a regulatory target. In the marine industry, regulations designed to lower sulphur emissions have greatly influenced the fuels in use. Since 2020, when a global fuel sulphur cap went into effect, the impact has been extreme.

SOx forms during combustion when the sulphur in the fuel combines with oxygen in the combustion chamber. There are good reasons to prevent SOx – and other sulphur compounds – from being released into the air. Atmospheric sulphur contributes to water and soil acidification, and it has a negative impact on human health. When the sulphur reacts with air, it forms small particles known as sulphate aerosols, which can pass through the lungs and enter the bloodstream. When breathed in, they can trigger lung inflammation and lead to cardiovascular disease, as well as lung and heart failure (IMO, 2020).

2.3.1 Sulphur in MARPOL Annex VI

Two regulations form the bulk of the MARPOL Annex VI legislation regarding sulphur emissions: Regulation 14 and Regulation 4.

- **Regulation 14 – Sulphur Oxides (SOx) and Particulate Matter**
  This regulation covers SOx and particulate matter, and it applies to all fuels used by vessels in operation after the introduction date. It addresses these emissions by defining maximum fuel sulphur content, where compliance is to be achieved based on the fuel as loaded.

  Regulation 14 sets two different fuel sulphur limits. One limit applies inside Emission Control Areas (ECAs), which are areas defined by IMO as requiring a higher level of protection. Another limit applies outside of them.

  ECAs are subject to change, meaning that additional ECAs may be introduced in the future. It should also be noted that different ECAs exist for different types of emissions and pollution. In addition to SOx ECAs (SECA in Figure 3), there are also nitrogen oxide (NOx) ECAs (NECA in Figure 3) and ECAs related to ballast water.

  The fuel sulphur limits have gradually been reduced, both inside and outside ECAs. In 2020, a global fuel sulphur cap of 0.50% came into effect, whereas the limit within an ECA is 0.10%.

- **Regulation 4 – Equivalents**
  This regulation covers equivalents, meaning alternative methods of compliance that achieve an emissions reduction matching (or exceeding) the use of compliant fuels as defined by Regulation 14. The most common equivalent is the use of an exhaust gas cleaning system (scrubber) to abate SOx when using high-sulphur fuels.

2.3.2 Sulphur in EU regulations

To implement the MARPOL Annex VI regulations in EU legislation, the EU originally developed Directive 1999/32/EC, which was subsequently amended by Directive 2005/33/EU. Over time, certain additional requirements have been introduced. Notable additions include:

- As of 1 January 2010, vessels at berth in an EU port must use fuel with a maximum sulphur content of 0.10%, except for vessels that, according to published timetables, are due to be at berth for less than two hours.
- As of 1 January 2011, European Parliament Directive 2009/30/EC requires that vessels in inland waterways use fuel with a maximum sulphur content of 0.0010% (10 mg/kg).

Directive 2016/802, which incorporates the latest MARPOL Annex VI regulations and is the directive in force today, contains the following additional stipulation:

- Fuel with more than 3.50% sulphur content will only be allowed for sale to and use by vessels equipped with an approved closed-loop exhaust gas cleaning system (i.e., one with no discharge of wash water overboard).

All EU regulations related to fuel sulphur can be found at EUR-Lex: http://eur-lex.europa.eu

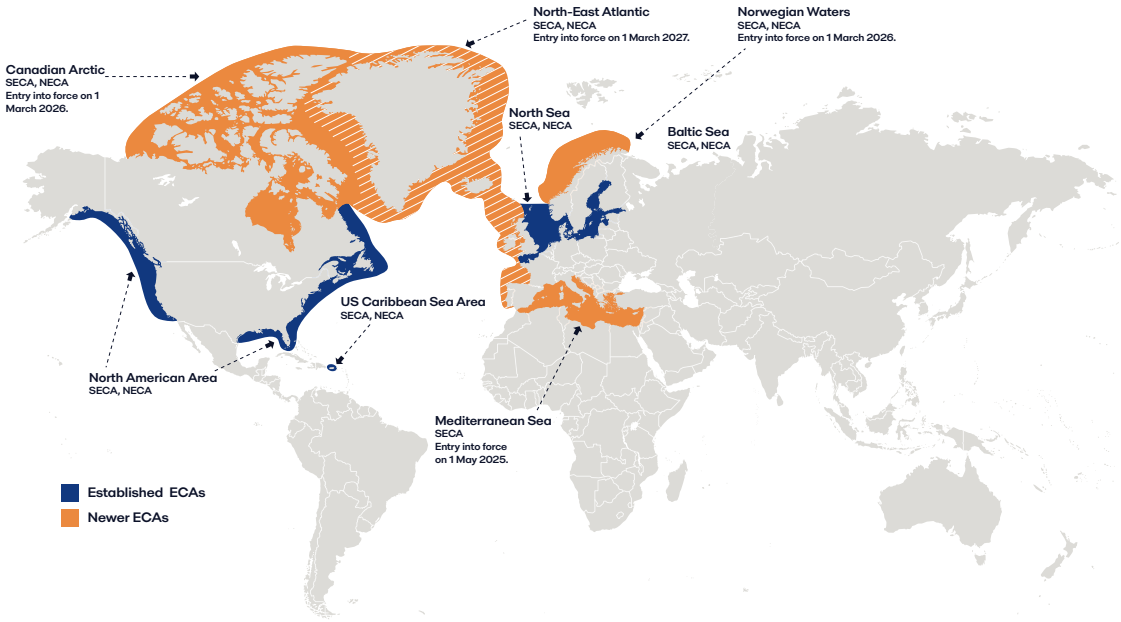


Figure 3:
Emission Control Areas
The map shows established and newer ECAs, where there is more stringent control of SOx (SECA) and NOx (NECA) emissions (ABS, 2026).

2.4 Greenhouse gas regulations

Reducing GHG emissions is crucial to slowing climate change, protecting ecosystems, ensuring clean air and safeguarding future generations from extreme weather, rising sea levels and biodiversity loss. International shipping has a major role to play in this effort, even if it is not directly included in the national targets of the 2015 Paris Agreement. Emissions from shipping represent around 3% of the world's total GHG emissions (IMO, 2020).

IMO has set its own targets for reducing GHG emissions from vessels. As agreed at MEPC 80 in 2023, the aim is to reach net-zero GHG emissions by 2050, which aligns with the Paris Agreement. Intermediate checkpoints have also been set, calling for at least 20% reduction by 2030 and at least 70% reduction by 2040 compared to 2008 levels.

Over the long term, the IMO GHG strategy is driving a transition to lower-carbon fuels like LNG and methanol – and eventually to carbon-free ammonia. These fuels are beyond the scope of this book. However, it is also forcing vessels to adopt energy efficiency measures today, reducing fuel consumption no matter which fuels they use. Likewise, there are economic incentives that push for an immediate transition to biofuels.

2.4.1 Greenhouse gases in IMO MARPOL Annex VI

In recent years, two major chapters with GHG emissions in focus have been added to the MARPOL Annex VI legislation: Chapter 4 and Chapter 5.

- **Chapter 4 – Energy Efficiency Regulations**

  MARPOL Annex VI Chapter 4 contains a range of regulations that force vessels to adopt energy efficiency measures. The measures are intended to reduce GHG emissions by reducing onboard energy use, thereby reducing the need to combust fuel. The key measures are:

  - **Energy Efficiency Design Index (EEDI)**, which entered into force in 2013, sets a minimum energy efficiency standard for the design of new vessels leaving the shipyard. Over the years, the standard has grown more stringent in phases. Phase 3, which is the strictest and final phase, is now in place.
  - **Energy Efficiency Existing Ships Index (EEXI),** which entered into force in 2023, sets a minimum energy efficiency standard for existing vessels. Vessels must undergo a one-time assessment to ensure that their GHG emissions are acceptable. To comply with the standard, many vessels have had to implement engine power limitation (EPL), eliminating the possibility of inefficient sailing at high power.
  - **Carbon Intensity Indicator (CII),** which entered into force in 2023, is an annual operational assessment of a vessel's fuel consumption per nautical mile. Vessels are rated on a scale from A to E, where ratings D and E demand corrective actions to improve energy efficiency. Each year the CII requirements become more stringent, and vessels are required to maintain a Ship Energy Efficiency Management Plan (SEEMP).

    The interim guidance provided in MEPC.1/Circ.905, also in effect since 2023, allows certified biofuels to be used for a positive influence on CII ratings.

- **Chapter 5 – Regulations on the IMO Net-Zero Framework**
  At the MEPC 83 session in April 2025, IMO decided to introduce a new chapter into MARPOL Annex VI. Chapter 5 is a well-to-wake (WtW) consideration of the fuels, energies and technologies that vessels use. It contains a technical element and related economic elements:

  - **GHG Fuel Intensity (GFI)** is a metric of GHG emissions per unit of energy used in shipping, evaluated over the entire fuel life cycle. The weighted average GFI of the fuels used must not exceed a specified maximum, which decreases year by year and is averaged over the calendar year.
  - **A two-tier penalty system** is implemented when the specified GFI maximum is exceeded. The system is a pay-to-comply arrangement where vessels must buy Remedial Units (RUs), i.e. pay a fine, to compensate for the infraction.
  - **Rewards** can be issued to vessels using zero or near-zero (ZNZ) fuels. Vessels that perform better than the GFI target can generate Surplus Units (SUs), which can be traded within the fleet to help other vessels comply. Monetary rewards, derived from RU payments, may also be offered.

At the time of this publication, the implementation date for Chapter 5 has not been finalized. However, it will have a significant impact when it enters into force.

For vessels to comply with Chapter 5 rules without using LNG, methanol, ammonia or some other ZNZ fuel, the only alternative is to use biofuels. (See Section 1.3.) By adding an incremental amount of biofuel into the total amount of fuel used on a yearly basis, penalties can be mitigated, avoided or compensated with SUs. It is important to note that GFI is calculated as a weighted average over the calendar year, which opens the door for multiple compliance strategies. These include:

- Using low-concentration biofuel blends
- Using high-concentration biofuel blends for short periods of time
- Using biofuels on one vessel and sharing SUs to compensate on other vessels within the fleet

2.4.2 Greenhouse gases in EU regulations

The EU has also adopted legislation that places a monetary value on the amount of GHG emitted. Fuel EU Maritime and the EU Emissions Trading System (EU ETS) are key EU tools for promoting decarbonization.

- FuelEU Maritime sets limits on the GHG intensity of the energy used by vessels, pushing vessel operators to use cleaner fuels and technologies. The limits apply to all energy used within the EU, as well as to half the energy used on voyages to or from the EU.
- The EU ETS, extended to shipping in 2024, requires vessel operators to buy allowances for their CO_2 emissions on voyages within the EU, as well on half of international voyages to or from the EU. This creates a financial incentive to reduce emissions.

Together, these measures drive the maritime sector towards greener operations that will help meet EU climate targets. Moreover, they explicitly promote the use of biofuels to reduce carbon footprint.

As will be the case with MARPOL Annex VI Chapter 5 when it takes effect (see Section 2.4.1), vessels that are not equipped for advanced ZNZ fuels will need to use biofuels to avoid penalties when calling in the EU. It is very important for vessels coming to and leaving the EU to report the use of biofuel in the most optimized way to comply with the required GHG intensity.

"The goal of this chapter is to reduce greenhouse gas (GHG) emissions from international shipping as soon as possible, delivering on the reduction targets set out in the 2023 IMO Strategy on Reduction of GHG Emissions from Ships, effectively promoting the energy transition of shipping and providing the world fleet with a needed incentive while contributing to a level playing field and a just and equitable transition."

(IMO, Circular letter No. 5005)

The Alfa Laval Adaptive Fuel Line

3 Operational challenges in working with today's fuels

ISO 8217 (see Section 1.1) defines the fuels for use on vessels, and fuels are expected to be delivered within its limits. However, as the standard ensures only minimum product viability, vigorous onboard treatment by trained professionals is still required.

The fuel oils introduced to comply with sulphur and greenhouse gas (GHG) regulations (see Chapter 2), as well as the need to work with multiple fuels, have increased treatment complexity. Before fuel treatment equipment and procedures are examined in following chapters, this chapter details key challenges posed by the fuels themselves in relation to storage, cleaning and final preparation for delivery to the engine.

3.1 Catalytic fines (cat fines)

Cat fines are tiny, very hard particles that typically consist of silicon and aluminium compounds. Their presence in marine residual fuel oils is a consequence of the refinement process known as catalytic cracking, where they form through the breakup of the catalyst due to continuous recycling (see fact spread in Section 1.4).

Cat fines are undesirable in fuel oil. Though virtually invisible to the human eye, they are hard enough to scratch metal easily (Alfa Laval, BP Marine, MAN B&W Diesel, 2007). If they remain present after fuel treatment, they can cause severe abrasive engine wear (MAN B&W Diesel A/S, 2017). This is why they must be removed to the greatest extent possible by the fuel cleaning system, a process discussed at length in Chapter 4.

Cat fines will remain a primary target of fuel cleaning so long as residual fuels are in use. While a growing amount of biofuel is now being mixed into residual fuel blends, dilution with biofuel does not remove the issue. Any cat fines present in the fuel are a significant danger.

3.1.1 Cat fine composition

The composition of cat fines varies, depending on the type of feedstock used and whether the main unit of the catalytic cracker is optimized towards production of light-grade petrol (gasoline) or heavier-grade diesel.

Although refiners today do not disclose the catalyst composition, all catalysts contain various forms of synthetic crystalline zeolite. The zeolite used in fluid catalytic cracking is typically composed of alumina and silica tetrahedral molecules, possessing one aluminium or silicon atom at the centre and one oxygen atom in each corner.

Aluminosilicate zeolite is especially suitable because of its microporous material structure, which allows the catalyst particles to hold high amounts of cations. The pores comprise around 10–60% of the particle volume (Figure 4), and specific rare metals are added to yield catalytic properties. The pores give the particles a large surface area, which enhances the chemical reaction in the cracking process.

Judging from scarce references in technical literature, the density of cat fines may vary between 0.9 and 1.3 g/cm^3, compared to a typical HFO density of 0.90–1.01 g/cm^3. The similar densities, plus the fact that zeolite pores are most likely filled with oil after the cracking process, suggest that settling alone is not an effective means of separating cat fines from the oil.

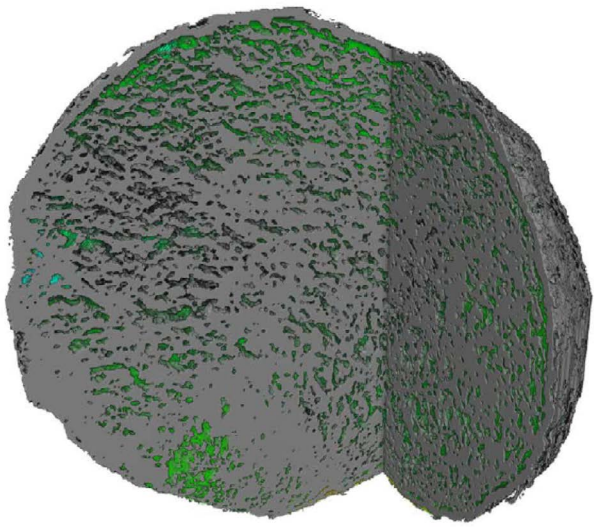


Figure 4: A magnified cat fine
Cat fine particles are porous and vary considerably in size and shape.

3.1.2 Quantifying cat fines

When discussing cat fines further, two quantifying measurements are needed: particle concentration and particle size.

- Particle concentration, which describes the mass ratio between the cat fines and fuel oil, is measured in parts per million (ppm). As an example, 60 mg/kg = 60 ppm.
- Particle size is measured in micrometres (µm), often referred to as microns. One micron is one millionth of a metre (10-6 m). Cat fines vary in size from submicron levels to approximately 30 µm or occasionally up to 100 µm – the size of a speck of dust or a grain of pollen up to the width of a human hair.

3.1.3 Cat fine concentration standards

The most recent revisions of ISO 8217, which is the globally accepted quality standard for fuels on the marine market, have restricted the concentration of cat fines in fuel oils to 60 ppm Al+Si (aluminium plus silicon) by mass. Marine engine makers, however, currently set 10 ppm as the maximum acceptable level of cat fines in fuel prior to injection. An allowance for 15 ppm can be made for short periods of time.

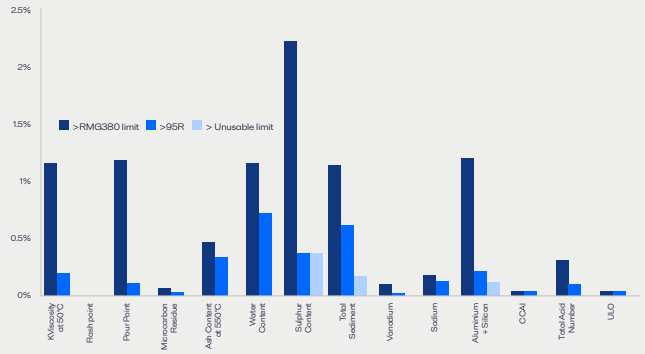
The large discrepancy between ISO 8217 and the limit set by engine makers highlights the importance of proper fuel cleaning procedures on board. Separation and filtration are needed to reduce the concentration of cat fines in bunker fuel to a level acceptable for the engine.

3.1.4 Measuring cat fine content

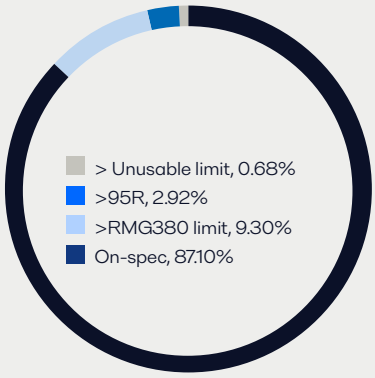
There are two reasons for determining the concentration of cat fines in fuel oil. The first is to check if the refined oil from a plant fulfils the ISO 8217 fuel standard, i.e. that it has an acceptable level of cat fines upon delivery. The second is to provide continuous updates on the quality of the fuel used on board, in order to meet engine maker specifications and thereby minimize engine wear.

ISO 10478 is the standard method of determining the aluminium and silicon content of fuel oils. Using inductively coupled plasma emission and atomic absorption spectroscopy, it identifies the concentration of cat fines in fuel oil. It is worth mentioning, however, that this method does not give any indication of cat fine size distribution, which is highly relevant in the context of onboard fuel treatment.

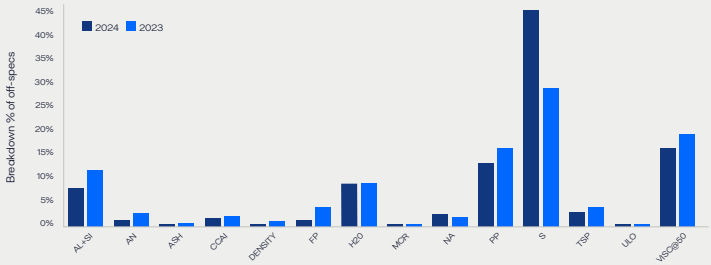
Considering the severe impact of cat fines on the engine, measuring the cat fine content of fuel oil has significant value as a part of onboard routines. Unfortunately, cat fines can only be reliably measured in a laboratory. Beyond testing cat fines by mass according to ISO 10478, it is possible to ask a laboratory to measure cat fine size distribution and propose a strategy according to the results.



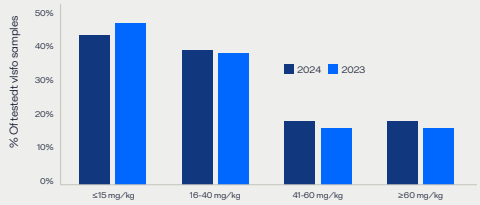
Residual off-spec (ISO 8217:2010 limits for RMG380 grade)
Source: VPS



Residual off-spec
Source: LR



VLSFO off-specs by parameter
Source: VPS



VLSFO cat fines
Source: VPS

Figure 5: Fuel statistics from Veritas Petroleum Services and Lloyd's Register

3.1.5 Cat fines in today's VLSFO

The presence of cat fines has not diminished over time. According to reports from Veritas Petroleum Services (VPS) (VPS, 2026) and Lloyd's Register (LR) (LR, 2026), the off-specification rate for VLSFO ranged from 5.4% to 9.3% during 2024 and the first half of 2025. (See off-spec statistics for VLSFO and residual fuels as a whole in Figure 5.)

VPS reported that 19% of all VLSFO samples tested exhibited cat fine concentrations above 40 ppm. Cat fine concentrations exceeding 60 ppm were found in 0.6% to 1.2% of all samples. Strikingly, the distribution of cat fine results in 2024 closely mirrored the distribution in 2023 across all VLSFO samples. (See distribution chart for VLSO cat fines in Figure 5.)

It is worth noting that the bunker quality may vary from one bunkering hub to another. While global quality is generally stable, specific regional issues highlight vulnerabilities in the supply chain. As an example, the ARA (Amsterdam-Rotterdam-Antwerp) region is one of the locations where off-specification fuel was most frequently identified. The region's large bunkering ports handle the largest quantities of bunker fuel globally, and they employ complex fuel blending, using various fuel components from diverse global sources to meet specifications. The complexity of their supply chains increases the inherent risk of occasional quality variations or contamination incidents.

3.1.6 HSFO fuel quality

Although VLSFO is increasingly in focus, HSFO represents almost 32% of all bunker samples tested by VPS. This highlights the fact that a significant portion of the global fleet is still using scrubbers for fuel sulphur compliance.

In 2024, 10.4% of HSFO samples were off-specification for at least one parameter, with cat fines accounting for 3% of cases – a reduction from 4% in 2023. Of all HSFO samples taken in 2024, 20% displayed cat fine concentrations above 40 ppm.

3.2 Characteristics affecting fuel storage and treatment

While cat fines remain the most acute threat in marine fuel oils, additional challenges are posed by the diversity of fuel oil types and the need for vessels to work with multiple fuels. Onboard fuel storage has become more complicated, and it is crucial to understand the characteristics of the fuels in use. Some of the most important characteristics relating to storage and treatment are explained here.

3.2.1 Instability

Instability refers to the tendency of marine fuels – especially residual fuels like heavy fuel oil – to undergo undesirable chemical changes during storage and use. Such changes can result in the formation of sludge, sediments and asphaltene agglomerates, which can clog filters, damage engines and disrupt vessel operations.

Fuel instability is measured with three tests defined in ISO 8217: potential total sediment (TSP), accelerated total sediment (TSA) and existent total sediment (TSE). These tests are described further in Section 4.2.

3.2.2 Incompatibility

Incompatibility is a phenomenon where blending two different fuels creates an unstable mixture, causing asphaltenes in the fuels to precipitate out of the liquid. This is an explicit risk when blending diesel oil into heavy fuel oil – something that should be avoided. But even two individually stable VLSFO types can, when mixed in a tank, become unstable due to incompatibility. This may result in filter clogging or separator blockage (see Figure 6). In extreme cases, it may even lead to engine fuel starvation and subsequent engine shutdown.

Because a certain amount of fuel mixing is unavoidable, proper housekeeping is key to avoiding unwanted fuel behaviour related to incompatibility. For example, bunker tanks should be as empty as possible before putting new fuel in. Likewise, when changing from one fuel batch to the next, the settling tank should be emptied to the lowest possible level. The same is true for the service tank – as far as it is safe to do so – before filling it with a new fuel. More on tank storage and fuel handling procedures can be found in Section 4.2.

Figure 6: A separator subjected to instable fuel

3.2.3 Viscosity

Fuel viscosity has always been a factor in fuel storage and treatment, but today's diversity of fuels makes it a more significant challenge. As a result of the manufacturing process, which includes various levels of fuel blending, VLSFO has a lower average viscosity than the HSFO that previously dominated the market – and tends to have a lower average density as well. Moreover, there can be wide variations in viscosity within fuels of the same grade. Even fuels sourced from the same supplier may differ substantially in their characteristics.

All this impacts the storage and treatment of the fuels on board, including the final delivery of fuel to the engine. The fuel supply system, which secures correct parameters at the engine inlet, is generally designed for the maximum viscosity of the fuel grade it is specified for. Since the actual viscosity of the fuel in use may be significantly lower, the fuel supply system must be able to operate efficiently with a wide range of viscosity values. In addition, it must be able to safeguard the changeover process between fuels with different characteristics. (See Section 3.3.)

3.2.4 Cold flow properties

Distillates are all characterized by low viscosity. However, they can differ in their chemical nature and exhibit large variations in their cold flow properties. At low temperatures, these properties can impact the fuel's viscosity and its ability to be pumped.
The cold flow properties of a distillate depend mainly on the wax content and the ability of long paraffinic hydrocarbon chains to precipitate as wax crystals. Cold flow properties is a collective name for several individual characteristics:

- Pour point (PP) is the lowest temperature at which the fuel will flow.
- Cloud point (CP), also known as wax appearance temperature (WAT), is the temperature at which dissolved paraffins begin to precipitate and give the fuel a cloudy appearance.
- This book uses both terms, referring to CP for distillates but to WAT for residual fuels. This reflects the fact that CP is a required measurement for distillate in ISO 8217 with a specified test method (ISO 301), whereas no such requirement exists for residual fuels. Alfa Laval recommends testing WAT for residual fuels in the same way, as this is the only test method available.
- Wax disappearance temperature (WDT) is the temperature at which the last solid wax crystals melt into the fuel when heated. The WDT is typically higher than the WAT.
- Cold filter plugging point (CFPP) is the lowest temperature at which the fuel will pass through a filter under specified conditions.

To avoid precipitation in fuel storage tanks, vessels operating in cold areas should demand distillates with winter quality specifications. Heating the distillate before separation is also recommended to prevent any waxes from precipitating within the treatment system.

Note that even biofuels can exhibit problematic cold flow properties. While it is not a universal phenomenon, the cold flow properties of FAME can be worse than those of most common diesel oil. Depending on the batch, FAME may crystallize at a higher temperature than fossil fuel – although the reverse may also be true.

3.3 Changeover between multiple fuels

Working with multiple fuels on board is an issue that extends beyond storage. Most operators have experience of changing over between residual and distillate fuels, and vice versa. Today, biofuels may also be part of the changeover equation.

Most vessels are not equipped with scrubbers, for example, which means they generally run on VLSFO. When entering an Emission Control Area (ECA), they need to switch to ULSFO to achieve compliance. When exiting, they usually switch back to VLSFO to reduce fuel costs – unless a return to the ECA is imminent. The changeover must take place while approaching the ECA boundary on entry or after passing it on exit, so that no non-compliant fuel is present in the system during ECA operation. While the vessel is within the ECA boundary, it must comply with the 0.10% fuel limit. When introducing a biofuel into the engine system, the changeover process does not have to be as abrupt as it is when switching between VLSFO and ULSFO for ECA operation. That said, vigilance is always advisable. The crew should be prepared to mitigate potential issues, such as filter clogging if residues from the pipes and tanks are flushed out by the biofuel.

Control over temperature and viscosity variations during changeover is paramount. (See Section 3.3.2.) Automatic fuel changeover systems are available, and these offer the highest level of protection, as they can be specified to control the temperature ramp throughout the changeover process. Changeover can be handled manually as well, but it is mandatory to have detailed changeover procedures in place, which must be documented in the vessel's Fuel Management Plan. Likewise, the crew must be familiar with the operation. Insufficient knowledge of the required actions may result in equipment damage or engine shutdown, which can be avoided with an automatic system.

3.3.1 General recommendations related to fuel changeover

While not part of the changeover procedure itself, there are a few associated recommendations that are good to be aware of:

- To avoid compounding incompatibility problems (such as asphaltenes precipitating in the tanks or contamination of the distillate with high-sulphur fuel, which will make it non-compliant), mixtures of residual and distillate fuel should not be returned to the residual or distillate service tank. (See Section 3.2.2.)
- Installing dedicated coolers is strongly recommended to control the distillate temperature. Automatic temperature control during changeover will secure a smooth temperature change at the engine inlet, keeping it within the gradient recommended by the engine maker (see Section 3.3.2).
- When a two-stroke engine is to be operated with low-sulphur fuel, engine makers recommend that the cylinder oil be switched to an oil with an appropriate base number (BN). Cylinder oil feed rates should also be taken into consideration, and engine maker recommendations must be followed. While using low-sulphur distillate fuel, operating two-stroke engines with high-BN cylinder oil at high feed rates can lead to rapid accumulation of piston crown deposits, which result in severe scuffing.

3.3.2 Technical considerations during fuel changeover

For detailed advice on fuel changeover procedures, specific recommendations from the relevant equipment manufacturer should be consulted. However, there are certain technical aspects that should always be considered during changeover: temperature gradient, viscosity, filtration and fuel consumption monitoring.

- **Temperature gradient**
  Rapid changes in fuel temperature will increase the likelihood of pump malfunction and seizures. To ensure fuel injection equipment continues to function properly, vessels should not exceed the recommended maximum temperature gradient during fuel changeover.

  Generally, engine makers recommend a gradient of no more than 2°C per minute. With this in mind, fuel changeover can take considerable time from initiation to completion – in some cases, more than 60 minutes for the fuel temperature change alone.

  Many engine makers recommend actions that can increase protection during the procedure. For example, reducing engine load when switching between HFO and distillate or MDO (or vice versa) helps to slow the rate of temperature change.

- **Viscosity**
  Typically, the optimum operational viscosity of a fuel at the engine fuel pump is within the range of 10–20 cSt, although it is vital to ensure that the specific requirements for each engine are met.

  To achieve optimum viscosity with residual fuels, it may be necessary to heat them to more than 100°C. However, distillate fuels have significantly lower viscosities than residual fuels, typically in the range of 2.0 to 11.0 cSt at 40°C. Distillates must not be heated unless demanded by challenging cold flow properties (see Section 3.2.4) – instead, they may have to be cooled or chilled.

  Engine makers recommend a minimum fuel viscosity at the engine fuel pump inlet of 2.0 to 3.0 cSt. Fuel with a viscosity that is too low may lead to excessive leakage within the engine fuel pumps, consequently lowering the fuel pressure. In turn, this can lead to startup difficulties and problems when operating at high load. Insufficient viscosity may also lead to fuel pump seizure and premature wear due to a reduced hydrodynamic lubricating oil film.

  In addition to the engine-mounted pumps, the pumps in the fuel handling system should be taken into consideration. The minimum viscosity for their operation is also close to 2 cSt, with lower viscosity carrying the risk of seizure or excessive wear.

  To achieve the equipment manufacturer's minimum requirements, distillate fuels should be sourced with sufficient viscosity. Fuel coolers or chillers can be used, if necessary, to help prevent the fuel viscosity from becoming too low. Additionally, shutting down pipework steam and trace heating systems early will assist in reducing the fuel temperature when changeover occurs.

  Conversely, when changing over from distillate and back to residual fuel, it is critical to ensure that the fuel temperature is sufficiently high to achieve the required viscosity at the fuel pump inlet. Pipework steam and trace heating systems can be switched on to assist this process. However, heating of the distillate must be avoided.
- **Filtration**
  Filters are impacted by the flushing effect of diesel oil during changeover, which forces accumulated residues from inside the piping to the filter. This can lead to increased manual cleaning intervals.
- **Fuel consumption monitoring**
  The need to prove compliance makes measuring the use of VLSFO and ULSFO more critical. Installing a dedicated flow meter for each fuel improves measurement accuracy, showing authorities clearly when it enters the fuel system. Mass flow meters are preferable to the volumetric type, since they allow direct measurement in weight units that are unaffected by density changes.

3.4 Energy efficiency and fuel flow

Saving fuel has been a priority at sea since machine propulsion was introduced – fuel being the largest operating expense in running a vessel. Traditionally, the motivation to conserve fuel has been balanced against speed, meaning the need to arrive on time or to be the first admitted to port. But today's greenhouse gas (GHG) regulations (see Section 2.4) are changing that relationship.

The regulations target emissions by demanding greater energy efficiency, placing legal and financial pressure on vessels to reduce the power they consume and the amount of fuel they burn. As result, slow steaming is the norm, and the fuel consumption of most vessels today is lower than the maximum design parameters of their fuel systems. In many cases it is far lower, which has operational consequences.

Operating at a fuel flow that is perhaps 30% of the design flow has a cascading impact. For example, it can influence heater regulation, affecting fuel temperature stability and the resulting fuel viscosity. In turn, this affects the separator, where it impairs fuel cleaning efficiency. By making it harder to remove a sufficient amount of cat fines and other impurities, temperature instability may lead to increased wear of engine equipment. Engine wear, in turn, quickly leads to poorer combustion and additional energy consumption.

A further consideration is the energy consumption within the fuel line itself. A fuel line that is only set up for maximum flow will always consume the same amount of energy – the maximum amount – no matter how much fuel is actually required by the engine. The individual systems should be adjusted to match the engine's fuel consumption. This is especially important when it comes to the separator, as reducing the flow not only reduces energy consumption but also significantly improves separation efficiency. This is explained more in Section 4.3.3.

4 Fuel oil treatment and engine performance

Marine diesel engines are designed to accept all commercially available fuel oils, provided they are adequately treated on board. For this purpose, a well-designed fuel treatment system is required. This chapter explains the main equipment and steps involved in fuel oil treatment, providing a basis for discussing modern optimization in Chapter 5.

4.1 Fuel oil treatment equipment in overview

Fuel oil treatment comprises two main processes: fuel cleaning and fuel conditioning. Centrifugal separators, in combination with a settling tank, are generally accepted as the fuel cleaning system within the industry. They are followed by a fuel supply system, which conditions the fuel to match engine maker specifications, and a filtration step as a last line of engine defence.

A typical fuel oil treatment system can be seen in Figure 7. The main components are described briefly below, and deeper exploration of the main treatment steps follows.

- **Settling tank**
  The settling tank relies on gravity to remove large and heavy particles from the fuel oil, such as large cat fines (see Section 3.1). Over time, these will accumulate at the bottom of the settling tank. However, high seas and rough weather may stir up the particles, causing them to be fed to the separators. Since the particle-removing capacity of the separators is limited, this may influence the purity of the cleaned fuel. Regular draining of the settling and service tanks is therefore crucial.
- **Separators**
  Separators remove particles by means of centrifugal force, applying many times the force of gravity. If properly operated, most separators can remove nearly 100% of the cat fines larger than 10 µm. However, separators will not remove most cat fines smaller than 3 µm when operating at the maximum recommended capacity (see Section 4.3.2). To check separation efficiency, it is recommended to take samples from the separator feed and outlet at least every four months, sending them to an established third-party institute for analysis.
- **Fuel supply system**
  The fuel supply system, sometimes referred to as a booster or fuel conditioning module, handles the delivery of fuel for injection into the engine. It conditions the fuel to meet engine maker specifications, ensuring that key properties like viscosity, pressure and flow fall within the appropriate range. This is ideally an automated process, especially considering modern fuel complexity. The fuel supply system may also incorporate the final filtration stage before the engine.
- **Filters**
  Filters are a final protective cleaning measure to prevent any remaining particles from entering the fuel injection system and engine. In some cases, a filter is incorporated into the fuel supply system. Since the particles trapped are low-density particles that have managed to pass through the separators, monitoring the pressure drop across the filter provides information about overall treatment system performance.

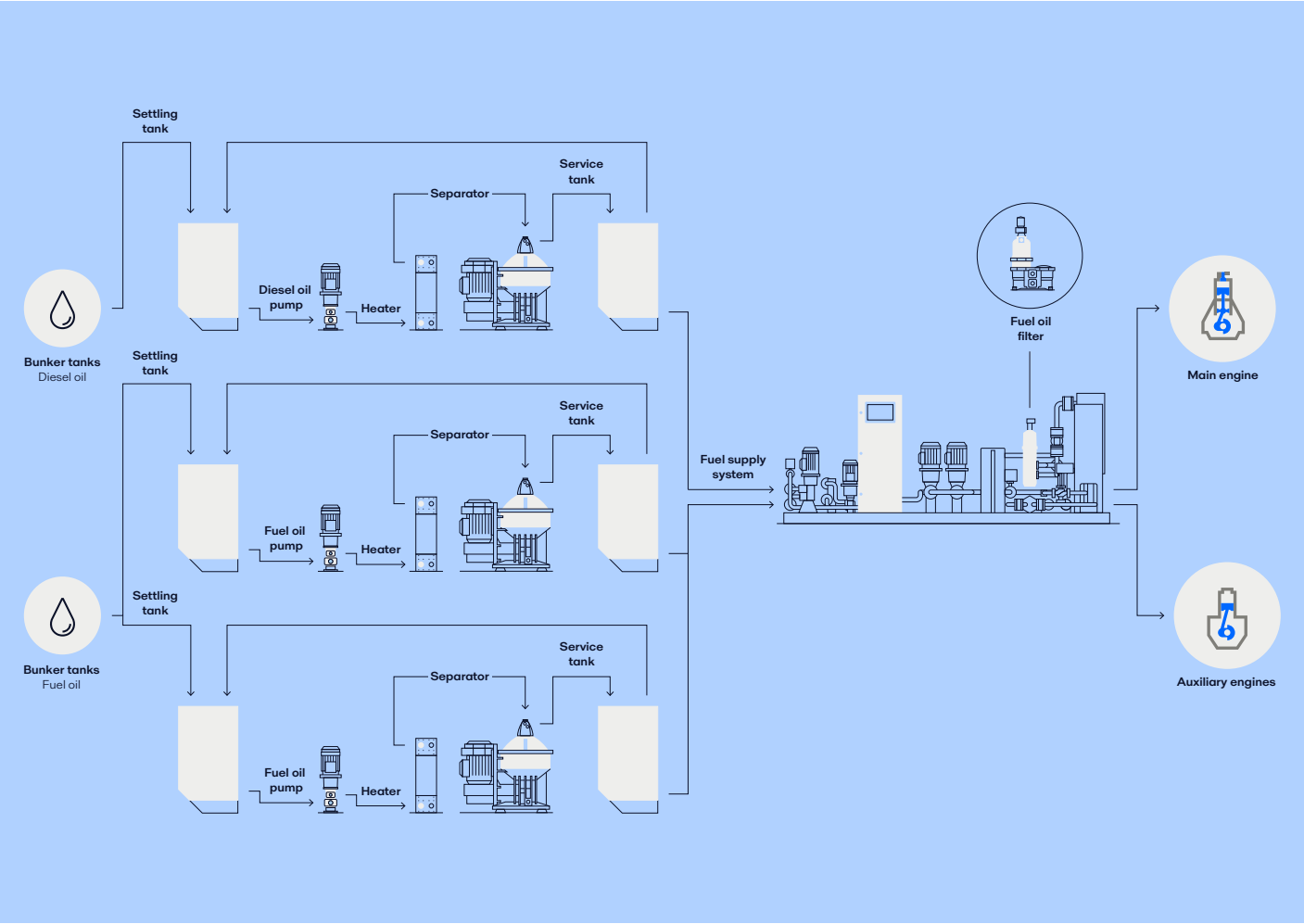


Figure 7: A typical fuel oil treatment system

Standards and recommendations for fuel oil treatment

The International Organization for Standardization (ISO) is an organization where industry experts and stakeholders convene to set up standards for international use. The international marine fuel standard, ISO8217 (see Section 1.1), is regularly updated by the relevant working group, comprising shipowners, fuel suppliers, engine makers and suppliers of fuel treatment equipment, e.g. Alfa Laval.

The International Council on Combustion Engines (CIMAC) is a non-profit collaboration that promotes the exchange of insights, technology and advancements among its members in 26 countries. Members include engine makers, equipment suppliers, oil companies, research organizations, classification societies and universities. CIMAC working groups develop solutions and guidelines that address technical, commercial and regulatory challenges in the large engine industry. Within the area of fuel oil treatment, the CIMAC and ISO 8217 working groups are somewhat similar.

Concerning onboard cleaning of the fuels in the ISO 8217 standard, CIMAC fuel guidelines (CIMAC, 2024) and Alfa Laval product guidelines converge in three basic – but essential – precautions for safe and efficient separator operation:

- Fuel must be preheated to the correct temperature before entering the separator.
- The correct separator capacity must be installed, meaning the fuel throughput must correspond to the specified flow.
- The separator must be properly operated and maintained.

In response to the growing issue of cat fine attacks (see Section 3.1), both ISO 8217 and CIMAC guidelines state that the content of cat fines in fuel oil delivered to vessels must not exceed 60 ppm. Engine makers demand further reduction of cat fine content by the fuel cleaning system on board, generally requiring a maximum of 10 ppm prior to fuel injection into the engine.

CIMAC
INTERNATIONAL COUNCIL ON COMBUSTION ENGINES

IMO

4.2 Fuel oil quality prior to treatment

Fuel treatment considerations begin when the fuel oil is taken aboard – before it actually enters the fuel treatment equipment. Changing demands have brought new fuel oils to the market, and quality varies even among fuels that are nominally classified as the same type. (See Chapter 1.) It is therefore essential to have accurate specifications for the fuel bunkered. Likewise, it is important to interpret the parameters correctly and to know which ones can be influenced by onboard fuel treatment.

Table 4.2 lists significant fuel oil parameters along with their main implications for vessel operation. The right-hand column indicates the degree to which each property can be affected by the fuel treatment system – in particular, the separators. Most of the parameters in Table 4.2 are included in the ISO 8217 marine fuel standard, some of them being derived from the VLSFO and/or biofuel blend tests that were introduced in ISO8217:2024.

It is important to understand the fuel's stability and how it will behave on board. Ideally, all sediment tests defined in ISO 8217:2024 should be carried out on a bunker sample. The test of potential total sediment (TSP) is obligatory, whereas the tests of accelerated total sediment (TSA) and existent total sediment (TSE) are recommended and do not impose set limits. Together, TSP, TSA and TSE provide a good indication of fuel stability, both in the bunker tank and in the separators. If any of these tests returns high values, it may indicate unstable fuel and the potential for high sedimentation – causing such high separator sludge loads that the required discharge rate prevents fuel processing.

Cold flow properties, such as cloud point (CP) and cold filter plugging point (CFPP) for distillate-biofuel blends and wax appearance temperature (WAT) and wax disappearance temperature (WDT) for residual-biofuel blends, must also be known to ensure that the fuel can be pumped once taken aboard. (See Section 3.2.4.)

Water content, sediments, sodium and cat fines can be reduced effectively by the onboard cleaning system. Some ash content can be reduced as well. It is also important to evaluate the levels of zinc, phosphorus and calcium, since these may indicate the presence of lube oil in the fuel.

Fuel property	Implication	Affected by separation
Density	Bunker price and separator adjustment	Not affected
Viscosity	Injection temperature and required heating/cooling	Not affected
Water content	Corrosion and deposits in tank	Strongly
Micro carbon residue (MCR)	Deposits in engine	Not affected
Sulphur content	Emissions, lubrication and base number (BN)	Not affected
Accelerated/existent/potential total sediment (TSA/TSE/TSP)	Separator (and filter) load	Strongly
Ash content	Engine wear	Moderately
Vanadium content	High-temperature corrosion in engine	Not affected
Sodium content	Deposits and salt corrosion in engine	Moderately
Aluminium and silicon (Al + Si) content (cat fines)	Abrasive wear	Moderately to strongly
Calculated Carbon Aromaticity Index (CCAI)	Engine ignition quality	Not affected
Flashpoint	SOLAS and classification society rules require temperatures of at least 60°C	Not affected
Acid number	Corrosion on parts	Not affected
Strong acid number	Corrosion on parts – a fuel rejection parameter as the equipment will agressively corrode to the point of breakdown	Not affected
Hydrogen sulphide (H2S) content	Corrosion on parts	Not affected
Oxidation stability (for DF grades)	Corrosion and deposits in tank	Moderately
Pour point (PP)	Filter clogging	Not affected
Fatty acid methyl ester (FAME) content	Bunker price, compliance and separator adjustment	Not affected
Cloud point (CP)	Tank storage issues and filter blockage	Not affected
Cold filter plugging point (CFPP)	Tank storage issues and filter blockage	Not affected
Wax appearance/disappearance temperature (WAT/WDT)	Tank storage issues and filter blockage	Not affected

Table: 4.2

4.3 Fuel cleaning to remove engine-damaging contaminants

In the fuel cleaning system, the settling tank and separators remove particles – rust, sand, dust and especially cat fines (see Section 3.1) – and water by leveraging the greater density of the contaminants in relation to the oil. The vast majority of the water can be removed from the tank manually after settling, and all particles will settle to the bottom of the tank if given enough time in stable conditions. Very small and less dense particles, however, will settle very slowly.

The separation force in the settling tank, where only gravity is at work, is 1 g (9.8 m/s2). In the separators, high-speed rotation creates a separation force many thousand times greater. The centrifugal force acts upon the cat fines and other particles in the way that gravity does in the tank, pushing them to the outside of the disc stack when they come into contact with a disc. The particles collect at the disc stack periphery, where they are removed by discharging the bowl.

The oil flow, however, moves in the opposite direction, passing through the centre of the bowl on its way out of the separator. If the flow rate is high enough that particles avoid contact with the discs, they may be carried along with it. At a certain rate, particles begin escaping with the oil – rather than being separated from it. This situation is similar to that of a settling tank on rough seas, where there is not enough time for the separation force to accomplish its job. With this in mind, sizing separators correctly is of utmost importance.

4.3.1 General factors in separator sizing

The maximum required flow through the separators is determined by the maximum expected need of the fuel consumers on board, i.e. the engines and boilers. This design consumption is normally calculated by the shipyard. The fuel flow through an engine can be calculated using the formula below, based on the maximum continuous rating (MCR) defined by the engine maker:

$$Q = \frac{P \cdot b \cdot 24}{\rho \cdot T} \text{ (l/h)}$$

Q = Fuel oil consumption (l/h)
P = MCR (kW or HP)
b = Specific fuel oil consumption (kg/kWh or kg/hph), specified by the engine supplier
ρ = Fuel oil density (presumed to be 0.96 kg/l)
T = Daily net operating time (number of operating hours per 24-hour day)

Flow is only one part of the sizing equation, however. The ability to separate particles from a liquid is determined by Stokes' law:

$$V_{settling} = \frac{d^2 (\rho_p - \rho_l)}{18\mu} \alpha$$

d = Particle diameter
ρρ = Particle density
ρl = Liquid density
μ = Liquid viscosity
α = Gravitational or, in a separator, centrifugal acceleration

The takeaway from this basic formula for separator performance is that centrifugal force provides effective separation when there is a large difference in density. Small particles with low density, on the other hand, remain difficult to remove.

4.3.2 Separator sizing and efficiency

A separator's flow capacity reflects its separation efficiency, i.e. its effectiveness at removing contaminants like cat fines. This can be determined either theoretically or practically. Theoretical performance is modelled using the design characteristics of the separator. A practical determination relies on a real-world simulation of cat fine removal, witnessed by a classification society.

- **Model-based: maximum recommended capacity (MRC)**
  The MRC of a separator is determined through factors like disc size, the number of discs and the speed at which the separator bowl rotates, based on the typical characteristics of the fuel oil grade the vessel is designed for. Suppliers set the MRC for their separators using their own individual criteria, which are not commonly known and are not absolutely comparable.
- **Observed: Certified Flow Rate (CFR)**
  The CFR method of measuring separator efficiency was introduced through a workshop agreement in 2005. CFR testing uses spherical particles of 5 µm in size, which are mixed into oil to simulate cat fines. The CFR on a separator's certificate is the rate at which 85% of the particles are removed at normal treatment viscosity, which is defined as 35 cSt for 380 cSt (at 50°C) fuel oil and 55 cSt for 700 cSt (at 50°C) fuel oil. These are the respective fuel viscosities at the standard separation temperature of 98°C.

The original workshop agreement, CWA 15375:2005, expired in 2014. But the testing procedure has remained in use due to the valuable transparency it creates. In 2022, an improved standard was finally released: EN 17763:2022. Unlike the original agreement, which allowed individual test results to be scaled across multiple separator sizes, today's CFR standard requires testing of each size within a separator range.

4.3.3 Reducing flow to improve the efficiency of existing separators

In separators, as in settling tanks, separation efficiency is partly a function of time. The longer the separation force is applied to the fluid, the more complete the separation will be. For this reason, reducing the flow through existing separators can have a positive effect.

When the flow is reduced, the fuel moves more slowly through the separator, spending more time in the separator bowl. This allows more time for water, cat fines and other particles to be separated from the fuel. In addition, the lower flow rate decreases turbulence, which makes the separation of water and heaver particles more effective.

In theory, the relationship between flow and separation efficiency is inversely proportional – when the flow is decreased by half, the separation efficiency should double. Utilizing this relationship can result in cleaner fuel output and less risk of contaminants reaching the engine. The equipment for doing this is explored in Section 5.3.1.

Cat fine removal and engine performance

The importance of the fuel cleaning system – and, above all, the efficiency of its separators – cannot be overstated. Any cat fines that remain in the fuel oil after cleaning have the potential to cause abrasive wear and engine damage (see Figure 8), leading to inefficient operation and possible safety risks.

Engine makers consider cat fines smaller than 4 µm in size to be less harmful than larger cat fines (CIMAC, 2013). The higher the cat fine concentration, however, the greater the potential threat. Engines subjected to high cat fine levels will likely require more frequent maintenance and face an increased risk of breakdown. The fuel injection system and combustion chamber are the parts of the engine system that are most susceptible to cat fine wear.

In the fuel injection pumps, which increase the pressure of the fuel before it enters the engine, there are small tolerances between the plunger and the barrel. As a result, particles can become trapped between these surfaces and embed themselves in the material. Corresponding problems can occur in common rail systems with similar tolerances.

After injection into the combustion chamber, the cat fines may become embedded between the piston ring and cylinder liner. Due to the relative movement between these surfaces, this causes abrasion and accelerated wear of the components.

Apart from the wear itself, there is a cumulative effect on engine efficiency. If the pumps are damaged, they will deliver subpar performance and lower fuel pressure to the engine. This, in turn, will reduce the engine's efficiency and increase its operational costs. Engine wear and damage are expensive in multiple ways, which means they should be avoided.

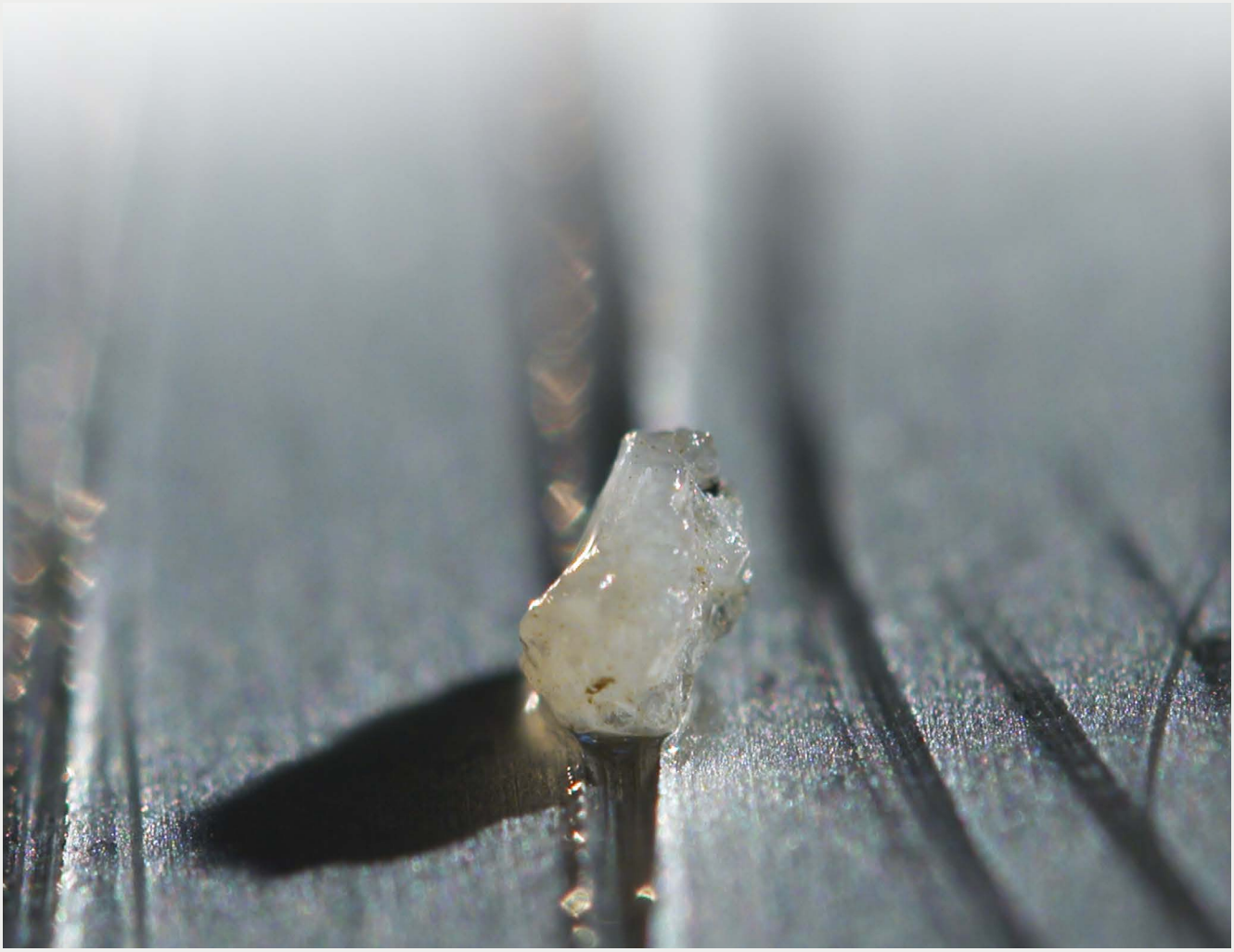


Figure 8: A magnified view of scratching/cutting damage caused by cat fines

4.4 Fuel supply with the correct parameters for the engine
After fuel cleaning, the fuel supply system delivers the fuel oil from the service tank for injection into the engine. The fuel must be properly conditioned to secure engine performance, meaning that parameters such as fuel viscosity, pressure and flow must fall within the engine maker's specifications.

Viscosity, which is linked to fuel lubricity, is a greater challenge than ever before. (See Section 3.2.3.) Fuel sulphur limits (see Section 2.3) have increased the use of diesel oil as a blending component for sulphur compliance in VLSFO, as well as the use of distillate fuels. Now, greenhouse gas (GHG) regulations (see Section 2.4) are driving the use of FAME and HVO, both of which have low viscosity values.

To control the viscosity of these fuels throughout the fuel supply process, protecting not only the engine fuel pumps but also those within the fuel supply system, it is vital for the fuel supply system to regulate the fuel temperature and ensure that it complies with the appropriate setpoint. The system must also be able to control the temperature ramp during fuel changeover, ensuring that the viscosity remains within the set limits. The latter is complex to achieve, given the varying composition of the fuel blends within the system during the procedure.

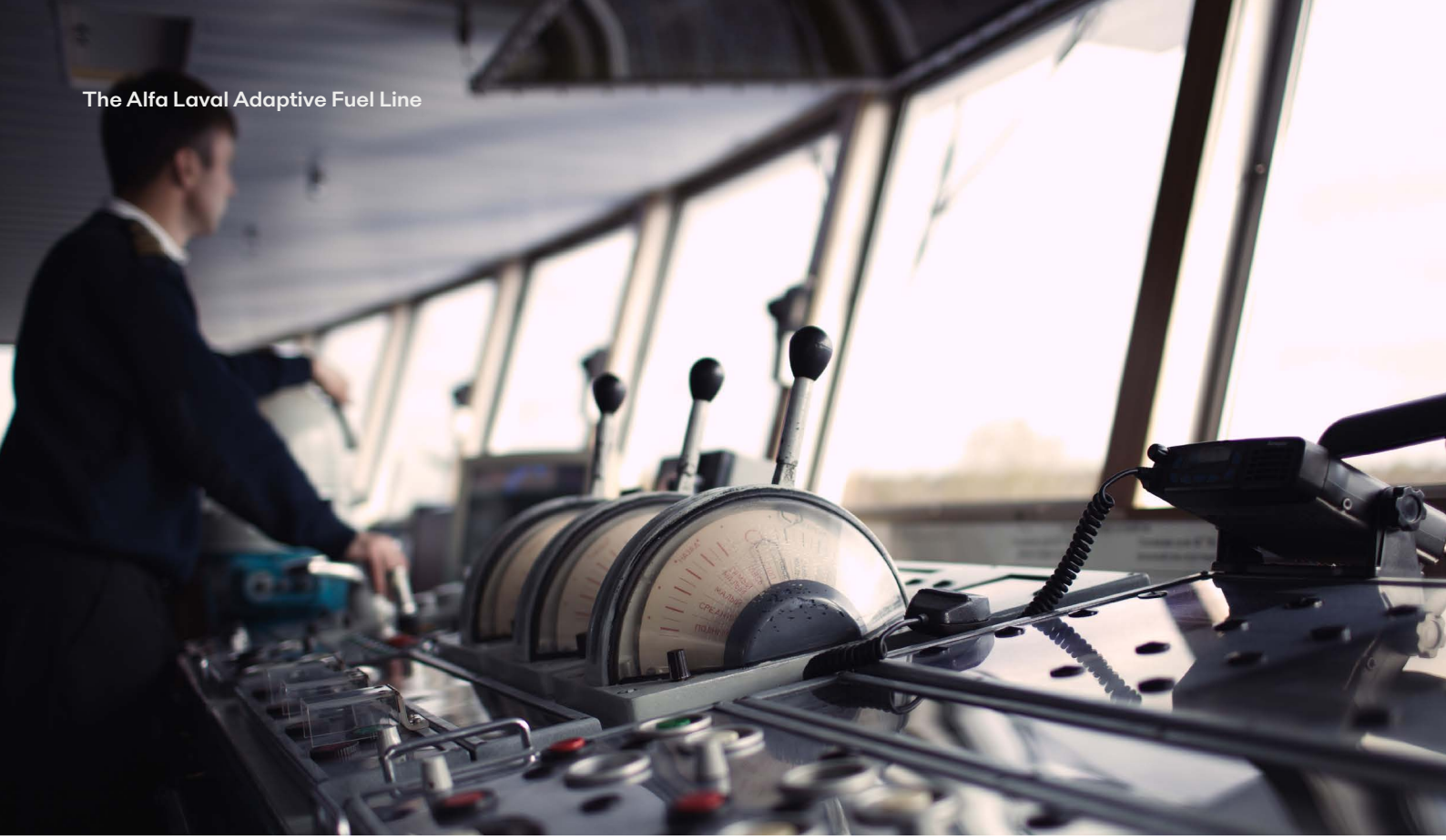
Automatic and efficient regulation of the heaters and coolers is the key to reliable control over both temperature and viscosity, regardless which fuels are in use.

4.5 Final filtration as a last line of engine defence

Filters are the final component of fuel oil treatment. They are a protective cleaning step located right before the engine, either downstream from the fuel supply system or integrated into the fuel supply system itself.

Filters act as a last barrier before the fuel oil enters the engine, trapping particles that have either passed through the separators or found their way in after separation. This makes them an important complement to initial fuel cleaning. Indeed, their maintenance can provide an indication of separator performance. If they require more cleaning cycles than usual, it may suggest a need for separator optimization (MAN B&W Diesel A/S, 2017). A differential pressure transmitter installed in the filter, by detecting any unexpected pressure drop, can make this indication more exact.

In the past, fuel filters were usually coarse and located on the supply line (cold) side of the fuel supply system. While this was cheaper, engine makers today recommend using fine filters – having a 10 µm or even 6 µm mesh size – with automatic back-flushing. These should be placed on the recirculation (hot) side.



5 Cutting-edge fuel oil treatment – the Alfa Laval Adaptive Fuel Line

As explored in previous chapters, the requirements for working with fuels on board are completely different than they were at the beginning of the 21st century. Single-fuel operation has been replaced by multi-fuel operation, and strict regulations have created a complex landscape of new fuel oils and blends. At the same time, the threat of cat fines remains. This chapter looks at how today's fuel oil treatment systems can be adapted to balance the many concerns – optimizing safety and economy for vessels and their operators.

5.1 The Alfa Laval Adaptive Fuel Line – concept and key aspects

A modern approach to fuel oil treatment must take many aspects into account. It needs to ensure engine protection by optimizing fuel quality at the engine inlet, while at the same time handling all fuel oils required for environmental compliance and processing them in an energy-efficient manner.

Accomplishing this requires scrutiny and optimization of the following areas:

- Fuel system layout
- Fuel oil cleaning setup
- Multi-fuel management
- Process monitoring and automation

The Alfa Laval Adaptive Fuel Line is a complete fuel oil treatment solution that addresses and combines all the above. It is not a single product, but rather a comprehensive and systematic approach based on several key products and Alfa Laval knowledge.

Combining best practices and groundbreaking technologies, it utilizes synergies within the fuel treatment system and provides expanded capabilities for handling diverse fuels. In the process, it increases the effectiveness of engine protection and the total efficiency with regard to energy and fuel.

The following sections summarize the Alfa Laval Adaptive Fuel Line concept, aspect by aspect. They explain the targets, principles and outcomes within each. The specific Alfa Laval equipment solutions, noted briefly in the respective tables, are presented afterwards in Section 5.6.

5.2 Fuel system layout

Effective fuel oil treatment depends not only the treatment equipment itself, but also on the tanks where fuel is stored and the way components are connected or isolated.

5.2.1 Tank design and overflow piping

The design of the tanks and the connections between them play a limited but important role in protecting the engine:

- Tank bottoms should be slanted to facilitate the collection and removal of cat fines, solids, and water – and to help prevent them from being stirred up in rough weather.
- Overflow piping between the service tank and settling tank routes the oil back to the settling tank at reduced engine load. Locating the overflow piping at the service tank bottom directs oil with the highest concentrations of cat fines (see Section 3.1) away from the engine.

5.2.2 Fuel segregation

Today's sulphur emission regulations (see Section 2.3) have led to high demands on fuel cleaning system design. Since the global 0.50% sulphur cap took effect in 2020, the supply of VLSFO types with widely varying viscosities – and potential incompatibility issues (see Section 3.2.2) – has made parallel fuel cleaning systems a necessity on most vessels.

Not only must VLSFO be kept separate from the ULSFO used in Emission Control Areas (ECAs), as discussed in the adjacent fact box, but different VLSFO batches should ideally be kept separate as well. In addition to having separate bunker, settling and service tanks for distillate and residual fuels, it is wisest to have a multi-fuel system for handling different types of VLSFO.

- **Single-fuel cleaning systems**
  Even when a single-fuel cleaning system is used for VLSFO, two separators are recommended. One separator is usually sufficient to supply the service tank when running at full steam, while the other usually remains in standby mode. This is a simple and straightforward setup, but it lacks the flexibility of a multi-fuel system. With only one set of tanks, there is a greater risk of fuel incompatibility issues when one type of VLSFO is exchanged for another.
- **Multi-fuel cleaning systems**
  In a multi-fuel cleaning system, the setup is duplicated in two separators but also in two sets of settling and service tanks. By providing separate fuel paths, this minimizes the risk of incompatibility issues when switching between different VLSFO types. Moreover, if difficulties with incompatibility arise in one path, fuel can continue to be processed in the parallel path.

The importance of cleaning VLSFO and ULSFO in different separators

Using VLSFO separators to clean ULSFO can be problematic. When changing from VLSFO to ULSFO, even the piping, pumps and heaters are filled with fuel that has a higher sulphur content.
Inadvertently mixing a higher-sulphur fuel into ULSFO, even in small quantities, can result in off-spec fuel and handling issues. To prevent this, ULSFO must be flushed through the pipes until the system is cleaned of higher-sulphur fuel.

Even if flushing is carried out, it is not possible to confirm fuel sulphur compliance without taking samples of the ULSFO and sending them to a laboratory for analysis. Such analysis takes time and is not a practical option for most vessel operators.

Mixing of ULSFO into VLSFO is not recommended, as it may result in severe handling issues. If the VLSFO becomes unstable, large amounts of sludge will be produced, which may – in the worst cases – clog the entire fuel treatment system.

Solution	Outcome
Modern multi-fuel system layout	– Keeps different fuel oils separated in storage and processing – Reduces risk of incompatibility and/or non-compliance

Table 5.2: Fuel system layout

5.3 Fuel oil cleaning setup

The fuel oil cleaning system comprises the settling tanks and separators, as well as the final filtration step before the fuel is injected into the engine. All fuel oil cleaning equipment must be prepared for the properties of current fuels, which are more complex and varied due the need for regulatory compliance. (See Chapter 1.) Filters, for example, should have a fine mesh size (10 µm or even 6 µm), as today's high-pressure engine systems are at risk from even the smallest cat fines and asphaltenes.

Modern, fully automated separators are best suited to handle density fluctuation and other challenging characteristics – including those posed by biofuels like FAME and HVO (see Section 1.5). Older separator technology generally has poorer separation efficiency and insufficiently accurate process control. There are, however, opportunities to enhance the performance of any separation system. Working with two key parameters – fuel flow rate and fuel temperature – can improve both separation and energy efficiency.

5.3.1 Separator flow control

The flow through the separator has a major impact on the separation result. For the highest possible separation efficiency, the feed flow should be kept as low and as stable as possible.
If a high flow is required, and if the oil contains large concentrations of dirt or cat fines, the entire separator base should be used in parallel at the lowest possible flow rate. If two separators are installed, for example, they should be run in parallel at 50% flow. However, this is seldom needed in modern vessel operations.
Most vessels today operate well below their maximum design speed, which is often referred to as slow steaming. (See Section 3.4.) The vessels save fuel by running their engines below the maximum continuous rating (MCR). But by matching the separator feed to the actual engine load, they can also improve separation efficiency.

The fuel cleaning system is normally laid out to support 100% engine fuel consumption, plus constant values for various margins. However, with the engines seldom running at 100% load, there is rarely a need to deliver so much fuel to the service tank. Decreasing the flow through the separators in relation to the engine fuel consumption will result in higher separation efficiency, because the fuel will spend more time being processed in the separator bowl. (See Section 4.3.3.) This can be seen clearly in Figure 9.

This makes flow control a simple and effective way of improving separator performance, especially if the process is continuous. The feed to the separators can be controlled in two ways: manually or automatically.

- **Manual flow control**
  To manually control the separator feed, a flow-regulating valve is installed before the separator. When throttling causes the pressure to exceed the set opening pressure, the spring-loaded valve opens and the oil is returned to the settling tank. This is a simple solution that should be utilized if installed, but it requires that the crew supervise and adjust the operation.
- **Automatic flow control**
  A variable-frequency drive (VFD) can be used to control the speed of the feed pump motor, adjusting the feed rate automatically to match the actual engine load. Unlike using a fixed mechanism to throttle the flow, varying the pump flow reduces energy use in both the feed pump and the separator. Apart from enabling continuous optimization, this solution requires no active intervention on the part of the crew.

5.3.2 Separation temperature

Processing fuel oil at the right temperature is crucial, as temperature is the main parameter for controlling fuel viscosity in the separator. Optimizing viscosity can improve separation efficiency.

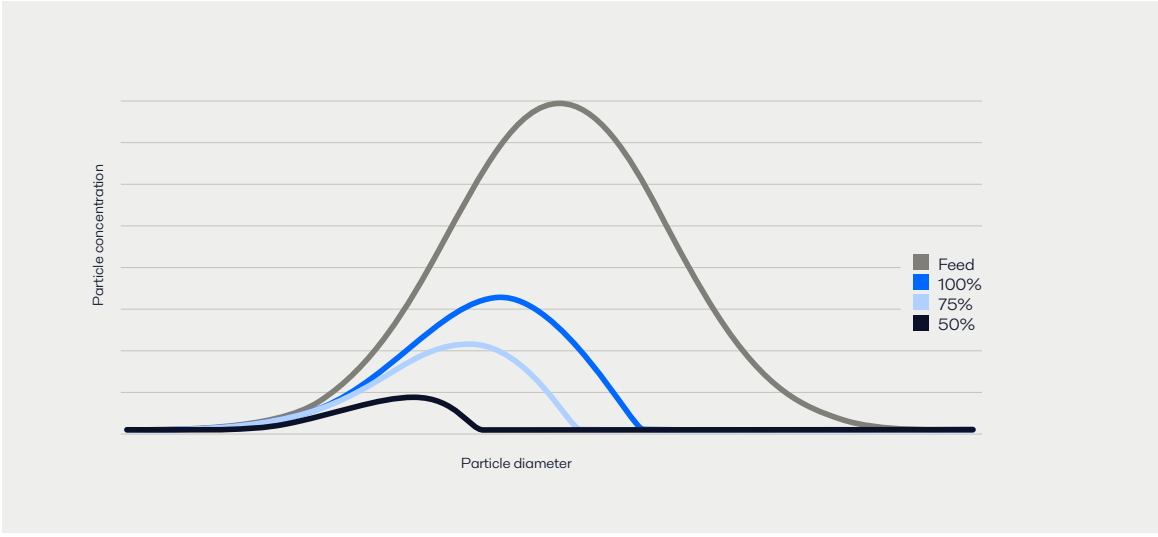


Figure 9: The effect of flow rate on separation efficiency
Separation efficiency, illustrated by particle concentration after separation, when flow is reduced from 100% to 75% and 50% of maximum recommended capacity. The red curve represents the particle concentration at the separator inlet.

Solution	Outcome
ALCAP™ technology in high-speed separators *(See Section 5.6.1)*	– Measures the water content at the oil outlet – Automatically adjusts cleaning to varying fuel density – Ready to meet the biofuel challenges associated with FAME and HVO
Moatti fuel filters *(See Section 5.6.4)*	– Provide a final 6 µm barrier before the engine – Backflush continuously using filtered oil – Allow real-time monitoring of pressure drop – Ready to meet the biofuel challenges associated with FAME and HVO

Table 5.3: Fuel oil cleaning setup

The standard temperature for fuel oil separation is 98°C. As the oil's temperature decreases, its viscosity increases. If the temperature drops to 90°C, for example, the flow must be reduced to 72% of the nominal flow to achieve the same separation efficiency as at 98°C. At 85°C, the flow must be cut to 50%. Figure 10 illustrates what happens to separation efficiency if the temperature is reduced while the flow rate is maintained.

In light of this, it might seem natural to consider separation temperatures higher than 98°C. Higher temperatures and correspondingly lower viscosities could further improve separation efficiency. However, the limit of 98°C is in place for important safety reasons. Today's onboard separators are designed as open atmospheric systems, and the presence of water in the process means steam could escape into the engine room if the separation temperature were increased to more than 100°C.

In determining the right temperature for separation, there are multiple factors to consider, including differing fuel viscosities, the need to save energy and the effects of temperature on biofuels. The following guidelines can be useful:

1. Residual fuel oil will always be cleanest when processed at the lowest possible viscosity. When in doubt, the highest possible temperature (98°C) should always be used.
2. Engine injection temperatures for VLSFO are typically higher than the maximum separation temperature. However, if the viscosity of a fuel is very low when supplied, a temperature lower than 98°C might be required for engine injection. In such cases, separation should be set to the temperature recommended in the bunker analysis for a viscosity of 10–20 cSt. This will maximize separation efficiency without producing a viscosity that is too low for the engine.
3. For distillates, heating should only be used to deal with cold flow properties. (See Section 3.2.4.)
4. For biofuels, which age rapidly with increased temperature, the fuel analysis and supplier recommendations should be followed. Short-term exposure does not pose a problem when the fuel is used directly, but the higher the temperature, the greater the impact. In any case, the temperature should never be higher than the recommended injection temperature.

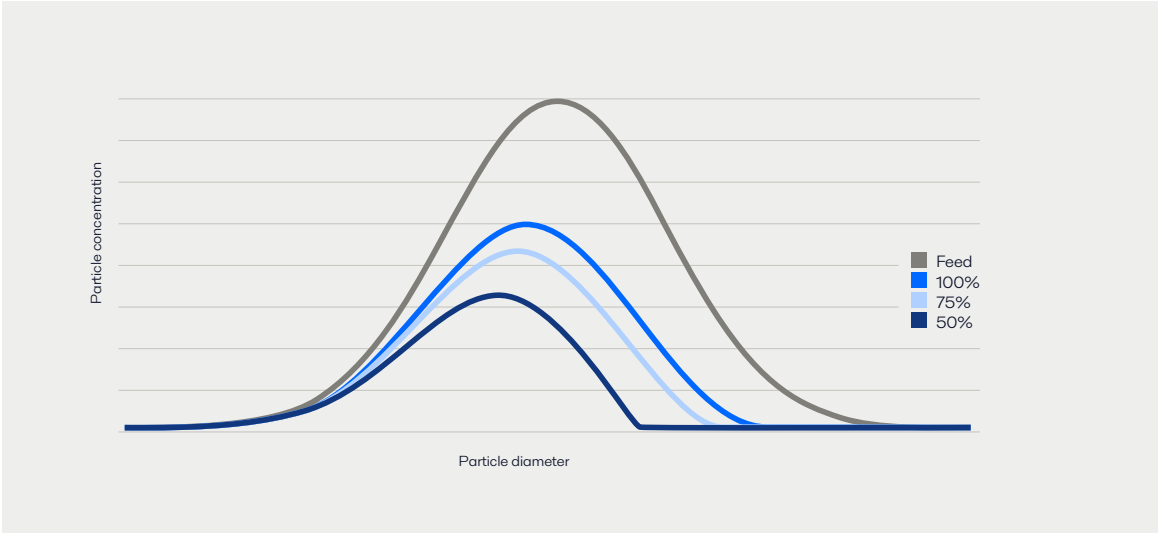


Figure 10: The effect of temperature on separation efficiency
The red curve shows the particle concentration in the feed, while the other curves indicate the particle concentration at the separator outlet at separation temperatures of 85°C, 90°C and 98°C.

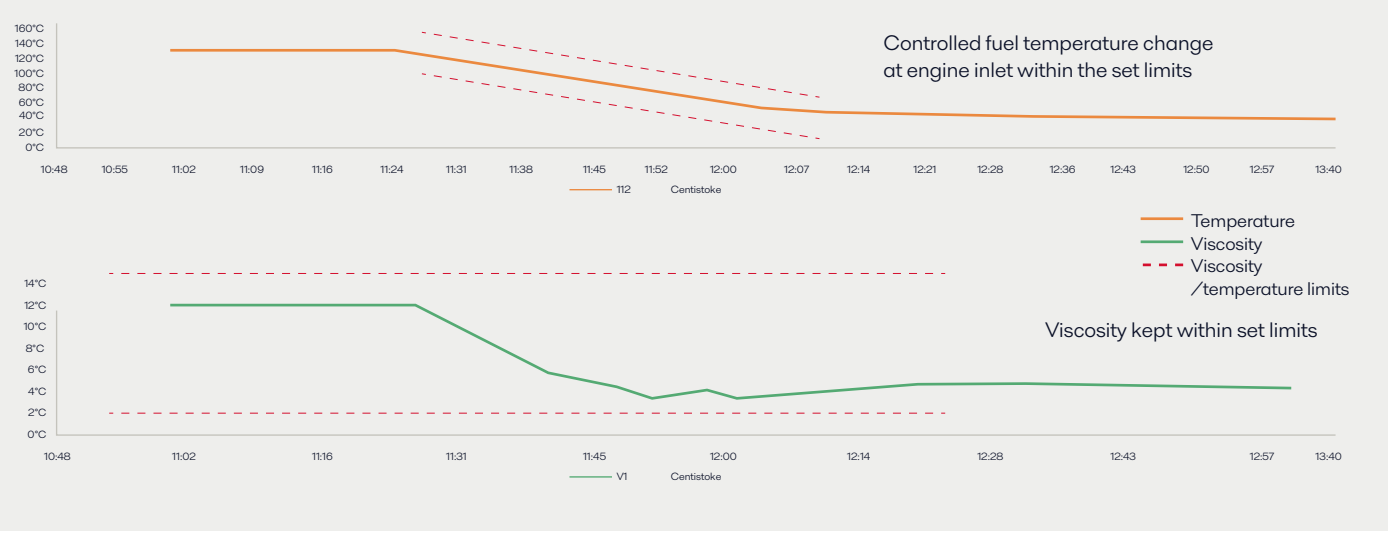


Figure 11: Fuel changeover from residual (VLSFO) to distillate (ULSFO) as handled by the Alfa Laval FCM 1.5 fuel supply system

5.4 Multi-fuel management

Today's vessels use a large variety of fuel oils with widely differing properties. The majority of vessels work with multiple fuels on board, and fuel blending has become commonplace. (See Chapter 1.) All this places greater demands on the fuel supply system, which should be capable of multi-fuel management. Multi-fuel management enables precise control over fuel changeover (see Section 3.3), which includes the recording of data related the process. It is needed not only to secure safe engine operation but also to prevent non-compliance.

5.4.1 General demands on the fuel supply system

As always, the purpose of the fuel supply system is to condition the fuel, ensuring its delivery to the engine within the parameters set by the engine maker. To do this when working with multiple fuels, the fuel supply system must be able to:

- Control the transition from the high injection temperature of residual fuels to the low injection temperature of distillate fuels, so that the temperature gradient remains within the engine maker's recommended limit. A typical rate of temperature change at the fuel pump inlet is 2°C per minute.
- Keep the temperature and viscosity of distillate fuel oils within the engine maker's recommended limit in order to secure proper fuel lubricity.

5.4.2 ECA fuel changeover

Changeover between residual and distillate fuels when entering or leaving an ECA (see Section 3.3) is an essential part of multi-fuel management. The fuel supply system should be able to run this process automatically, securing a smooth temperature gradient while keeping the fuel viscosity within the acceptable range for the engine.

It is vital that no fuel is returned to the tank during the changeover procedure. Contamination of the distillate fuel could result in non-compliance, whereas the introduction of distillate into the residual fuel could lead to precipitation and sludge (see Section 3.2.2). If the fuels are properly segregated, i.e. stored in different tanks and cleaned in different separators, the fuel supply system is where they will be blended during the changeover procedure.

Solution	Outcome
FCM 1.5 fuel supply system *(See Section 5.6.1)*	– Handles multiple fuels automatically, providing differentiated set points for all fuels in use – Safely manages the changeover between different fuels – Conditions fuels to match engine specifications exactly – Ready to meet the biofuel challenges associated with FAME and HVO

Table 5.4: Multi- fuel management

5.5 Process monitoring and automation

Monitoring and automation of fuel treatment equipment and processes can help prevent operational difficulties, undesirable effects on fuel quality and the risk of non-compliance. But it can also provide valuable information to operators, giving them tools to improve operations, engine protection, energy efficiency and more.

5.5.1 Applying system data on board

On a basic level, monitoring includes functions such as data logging by the control systems of individual equipment. In addition to startup/shutdown times, alarms and other standard running information, the collected data can include key process parameters such as temperature and viscosity. It can also encompass more detailed process control information, e.g. during fuel changeover, or information relevant for compliance, e.g. the exact consumption of specific fuels.

Ideally, the monitoring functions of individual systems should be extended to the main control room, for example via Modbus. Incorporating them into the vessel's integrated control and monitoring system (ICMS) enables wider real-time overview and easier access to information for troubleshooting and process optimization.

Further possibilities are created when data from individual systems is applied to other systems in the fuel line – especially when this is automated. A simple example is the monitoring of pressure drop by a differential transmitter in the fuel filter, as described in Section 4.5. An unexpected increase in pressure drop can indicate not only a need for filter maintenance but also reduced efficiency of the separators earlier in the fuel treatment process. A far more dynamic example is the automated separator flow control described in Section 5.3.1, where engine fuel consumption data is used to optimize pump control and separation efficiency in real time.

5.5.2 Connected opportunities

With the addition of connectivity, either via individual fuel line systems or through the ICMS, monitoring and automation data becomes even more useful for troubleshooting and optimization. Secure cloud access to system information, whether in the form of log files or current operating data, allows remote troubleshooting to a greater degree, enabling faster resolution and potentially avoiding the need for physical service attendance. In addition, it allows shore teams and equipment manufacturers to take a more proactive role in supporting, safeguarding and optimizing the fuel treatment processes on board. As connectivity develops and is implemented more broadly, even more of this will occur in real time.

Solution	Outcome
FCM 1.5 – fuel consumption monitoring function *(See Section 5.6.2)*	– Accurately measures fuel use – Provides data for optimization of the fuel treatment system
Connectivity and remote observation	– Allows crews to be supported by onshore experts, optimizing performance and ensuring compliance

Table 5.5: Monitoring and automation

5.6 Alfa Laval equipment solutions

The principles of the Alfa Laval Adaptive Fuel Line are universal, but they are supported by a range of key solutions in the Alfa Laval portfolio. These highly efficient fuel oil treatment products, supporting the entire fuel processing chain, are presented here in brief.

5.6.1 ALCAP™ technology – adaptive control of high-speed separators

ALCAP was developed to allow separators to handle fuel oils with high and fluctuating densities in an effective way. The name ALCAP derives from the two main separator functions:

- **Purifying,** which is separating two liquids of different densities (e.g. water from marine fuel)
- **Clarifying,** which is separating solids from a liquid (e.g.cat fines and asphaltene sludge from marine fuel)

In a conventional arrangement, a separator operating as a purifier would typically be followed by a second separator, operating as a clarifier.

When operated as a purifier, a conventional separator requires a gravity disc in the bowl, matched to the fuel oil's density and viscosity. The gravity disc sets the interface between the oil and the water, and the water is continuously discharged as the bowl spins. When the fuel density is higher than 991 kg/m^3 at 15°C, however, a gravity disc is no longer effective. The difference in density between the oil and the water is too small for a reliable interface. Water removal must be handled in a different way.

ALCAP does away with the gravity disc, enabling the separator to handle denser fuels and higher viscosities. In operation, an ALCAP separator acts as clarifier, but it automatically monitors the water content and drains it through an outlet valve when required. As soon as water is detected, the control unit initiates either draining or discharge, depending on the application.

The water content in the oil is measured by a water transducer at the clean oil outlet. Technically, the transducer acts as a capacitor, measuring the oil's conductivity. The capacitance varies with the dielectric constant of the liquid, which differs significantly between oil and water. Oil has a dielectric constant of approximately 4 to 6, whereas that of water is approximately 90 to 95. Even a small amount of water will drastically increase the conductivity reading, creating a very sensitive measure of changes in water content. Both free and emulsified water contamination are measured.

ALCAP is the only separation technology on the market that continuously measures water in the clean oil outlet. Using this measurement, it adjusts the oil/water interface in the separator bowl automatically. This allows separation of fuels with densities up to 1010 kg/m^3 and viscosities up to 700 cSt – without having to change gravity discs as required by conventional separators. Oil losses are negligible with ALCAP technology. Before the separator discharges, the oil inlet is closed and the oil is pushed towards the disc stack by adding displacement water to the bowl.

Figure 12: An Alfa Laval separation system with ALCAP™ technology

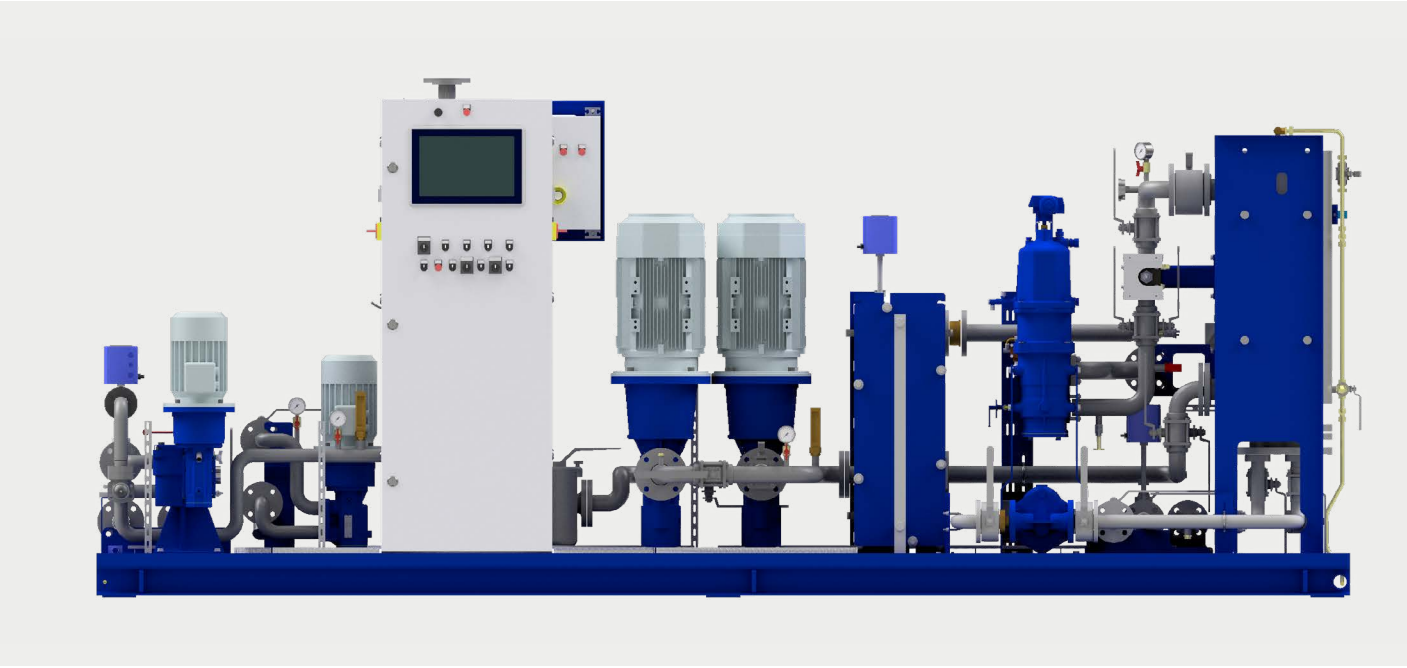


Figure 13: The Alfa Laval FCM 1.5

5.6.2 FCM 1.5 – fuel supply system for oil and biofuel

Fuel conditioning is the treatment of fuel oil to meet the temperature, viscosity, pressure and flow rate specified by diesel engine makers. These parameters are vital for engine combustion performance, which makes securing them an important part of both energy efficiency and emissions reduction.

Fuel conditioning today encompasses many different fuels, however. Emission regulations are forcing shipowners to use lighter and more expensive fuel oils and distillates, as well as biofuels, while fuel prices encourage reliance on residual fuels. Most vessels now operate on two fuels or more. (See Chapter 1.)

All this raises significant operational and safety concerns, especially when switching between fuels. (See Section 3.3.2.) Since the regulatory challenges can be addressed with different fuel strategies, vessels with the same engine specifications may place very different requirements on their fuel supply systems.

The Alfa Laval FCM 1.5 is a state-of-the-art fuel supply system, able to resolve the full spectrum of multi-fuel management issues. With its sophisticated automation, it handles multiple fuels automatically and measures their consumption. It delivers perfect control over fuel parameters at the engine inlet, providing dedicated set points for the fuels in use. Above all, it provides safe, automated control of the changeover between fuels, as certified by the Fuel Oil Bunker Analysis and Advisory Service (FOBAS) since 2017 (LR, 2017).

5.6.3 Viscochief – upgraded control for existing fuel supply systems

Burning distillate fuels in diesel engines involves critical aspects that can impact engine injection systems, pumps and other equipment. One aspect is the temperature gradient. The injection temperature of distillate fuel is much lower than that of HFO, and a sudden temperature change can cause thermal shocks within the injection system. Another aspect is fuel viscosity at injection, which affects the capacity to lubricate fuel injection components. (See Section 3.3.2.)

Many installed fuel supply systems lack the capabilities needed to address these issues simply and safely. To ensure the right fuel parameters upon injection, the fuel supply system must both control the temperature ramp within the system and maintain the correct temperature of the light fuel at the injection point. Alfa Laval Viscochief is an upgrade solution that can provide existing fuel supply systems with the necessary functionality. It delivers control that can optimize fuel supply performance, adding functions like multi-fuel management, cooling of the distillate fuels and fuel consumption monitoring. If additional components are needed to implement such functions, these are included in the scope of supply.

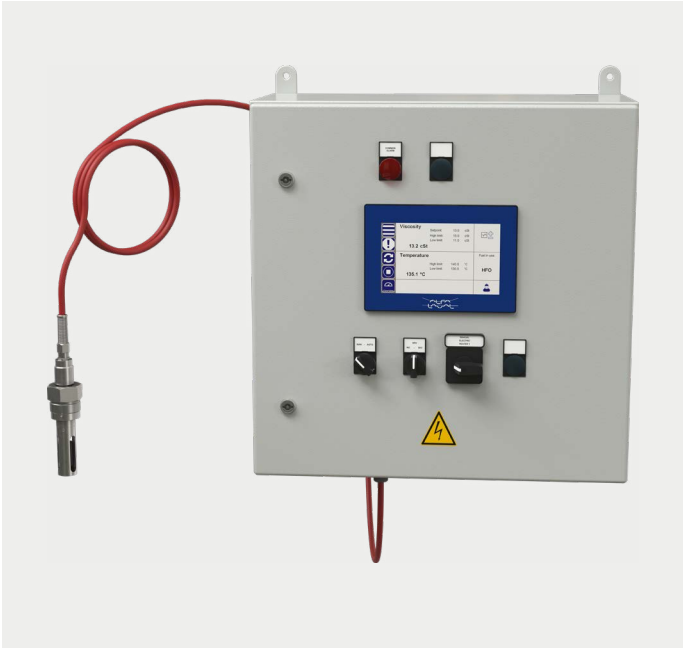


Figure 14: Alfa Laval Viscochief

Figure 15: An Alfa Laval Moatti fuel oil filter

5.6.4 Moatti fuel oil filters – reliable engine defence

Integrated into the FCM 1.5 but also available separately, Alfa Laval Moatti fuel oil filters (Figure 15) capture and remove any particles and impurities that remain after fuel treatment, preventing them from entering the engine. In line with current recommendations from engine makers, they use filter mesh sizes down to 6 µm and are placed on the recirculation side of the fuel supply system (hot side). (See Section 4.5.) This makes them the last piece of equipment prior to the engine.

Moatti fuel oil filters have a diversion chamber that lets them employ continuous, automatic backflushing, with filtered oil driving the backflushing process. This differs from other filter types on the market, which have only sequential backflushing. Sequential backflushing uses air to clean the filter element, sending backflushed oil back to the settling tank.

The drawback of an air-cleaned system is the low relative temperature of the air, which can shock asphaltenes in the fuel. The resulting thermally induced sludge can clog the filter. Moatti fuel oil filters, because they backflush with filtered oil, are not susceptible to this. Additionally, their diversion chamber allows continuous cleaning away of contaminants. The backflushed oil is refiltered before being recirculated, without the need for additional treatment.

Moatti fuel oil filters come equipped with a differential pressure transmitter for real-time monitoring of the filter condition. This enables smart, proactive maintenance to ensure the highest possible system availability. Additionally, monitoring the pressure drop can provide insights into the efficiency of prior cleaning steps.

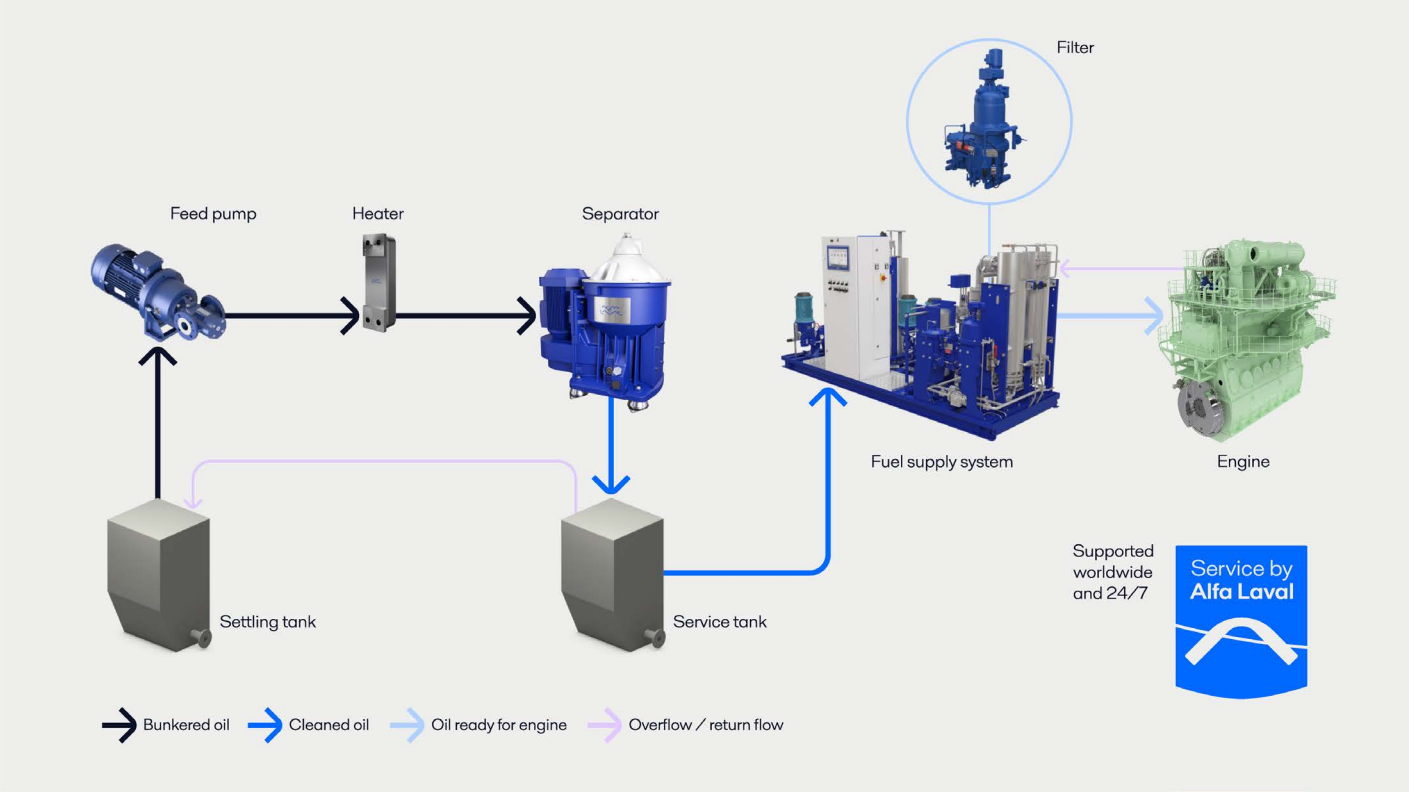


Figure 16: A typical configuration of the Alfa Laval Adaptive Fuel Line

5.7 The Alfa Laval Adaptive Fuel Line – a complete solution

When the Alfa Laval Adaptive Fuel Line concept is implemented with the equipment described, it provides a complete solution. It brings together all the individual fuel treatment aspects, creating a single, optimized fuel treatment system that enhances engine protection, ensures operational safety, improves energy efficiency and streamlines operating costs.

Well-designed tanks and proper segregation of multiple fuel oils are an important base, reducing the risks of fuel incompatibility or non-compliance. High-speed ALCAP separators follow, forming the core of the fuel cleaning system. Their ALCAP technology provides flexibility in handling different fuel densities, which vary significantly in today's fuel oils. Given the wide variety of low-sulphur fuel blends and the introduction of biofuels with their unique properties, a proper, up-to-date separation system is more important than ever.

The FCM 1.5 fuel supply system ensures the fuel is delivered within the limits for optimal engine efficiency, matching the temperature, viscosity, pressure and flow rate specified by the engine maker. Since multiple fuels are in use, it also handles the multi-fuel management, securing a smooth and safe transition during changeover between different fuel types. This is vital, for example, when entering or leaving an ECA.

Before the cleaned and conditioned fuel oil enters the engine, it undergoes final filtration. A Moatti fuel oil filter, integrated on the hot side of the FCM 1.5, defends the engine from any remaining solids with its 6 µm mesh. The filter's automatic backflushing, driven by a flow of cleaned oil, secures continuous performance. Monitoring of the pressure drop, enabled by the built-in differential pressure transmitter, allows early detection of any degradation in previous cleaning steps.

Figure 16 shows one possible configuration of the Alfa Laval Adaptive Fuel Line, bringing together the major elements and principles discussed in this book.

6 Acronyms

Acronym	Description	Acronym	Description
ABS	American Bureau of Shipping	LR	Lloyd's Register
ARA	Antwerp-Rotterdam-Amsterdam	MARPOL	International Convention for the Prevention of Pollution from Ships
BN	Base number	MCR	Maximum continuous rating
CCAI	Calculated Carbon Aromaticity Index	MDO	Marine diesel oil (a blend of distillates and residual oil)
CFPP	Cold filter plugging pint	MEPC	Marine Environment Protection Committee
CFR	Certified Flow Rate	MGO	Marine gas oil (distillate, practically sulphur-free)
CIMAC	The International Council on Combustion Engines	MCR	Micro carbon residue
CNSL	Cashew nutshell liquid	MRC	Maximum recommended capacity
CP	Cloud point	NMR	Nuclear magnetic resonance
ECA	Emission Control Area	POCC	Pyrolysis oil from cashew shell press cake
EPL	Engine power limitation	PP	Pour point
EU	European Union	ppm	Parts per million
EU ETS	EU Emissions Trading System	NGO	Non-governmental organization
FAME	Fatty acid methyl ester (biodiesel)	SEEMP	Ship Energy Efficiency Management Plan
FCC	Fluid catalytic cracking	TSE	Existent total sediment
FDR	FAME distillate residues	TSA	Accelerated total sediment
FOBAS	Fuel Oil Bunker Analysis and Advisory Service	TSP	Potential total sediment
GFI	GHG fuel intensity	ULSFO	Ultra-low-sulphur fuel oil
GHG	Greenhouse gas(es)	VFD	Variable-frequency drive
HFO	Heavy fuel oil	VLSFO	Very-low-sulphur fuel oil
HSFO	High-sulphur fuel oil	UN	United Nations
HVO	Hydrotreated vegetable oil (renewable diesel)	VPS	Veritas Petroleum Services
ICMS	Integrated control and monitoring system	WAT	Wax appearance temperature
IMO	International Maritime Organization	WDT	Wax disappearance temperature
ISO	International Organization for Standardization	WtW	Well-to-wake
LNG	Liquid natural gas	ZNZ	Zero or near-zero

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**Not available online.*

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