Cat Fines
Impact on engine wear and how to reduce the wear
Cat fines
– Impact on engine wear &
How to reduce the wear!

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1. Introduction

Successful optimisation towards long service life of components in modern two-stroke diesel engines requires that the condition is followed closely and that the operators act on the information obtained. Experience has shown that good fuel cleaning and correct lubrication followed up by proper inspections are the main tools to ensure good cylinder condition and long lifetime of the components.

Abrasive particles entering the combustion chamber will cause wear. Cat fines (catalytic fines) are small, very hard particles, which originate from the refining process, and thereby enter the marine fuel. High amounts are normally allowed in the fuel as bunkered as according to ISO 8217 [1], and in case of insufficient fuel cleaning on board the ships cat fines may enter the engine with the fuel and cause wear.

This paper describes the nature of cat fines, the impact they have on the wear – and also how to reduce the wear. The recommended maximum acceptable level of cat fines entering the engine should always be as low as possible and maximum 15 ppm Al+Si for short periods. Some best practise for fuel cleaning installations and operation procedures are also given.

**Summary – Fuel cleaning systems and operation:**

<table>
<thead>
<tr>
<th>Important points to achieve clean fuel – and increased reliability and low wear rates:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Install a best practise fuel cleaning system</td>
</tr>
<tr>
<td>2. Make high standard daily operational procedures</td>
</tr>
<tr>
<td>3. Check the results of the fuel cleaning</td>
</tr>
<tr>
<td>4. Act on the results obtained</td>
</tr>
</tbody>
</table>

**Summary – Cat fines influence:**

<table>
<thead>
<tr>
<th>Important points regarding cat fines related failures:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cat fines in fuel entering the engine will cause wear: The higher the amount of cat fines, the higher the wear will be</td>
</tr>
<tr>
<td>2. The recommended maximum acceptable level of cat fines entering the engine should always be as low as possible and maximum 15 ppm Al+Si for short periods</td>
</tr>
<tr>
<td>3. Cat fines accelerate corrosive wear</td>
</tr>
<tr>
<td>4. Cat fines accumulate in the service tank if the tank is not cleaned in service</td>
</tr>
<tr>
<td>5. Fuel cleaning is more important than fuel bunker cat fines content</td>
</tr>
<tr>
<td>6. Cat fines are found in both heavy fuel and ULSFO.</td>
</tr>
<tr>
<td>7. Cat fines are expected also to be found in fuels after 2020.</td>
</tr>
<tr>
<td>8. Cat fines in liner running surfaces prove unacceptable fuel cleaning</td>
</tr>
<tr>
<td>9. Cat fines disappear rapidly from liner surface if supply is stopped</td>
</tr>
<tr>
<td>10. Cat fines wear damages are mainly found in different positions for two-stroke and four-stroke engines</td>
</tr>
</tbody>
</table>

This document is intended for engine owners and operators, classification societies and ship yards. In addition it should be recommended reading for students and for all those involved with, or interested in, cat fines damages.
Wear from cat fines in two-stroke engines vs. four-stroke engines

The focus in this paper is on two-stroke engines, and wear from cat fines on small four-stroke Gensets (Holeby engines) are merely discussed in this section.

Wear from cat fines in two-stroke engines is found in the combustion chamber on cylinder liner, piston rings and piston ring grooves, resulting in high wear rates and possible scuffing. While the wear from cat fines in the small four-stroke Gensets are found primarily in the fuel system, where the fuel atomiser holes are worn out, and becoming too large for making suitable atomisation of the fuel, which is resulting in bad combustion, and thereby increased deposits in the turbocharger, resulting further in worse combustion in an evil spiral, and could eventually lead to possible engine failure and break-down.

An overview of the damages found in two-stroke engines and small four-stroke Gensets (Holeby engines) can be found in Table 1. More information on cat fines damages for Holeby engines can be found in [2] and [3].

<table>
<thead>
<tr>
<th>Damages found in two-stroke engines</th>
<th>Damages found in small four-stroke Gensets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear in combustion chamber parts</td>
<td>Wear in fuel equipment</td>
</tr>
<tr>
<td>Resulting in high wear</td>
<td>Resulting in poor combustion</td>
</tr>
</tbody>
</table>

Table 1 Overview of damages found in two-stroke engines and small four-stroke Gensets.
2. Purpose of this Paper

It is vital that cleaning system installations are carried out in accordance with the best practices, as described in this paper and in CIMAC Recommendation [4, 5] and in IACS Recommendations [6]. Furthermore, daily operation and regular checks must be made to high standard. These two parts: Best practice fuel cleaning system, and high standard daily operation will support long lifetime of components, easy operation for the crew on board the ship and reduce the risk of suffering damage to the system.

Reference is given to our Service Letter SL2017-638 “Cleaning of Heavy Fuel Oil and <0.1% Sulphur fuels – How to remove cat fines” [7].

Extra cost due to cat fines wear

If wear from cat fines causes the combustion chamber components to be exchanged premature, the cost will be high. For example, if a 6S80ME-C engine wears twice the rate as normal, the extra cost will be in the range of:

- Liners: 0.5 x 6 x 40000 EUR = 120000 EUR
- Piston rings: 0.5 x 6 x 5000 EUR = 15000 EUR
- Pistons: 0.5 x 6 x 16000 EUR = 48000 EUR
- Total: 183000 EUR

The total of extra cost for the cat fines wear of 183000 EUR is the components. The cost for the extra downtime and cost of installation must be added to this amount. Of course, if the wear rates are even higher, the extra cost will be higher.

An overview of estimated list prices for components in the combustion chamber for different engine bore sizes can be seen in Figure 1.

![Estimated list price in €](image)

**Figure 1** Estimated list prices for combustion chamber components.

29-11-2017/DOJA
3. Cat fines
Cat fines (Catalytic fines) originate from the catalytic cracking processes in the refineries where a catalyst is used to break down complex hydrocarbons into simpler molecules. The catalyst is a substance that assists the process of the chemical reaction, and they are recycled through the cat cracker plant. Most catalysts being used in these processes are based on Aluminum- and Silicon oxides. Some new, unused catalytic particles can be seen in the Figure 2 below.

![Figure 2](image1.png)  
*Figure 2 New, unused catalytic particles for the FCC (SEM photo)*

![Figure 3](image2.png)  
*Figure 3 Cross section of fresh catalytic particles (SEM photo)*

The cross section shows that the original, big catalytic particles contain smaller particles which are more dense than the surrounding material. In the violent flow in the FCC cat cracker, the big catalyst particles break up in to the smaller particles – and the small dense, strong and hard particles survive and become cat fines. See Figure 3.

These small particles escape the recycling process and some may end up in the slurry oil, also known as decant oil or FCC (Fluidized Catalytic Cracker) bottoms, which is the lowest value stream produced from the FCC unit. See Figure 4. Slurry oil is a low-sulphur by-product being highly aromatic, with a relatively high density of about 1000 kg/m³ at 15 °C and a rather low viscosity of approximately 30 to 60 cSt at 50 °C. Its most common uses are as a blend stock for heavy fuel oil and feedstock for carbon black production. Due to the relatively low sulphur levels of slurry oil, taken together with its high aromaticity it is an ideal blending component for residual fuels and some of the new types of Ultra Low Sulphur Fuels (ULSFO).
Photo of cat fines separated at a refinery can be seen in Figure 5. For comparison, photos of cat fines found in combustion chamber piston ring and liner can be seen in Figures 6-7.

**Figure 4** Equipment for the catalytic cracking process. [8]

**Figure 5** Cat fines received from a refinery (SEM photo)

**Figure 6** Cat fines found in a piston ring (see also Section 9.4) (SEM photo)

**Figure 7** Cat fines found in liner surface. See also Section 8.2.4. (Replica, micrograph photo)
**Amount of cat fines related to Sulphur in the fuel**

In July 2010, the regulation for max. Sulphur content in the fuel in SOx-ECA (Sulphur Emission Controlled Area) was changed from max. 1.5%S to max. 1.0%S. As the cat fines containing stream of the FCC cracker normally is found low in Sulphur, it is a common blending stream for low-Sulphur fuel. This can be seen in Figure 8 below. The figure show marine fuel samples analysed for Sulphur and cat fines (Al+Si), and it is obvious that the cat fines are concentrated in the low-Sulphur fuel – especially at the two limits: 1.5%S and 1.0%S.

![Figure 8](image)

**Cat fines in fuel after 2020**

In January 2020, the regulation for max. Sulphur in the fuel in global waters changes to max. 0.5% Sulphur. Again, as the cat fines containing stream from the FCC cracker normally is low in Sulphur, it will most probably also after 2020 be an important part of the marine fuel pool. Consequently, the cat fines will also be found in marine fuel after 2020.

**Hardness**

Cat fines are hard and abrasive in nature. They are made to withstand the violent motion and turbulence in the FCC (Fluid Catalytic Cracking) unit. Ceramics are measured on the Mohrs hardness scale going from 1 to 10, where diamond measures 10, and grinding materials: Aluminum-oxide (Al₂O₃) and Silicon-oxide (SiO₂) measures respectively 9 and 7. In this scale the hardness of cat fines measures approximately 8. Components in the engine are in some positions of almost similar hardness as the cat fines but at other positions the hardness of the components are considerably less than the hardness of the cat fines. The hardness of the ceramics and metallic materials are correlated to the same hardness scale and shown in Figure 9.

As a hard material will wear a soft material when in contact, the cat fines will wear the softer engine components when they are introduced to the engine.
Chemical composition

A modern FCC (Fluid Catalytic Cracking) catalyst has four major components: crystalline zeolite, matrix, binder, and filler. Most catalysts are forms of aluminium and silicon oxides. Some cat fines received from a refinery was analyzed in SEM-EDAX, and the analysis showed that it was mainly silicon-aluminum oxide. See figure 10.

The cat fines level in marine fuel is measured based on Aluminum (Al) and Silicon (Si). Testing of the cat fines level should be done in a laboratory according to ISO 8217 [1]: IP 501, IP 470 or ISO 10478. The standard test methods are rather complex sample preparations to resolve the issue with the particulate nature of the cat fines and also the potential risk of not getting a representative sample. So, the fuel is burned and heated, fused and digested in acids, and finally diluted to volume with water. Then all the oxides (cat fines) are dissolved, and the sample is analyzed in an ICP (Inductive Coupled Plasma) for the elements.

The standard methods do not cover the very low ranges for Aluminum and Silicon. However, as the sample is pre-concentrated with the burning and ashing procedure, very low concentrations can be analyzed by this method.
Graph in Figure 11 shows measurements of Aluminum and Silicon in more than 30000 fuel samples. It shows the typical correlation between Al:Si of 1:1.

Figure 11  Correlation between Aluminum and Silicon in more than 30000 fuel samples. Data from 2016. Data restricted to samples with less than 100 ppm Al+Si. Data courtesy: Lloyds Register FOBAS. Analysis: MDT.

**Cat fines size**

As described in Section 4, when cat fines are fed to the engine, some will embed in the soft graphite lamellas in the cylinder liner surface, and act like grinding paper towards the piston ring. The size of the cat fines vary from submicron up to 30 µm, and the shape is often close to being circular.

MDT PrimeServ has a service where they inspect replicas of cylinder liner surfaces for customers and give advice based on the findings. Experience show that a normal, healthy liner surface show below 200 cat fines/cm². Above this level increased wear is found.

810 cylinder liner replicas have been examined to date, and in 64 % of the cases cat fines have been found in the replicas. Amount of cat fines have been counted in 329 cases, and in 94% of the cases the level has been significant above the healthy level of 200 cat fines/cm², and the advice has been given to clean the fuel more carefully.

During the replica examination, the size of the cat fines has been counted, and the results show that most of the cat fines are found in the 5-15 µm size range. See Figure 12. However, when counting the number of cases where the different size distribution cases are found, it shows that in almost all cases both small and large cat fines are found in the same liner, showing that fuel cleaning has not been sufficient. See Figure 13. So, if a 10 µm had been installed in front of the engine, the increased number of cleaning cycles for the filter would have warned about the insufficient fuel cleaning.
4. Wear processes in the combustion chamber
Several wear processes may occur in the combustion chamber depending on the conditions:
- Abrasive wear
- Adhesive wear
- Corrosive wear

**Abrasive wear**
Abrasive wear is wear by displacement or removal of material caused by hard protrusions or hard particles which are forced against and moving along a solid surface. In case of protrusion or asperity contact the wear is called two body abrasion while it is named three body abrasion in the case of hard particles (e.g. cat fines) are involved. See schematic in Figure 14.

The amount of wear depends primarily on the hardness of the two materials in contact. If a surface has a hardness of more than half of the abrasive particle or protrusion, it is normally regarded as sufficient wear resistant.

In lubricated contacts abrasive wear will only occur when the lube oil is insufficient to separate the two components from each other.

Polishing, scratching and grinding are all a result of abrasive wear. Abrasive wear is the most common type of wear in industrial equipment.

**Adhesive wear**
Adhesive wear is the result of a high mechanical load of two opposing, sliding surfaces leading to increased duration of contact and/or increased temperature in the contact. This can lead to plastic deformation or micro welding, and will lead to tearing of material and/or transfer of material from one surface to the other. See schematic in Figure 15.
Load force, material hardness, crystal structure, affinity of the applied materials and material oxidation are important factors affecting the level of adhesive wear. Typical adhesive wear will start at the top of an asperity, where the local load can be very high, and can then from micro-seizure spread quickly to neighbouring surfaces in a self-acceleration manner. This is then known as scoring, galling, seizure or scuffing.

Lack of a lube oil film will not necessarily result in adhesive wear, depending on the affinity of the materials.

**Corrosive wear**

Corrosive wear is the result of chemical corrosion and mechanical wear acting simultaneous on the same surface. See schematic in Figure 16-17.

The chemical corrosion will result in corrosion products on the surface. These products will normally protect the surface against further corrosion, but when they are removed by either an abrasive (e.g. cat fines) or an adhesive wear process, the surface is left un-protected and the chemical corrosion process can continue. This leads to a high increase in the rate of material loss (wear).

Corrosive wear will be almost completely absent if either the corrosion factor or the wear factor is removed. Likewise, if either of the factors is increased, e.g. heavy wear from cat fines, the corrosive wear will also increase.
Wear mechanisms
A summary of the most commonly recognized wear mechanisms in the combustion chamber may be seen below in Figure 18, which is taken from MDT Operation Manual [10]. The wear mechanism from cat fines is abrasive wear.

Figure 18  Factors influencing wear of cylinder liner, piston rings, piston ring grooves and piston skirt. Factors relating to cat fines are marked with blue squares. [10].
**Abrasive wear from cat fines**

Abrasive particles cause wear when they enter the combustion chamber of the two-stroke engines. Here, the hard cat fines particles may be trapped between sliding surfaces such as the piston ring and liner, or the piston ring and ring groove. The particles are trapped either rolling freely between the sliding surfaces, or partially embedded in one of the surfaces. See figure 19 where the cat fines are being trapped between the piston ring and the liner. The wear process is 3-body abrasive wear. The more and bigger the particles are, the higher the wear will be.

![Figure 19](image1.png)

Figure 19  Schematic showing a cat fines being trapped between the piston ring and the liner.

Cylinder liners and piston rings are made of cast iron. Cast iron consists of different phases. The different phases have different inherent properties as e.g. hardness. The liners are made from cast iron with a flake graphite microstructure. Figure 20 show an example of liner material micro structure and the different phases. A SEM photo of flake graphite network can be seen in Figure 21. Table 2 show examples of hardness of the different phases.

![Figure 20](image2.png)

Figure 20  Polished and etched microsection of grey cast iron liner material, showing the different phases in the base material. Light optical microscope photo.

![Figure 21](image3.png)

Figure 21  Flake graphite in cylinder liner material. Iron-based matrix material has been etched away – leaving the graphite lamella network to be seen. SEM-photo. Courtesy: SinterCast
When the cat fines are being trapped between the piston ring and the liner, some will be forced into the soft graphite lamellas. See schematics in Figures 22-23.

An example of such trapping can be seen in Figure 24, where cat fines are embedded in the soft graphite lamellas in the cylinder liner surface.
5. Maximum limits for cat fines in marine fuel

Fuel is bunkered to the ship and is transferred to the storage tanks. The bunker sample (the Marpol sample) is taken during this process. So, the amount of cat fines (Al+Si) found in the bunker sample analysis show how much cat fines is found in the fuel entering the ship. The fuel cleaning systems on board must reduce this amount to a much smaller amount as the engine would otherwise wear down very fast. See schematics in Figure 25 below.

Figure 24  Replica print showing cat fines (examples at red arrows) embedded in the soft graphite lamellas in a cylinder liner surface.

Figure 25  High amounts of cat fines are allowed in the fuel as bunkered as according to ISO 8217 [1]. The fuel cleaning system on board must remove the cat fines before they reach the engine and cause wear.[7]
5.1 Cat fines in ISO 8217

Marine fuels are often purchased as according to the ISO 8217 international standard: Specifications of marine fuels [1]. The specifications in this standard define amongst others the limit for cat fines in fuel oils, expressed as Al+Si (Aluminum plus Silicon), as delivered to the ship. The most commonly used revision of the specification, ISO 8217:2005, lists a maximum limit of 80 mg/kg Al+Si for the thicker heavy fuel grades, whereas, the latest revisions, ISO 8217:2010, 2012 and 2017, have stricter requirement of maximum 60 mg/kg Al+Si for the thicker grades, and thinner grades are limited to 25, 40 or 50 ppm Al+Si. An overview of the ISO 8217 specified maximum limits for cat fines as Al+Si are given below in Table 3.

| Year    | DMC | RMA 10 | RMA 30 | RMA 80 | RMB 80 | RME 180 | RMF 180 | RMG 380 | RMH 180 | RME 380 | RMF 180 | RMG 380 | RMH 180 | RMG 380 | RMH 180 | RMG 500 | RMK 500 | RMK 700 | RMH 700 | RMK 700 |
|---------|-----|--------|--------|--------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 2005    | 25  | N/A    | 80     | 80     | N/A    | 80      | N/A     | 80      | N/A     | 80      | 80      | 80      | N/A     | 80      | N/A     | 80      | N/A     | 80      | N/A     | 80      | N/A     |
| 2010-17 | N/A | 25     | N/A    | 40     | 40     | N/A     | 50      | N/A     | 60      | N/A     | 60      | N/A     | 60      | N/A     | 60      | N/A     | 60      | N/A     | 60      | N/A     |

Table 3: Cat fines in ISO 8217.

The graph in Figure 26 show the distribution of the amount of cat fines found in samples examined by VPS (Veritas Petroleum Services) in 2016. It shows that the cat fines amount is widely spread from low amounts to high amounts – however most samples are found in the range between 7-50 ppm Al+Si.

![Figure 26](image)

5.2 Maximum limit for cat fines in the fuel entering the engine

Recent cases have shown that even small amounts of cat fines can be detrimental to the engine, so all measures must be taken to reduce the risk of introducing cat fines to the engine. Consequently, we have updated our recommendations, and specify keeping as low a cat fines level as possible before engine inlet. A maximum level of 15 ppm is acceptable for a short period of time, but the normal level must be kept lower. See Figure 27.

- Max. 15 ppm Al+Si at engine inlet – for short periods.

The Al and Si content should be measured according to ISO 8217 [1]: IP 501, IP 470 or ISO 10478.
A low level of cat fines can be achieved by cleaning the fuel at all times to a high standard. The maximum amount of cat fines in the fuel as bunkered according to ISO 8217-2005 are Al+Si: 80 ppm. The maximum recommended cat fines content before the engine is 15 ppm. So, the ship fuel cleaning system should be able to obtain such cleaning efficiency:

$$\text{Expected fuel system cleaning efficiency: } \frac{(80-15) \text{ ppm}}{80 \text{ ppm}} \times 100\% = 81\%$$

This expected fuel system cleaning efficiency are illustrated below in Figure 28. For example, when bunkering a fuel with 80 ppm Al+Si, it should be cleaned on board to 15 ppm, and when bunkering a fuel with 30 ppm Al+Si, it should be cleaned on board to 6 ppm Al+Si. Case studies for best in class fuel cleaning systems and also examples of fuel cleaning systems based on average results can be seen in Section 9.8.

MDT recommends always using the latest edition of ISO 8217, as the latest edition includes the latest and most relevant updates for the fuel of today.
5.3 Fuel sampling for check of cat fines content
Fuel cleaning systems are complex, and typically there are no clear measures telling whether the fuel is clean or not. That is why, we recommend that you check the efficiency of the fuel cleaning system by taking a full set of fuel samples every four months. Also, check the centrifuge efficiency when operating on a fuel with more than 25 ppm cat fines (Al + Si) in the fuel as bunkered. The sample positions are described in Table 4 and shown in Figure 29.

<table>
<thead>
<tr>
<th>Full set of samples</th>
<th>Check separator efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Every four months</td>
<td>- When the Al + Si content is above 25 ppm in the fuel bunkered</td>
</tr>
<tr>
<td>• At engine inlet</td>
<td>• Before separator</td>
</tr>
<tr>
<td>• Before separator</td>
<td>• After separator</td>
</tr>
<tr>
<td>• After separator</td>
<td></td>
</tr>
<tr>
<td>• Bunker sample</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 Fuel sample position. [7]

Send the samples to an established fuel analysing institute that can measure the Al + Si content according to ISO 8217: IP 501, IP 470 or ISO 10478.

Figure 29 Schematic fuel cleaning diagram – note the position of the sample valves in the green circles. [7].

6. Fuel cleaning systems
Fuel is bunkered to the ship and is transferred to the storage tanks. From the storage tanks the fuel goes to the settling tanks where some of the cat fines and other impurities will settle to the bottom of the tanks. From the settling tanks the fuel goes to the separators where the main fuel cleaning on board is performed. From the separator the fuel goes to the service tanks where further settling of cat fines and other impurities (and water) happens. From the service tank the fuel goes through a 10 µm filter, which also acts as an indicator for insufficient operation of the separators. Finally, the fuel reaches the engine. Now, the fuel should be clean and ready for use without generating increased wear on engine components.

Fuel cleaning systems on board ships are complicated and require thorough attention. It is important that they are designed and built to ensure acceptable cleaning and conditioning of the fuel. In some cases, it is seen that the fuel separator and preheater installed are too small, that the steam supply to the preheater is
limited, or that the temperature control is too slow. These are all factors that reduce the ability to clean the fuel efficiently.

We recommend consulting MAN Diesel & Turbo Project Guides and Operation Manuals, the CIMAC recommendations \[4, 5\], IACS recommendations \[6\], and separator manufacturers for information and advice when designing and installing ship fuel cleaning systems.

For fuels outside ISO 8217 \[1\] (e.g. with higher viscosity), special cleaning systems must be installed and operated to ensure the same, required good cleaning levels.

<table>
<thead>
<tr>
<th>Summary – Fuel cleaning systems:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experience has shown that, special attention must be drawn to the following installations:</td>
</tr>
<tr>
<td>• Separator sizing: 0.23 litres/kWh in relation to CFR</td>
</tr>
<tr>
<td>• Cleaning of the fuel in the service tank</td>
</tr>
<tr>
<td>• Fuel oil fine filter in front of the engine</td>
</tr>
<tr>
<td>• Fuel oil preheaters before the separators</td>
</tr>
</tbody>
</table>

### 6.1 Separator sizing

The lower the flow is through the separator, the longer the fuel stays in the separator, and the better the fuel is cleaned. Sizing of the fuel cleaning separators is a difficult task as there is no common recognized standard for measuring the cleaning efficiency of the separators. It is expected that the future development of the CFR standard for separators \[16\], which ensures a common standard for benchmarking flow rate, will drive the market to become more transparent and make it easier for customers to size the separator and obtain the correct cleaning efficiency.

Normally, a fuel separator has a layout for 100 % load fuel consumption of the engine plus constant values for different margins. MDT recommends that the size of the separator should be chosen according to the suppliers table valid for the selected viscosity of the thickest fuel oil to be used, and in compliance with CFR \[16\] or similar. To be able to clean the fuel to a suitable level, the separator should be able to treat approximately the following quantity of fuel oil:

- 0.23 litres/kWh in relation to CFR (Certified Flow Rate)

### 6.2 Cleaning the fuel in the service tank

Cleaning of the settling and service tanks in service must be possible. In calm weather, the cat fines will settle in the bottom of the tanks, but in high sea they can be hurled up and transferred further on in the system in high concentration. From the settling tank, the high concentration of cat fines may be led to the separators, which are unable to remove them to a satisfactory level. This means that the service tank will be contaminated with the high amounts of cat fines, which will be led to the engine where they will cause increased wear.

Even normal good cleaning of the fuel will lead to a concentration of cat fines in the bottom of the service tank if the system is not designed and operated with measures for continuous cleaning of the service tanks.

A generally acknowledged best practise is to:

- Use fuel tanks with sloped bottom – to concentrate the drain
- Drain the settling tanks and service tanks at regular intervals
Enable cleaning of the tanks in service by recirculating the fuel back to the separators. This can be done by:
- Having the overflow pipe in the service tank leading all the way to the bottom of the tank and led to the top of the settling tank. See Section 6.2.1. Or
- By means of a separate line from the service tank to the settling tank and a recirculating pump. See Section 6.22.

Clean all the fuel content in the service tank before use, if the tank has not been in use for some time (e.g. 1-2 weeks).

If equipment for tank cleaning is not installed, suitable procedures must be made to otherwise avoid feeding sludge and fuel with a high content of cat fines to the engine. Sections 9.1, 9.3 and 9.7 show cases where the service tanks have not been sufficiently cleaned, and high amounts of cat fines were led to the engines causing high wear and also scuffing and total replacement of liners and piston rings.

An overview of the recommended installations can be seen in Figure 30.

**Figure 30** Schematic drawing of fuel service tank – note that the overflow pipe goes to the bottom of the tank. [7]

### 6.2.1 Recirculating the fuel – Overflow pipe to the bottom of the tank
The simplest solution to enable cleaning of the service tank in service is by installing the overflow pipe in the service tank to lead all the way to the bottom of the service tank and back to the top of the settling tank. See Figure 30.

### 6.2.2 Recirculating the fuel – By a separate line
To ensure removal of the particles settled in the service tank, a cleaning flow must be established. The correct service tank design has an overflow pipe from the bottom of the service tank. If not installed by the yard, a retrofit solution with a small pump providing a flow from the drain point on the service tank and back to the settling tank should be fitted. See Figure 30.
6.2.3 Recirculating the fuel – the automated solution

To ease the operation of tanks and the separator, an automated solution could be installed. Such solution could consist of an automatic tank and separator system flow rate control to secure optimal cleaning efficiency at all engine loads. This automatic system is called “ATS” (Automated Treatment System).

The ATS system is designed to give a constant, but the smallest possible, overflow of the day tank. The overflow amount is determined by the target of having the day tank fully round-circulated in 72 hours at 100% consumption. Thereby, the flow rate should at any time be 1/72 times the day tank volume. The overflow is held constant by frequency control of the separator supply pumps, controlled by a flow meter in the return line from the day tank to the settling tank. This means that when the consumption of the engine goes down and the overflow has a tendency to increase, a signal is given to the separator supply pumps to slow down and, thereby, keep the overflow constant.

An overview of the solution are given in Figure 31.

**Figure 31** Example of fuel cleaning system with automated fuel cleaning optimization. For avoiding sulfur contamination a cleaning system for each fuel type is recommended.

*) Separator control is able to optimize separator efficiency by controlling the feed flow and temperature based on consumption from service tank. Consumption can be measured by a constant flow in overflow pipe back to the settling tank. Alternatively, level in service tank can be used for measuring the consumption for the separator control.

**) Overflow pipe in the service tank is fitted internally in the tank to reach the bottom to ensure flow of settlement to the settling tank.

***) For draining settlement in service tank after non usage. For the level control solution, pump can be used for constant recirculation of service tank.

6.3 Fuel oil fine filter in front of the engine

Removal of cat fines in the fuel has to be done in fuel separators because of the substantial amount of dirt and cat fines present in the fuel. However, as mentioned above, a number of factors may impact the separation efficiency, and we have seen very good results with installation of a max. 10 μm (absolute) full-flow automatic back-flushing filter positioned in the high-temperature fuel recirculation system, see Figure 32. Alternatively, the fine filter can be positioned in the supply system.
Such a filter is by no means sufficient to remove all the cat fines from the fuel, but it will act as an indicator for insufficient operation of the separators. For example, an increased number of cleaning circles for the filter indicates that the operation of the separators must be optimised. Section 3 – Cat fines size shows up to 270 cases where a 10 µm filter would have acted as indicator and also protection against poor fuel cleaning.

In summary, we have seen increased reliability and low wear rates when:
1. 10 µm filter is installed in front of the engine
2. filter cleaning cycles are logged on a daily basis
3. action is taken to improve the fuel cleaning if the cleaning cycle number increases to higher than normal.

6.4 Fuel oil heaters
The fuel cleaning system must be designed for optimal operation at both high and low flows with stable high temperatures. The separator temperature should always be kept as high as possible. The higher the temperature, the better the cleaning.

The fuel preheaters must raise the temperature of the fuel to the correct inlet temperature to the separators. Service experience shows both design and operational reasons for too low inlet temperature to the separators. Design related reasons could be preheaters having too small heating capacity and/or too limited steam supply or the controlling of the temperature is too slow. Operational reasons could be set point set too low or the heater being clogged by deposits, limiting the heating capacity. All these factors lead to a reduced separator inlet temperature and therefore poor separation.
To control the temperature at the correct and stable level, a proportional-integral-differential controller (PID controller) should be installed on the preheater to the separator. If only a P-function controller is installed, it will most likely cause excessive temperature variations and, therefore, too low or too high a fuel oil inlet temperature to the separator. If the inlet temperature goes too high, it may cause boiling of the control water in the separator, and cause an alarm and possible shut-down of the separator.

### 6.5 Automated separator flow control

Since the engine is rarely running 100% load, there is a large potential for increasing the separation efficiency by applying automatic flow control in relation to the actual fuel consumption. See also Section 6.2.3.

### 7. Operation

The cleaning system must be designed for optimal operation at both high and low flows with stable temperatures. Too low a temperature and too high a flow through the separators during fuel cleaning will result in insufficient removal of water, cat fines, sludge and other contaminants. See Figure 33.

#### Figure 33
Separator operations at different parameters. Note the increased cleaning at high temperature and low flow. [7]

---

**Summary – Fuel cleaning operation:**

To increase the efficiency of fuel cleaning and, thereby, remove more cat fines from the heavy fuel oil, there are three main issues to attend when operating a ship fuel cleaning system:

- separation temperature: Keep the temperature as high as possible
- flow rate through the separator: Keep the flow as low as possible
- operation and design of fuel tanks: Cleaning should be possible and also done in service

The recommendations for actual operation from the separator manufacturers should be followed. We also recommend consulting MAN Diesel & Turbo Operation Manuals [10] and separator manufacturer advice for information and advice for operation of the fuel cleaning systems on board.
7.1 Operation of separators
The separators are removing most of the impurities in fuel in the entire fuel cleaning system, and it is therefore necessary to use utmost care during operation and maintenance.

7.1.1 Particle separation fundamentals.
The well-known Stokes’ law is a formula for determining the rate of particles settling in a fluid. It states that a particle moving through a viscous liquid attains a constant velocity or settling rate. The rate can be very slow for particles which density is close to that of the liquid, for very small particles or where the viscosity of the fluid is high. Replacing the gravitational acceleration with the acceleration generated by a rotating centrifuge results in faster settling. Centrifugal acceleration can be thousands of times greater than that of gravity, so the centrifugal settling is thousands of times greater.

Stokes equation:

\[ v_{setting} = \frac{d^2(\rho_p - \rho_l)}{18\mu} \alpha \]

where \(d\) is the particle diameter, \(\rho_p\) and \(\rho_l\) are the particle and liquid densities and \(\mu\) is the liquid viscosity. The factor \(\alpha\) is the gravitational or (in a separator) the centrifugal acceleration. What a separator does is increasing \(\alpha\) from 9.8 m/s\(^2\), as in gravitational settling, to many thousand times that.

Figure 34 illustrates how particle size and flow rate affects the separation performance of a disc stack separator. A cat fines particle is subject to the same principle when being separated in a separator disc stack as it is in a tank. The centrifugal force acts to move the particle to the periphery, whereas, the flow of the oil brings the particle towards the centre of the bowl. As the flow reaches a certain rate, the cat fines particle will escape with the oil, un-separated.

![Figure 34](image)

Figure 34 Effect of the settling velocity dependence on particle size and flow rate in a disc stack separator.[9]

Figure 35 shows how the separation efficiency, defined as a percentage of the particles removed, depends on the parameters in the Stokes equation. Particle size and density difference are properties that are not possible to influence by on board measures. This leaves the flow rate and viscosity as the remaining parameters that can be altered to affect the separation performance.
Influence of particle density

In figure 36 is shown an example of sedimentation rate for a 5 µm particle made of iron and a 5 µm cat fine particle depending on temperature of a RMK type heavy fuel with density 1010 kg/m³ and viscosity 700 cSt at 50 ºC. It shows that at 98 ºC, the sedimentation rate is 400% faster than for the iron than for the cat fine, and it is therefore much easier to clean the fuel for the heavy iron particles than for the lighter cat fines.

Influence of particle size

In Figure 37 is shown an example of sedimentation rate for different size cat fines depending on temperature of a heavy fuel with 700 cSt at 50 ºC. It shows that at 98 ºC, the sedimentation rate is 200% faster for a 10 µm cat fine than for a 5 µm cat fine, and 400% faster for a 20 µm cat fine than for a 10 µm cat fine and 800% faster than for a 5 µm cat fine. It is therefore much easier to clean the fuel for the bigger cat fines than for the small cat fines.
Figure 37: Sedimentation rate increase with diameter of the particle. Example of sedimentation rate for different sizes of cat fines in a RMK type heavy fuel: Density: 1010 kg/m$^3$, viscosity: 700 cSt at 50 °C. Cat fines density used: 2100 kg/m$^3$

7.1.2 Separator temperature

The temperature of the fuel in the separator is a very important parameter to improve fuel cleaning efficiency as the temperature of the fuel affects the viscosity of the fuel. As the temperature of the fuel increases, the viscosity of the fuel decreases. The separator temperature should always be kept as high as possible. The higher the temperature, the better the cleaning.

Calculations using Stokes equation show that when reducing the temperature from 98 °C to 95 °C the sedimentation rate decreases by 11 % for a RMK type fuel, and when reducing further from 98 °C to 90 °C the sedimentation rate decreases by 28%. So, at small reduction in temperature has a high impact on the fuel cleaning efficiency, and it is very important to keep the temperature at the recommended 98 °C for heavy fuel.

The traditional diesel systems on board are dimensioned to operate on low-viscosity fuel at rather low temperatures. Compared to heavy fuel (HFO) cleaning systems, the separator and preheater are smaller dimensioned and the electrical equipment might not be certified safe equipment. The viscosity of the distillates, ULSFO (Ultra Low Sulphur Fuel Oils), and also heavy fuel (HFO) are very different. Therefore, it is important to pay attention to the recommended temperature for the different fuel types during the cleaning process. See Table 5. If a thin fuel is heated too high, the viscosity of the fuel may become too low, see [17] for more details. The viscosity at engine inlet should always be kept above 2 cSt.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Fuel temperature in the separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distillates</td>
<td>40-50°C</td>
</tr>
<tr>
<td>ULSFO</td>
<td>Viscosity @ 50°C</td>
</tr>
<tr>
<td>Up to 20 cSt</td>
<td>50°C</td>
</tr>
<tr>
<td>20-40 cSt</td>
<td>60°C</td>
</tr>
<tr>
<td>40-50 cSt</td>
<td>70°C</td>
</tr>
<tr>
<td>50-80 cSt</td>
<td>80°C</td>
</tr>
<tr>
<td>&gt;80 cSt</td>
<td>98°C</td>
</tr>
<tr>
<td>HFO</td>
<td>98°C or higher</td>
</tr>
</tbody>
</table>

Table 5 Recommended fuel cleaning temperature in the separator. [7]
Viscosity of ULSFO
Generally, the viscosity of the ULSFO are higher than distillates, and they are often sold as RMA10-RMD180 as according to ISO 8217 [1]. A majority of the ULSFO could be supplied as RMB30 as according to density and viscosity, but 80% of the samples were supplied as RMD80 due the high pour point. See Figure 38.

![Fuel data for ULSFO. Note the variation in viscosity. Data courtesy: Lloyds Register FOBAS. Analysis: MDT.](image)

Fuel temperature higher than 98 °C in the separator
There is a high potential for improved fuel cleaning efficiency by increasing the temperature above 98 °C. Calculations using Stokes equation show that when increasing the temperature from 98 °C to 110 °C the sedimentation rate increases by 54 % for a RMK type fuel. See also Sections 9.9 and 9.10 for results from service.

The present limit of 98 °C is set with respect to safety reasons. Some systems, as e.g. the Cat Fines Master from GEA, are capable of operating as temperature above 98 °C. But older and also some newer on-board separators are designed as open atmospheric systems. So, before increasing the temperature above 98 °C, the system and separator supplier should be contacted as not all systems are capable of increasing the temperature above 98 °C. Issues informed by separator manufacturers are concerning material strength and durability, process issues concerning water boil-off and steaming, and possibly regarding compliance with safety codes for the material used in the system.

7.1.3 Separator flow rate
The lower the flow is through the separator, the longer the fuel stays in the separator, and the better the fuel is cleaned. Normally, a fuel separator has a layout for 100% load fuel consumption of the engine plus constant values for different margins. Since the engine is rarely running at 100 % load, there is a large potential for increasing the fuel cleaning efficiency by decreasing the flow through the separator. The flow should always be kept as low as possible.

Figure 39 illustrate how the fuel cleaning efficiency increases as the flow rate decreases. Results from service can be seen in Section 9.9 and 9.10.
Automatic flow control in relation to the actual fuel consumption is a simple and effective way of ensuring optimised separation performance. Today, operators are recommended to use all separator capacity installed and run standby separators in parallel. Manual flow control is sometimes installed and should be used.

Automatic separator flow control systems are still rare, and work is ongoing to design systems that adjust the separation flow rate automatically according to the engine load.

**Flow-temperature combination**
Figure 40 [9] show how the flow through the separator and the fuel temperature interact to obtain similar fuel cleaning efficiency. The nominal flow is set to 1 (100%) at 98°C fuel temperature. If the temperature are reduced to 90°C, the flow must be reduced to 72% of the nominal flow to maintain separation efficiency at the same level as at 98°C, further down, at 85°C, the flow must be halved.

**Cat fines content higher than 25 ppm in the fuel as bunkered**
When the cat fines content in the fuel as bunkered is higher than 25 ppm Al+Si, MDT recommend to operate two separators in parallel to reduce the flow and increase the fuel cleaning efficiency. If flow reduction is not possible, we recommend operating the separators in series.
7.1.4 Maintenance
Proper maintenance of the separators is important, and it must be carried out in accordance with the recommendations from the separator manufacturers. For easy cleaning, the CIP (Cleaning In Place) systems can be used. If the bowl is not cleaned in time, the amount of deposits on the bowl discs will grow to an excessive level that will reduce the free channel height, increase flow velocity and thereby, reduce the separation performance. Results from service with low cleaning efficiency can be seen in Section 9.9.

According to [9], the distance between the bowl discs is normally 0.5 mm. The speed through the disc stack will increase by 20%, resulting in a theoretical 20% decrease in separation efficiency if a 0.1 mm sludge/oil residue layer is present on the discs.

7.2 Operation in heavy weather
The cat fines will concentrate in the bottom of the tanks during normal operation in calm weather. To reduce the risk of feeding cat fines to the engine in rough weather, the following can be applied:

- Use the standby separator simultaneously with the separator already in service and decrease the flow – to increase cleaning efficiency.
- Use the high-suction line – to better protect against cat fines settled in the bottom of the tank. See Figure 30 in Section 7.2.

8. On-board monitoring
Successful optimisation of the fuel cleaning and the cylinder condition depends on the operators following the condition closely and acting on the information obtained. It is recommended to check the fuel regularly for cat fines content, use cylinder lube drain oil analysis, and inspect the engine for wear of combustion chamber parts, i.e. piston rings, pistons and cylinder liners. In this Section are described a number of on-board techniques and how to use them to guide action and protection against cat fines.

**Summary – On-board monitoring:**
Important points regarding on-board monitoring of cat fines related failures:

1. In case cat fines attack is suspected, first step should be to improve the cleaning of the fuel.
2. Check the fuel for cat fines at regular intervals (min. every 4 months), and if the fuel as bunkered contains more than 25 ppm cat fines (Al+Si). Act on the results obtained.
3. Use the on-board analysis tools for checking the cylinder condition:
   a. High iron (Fe) amount in the cylinder lube drain oil means high wear. If the BN is also high, the wear is likely to be caused by cat fines.
   b. Regular scavenge port inspections and wear measurements will show whether the engine is subjected to high wear.
   c. Liner surface examination, e.g. with replica analysis, showing high amounts of cat fines in the graphite lamellas are subjected to wear from cat fines.

8.1 Fuel
Various on-board equipment like the on-line equipment: CatGuard (NanoNord) and also other equipment being developed at the moment may be used for trending of the cat fines level in the fuel. Based on such knowledge, it is up to the operator to act and protect the engine against increased wear.
8.1.1 CatGuard – online measurement of cat fines
The CatGuard from NanoNord is an online system for monitoring the amount of cat fines in the fuel. Depending on the system type, it can be connected at one or more positions in the fuel cleaning system. E.g. before engine, before and after the separator etc.

Figure 41 shows a schematic on-board fuel treatment system monitored by CatGuard with four automatic sampling points and one manually operated sampling point. With such installation it is possible to trace a high cat fines problem to the source by comparing the measurements from the different sampling locations.

Since 2012, several CatGuard systems have been involved in extensive tests, and have continuously delivered reliable measurements of the cat fines content. See also Sections 9.3, 9.7 and 9.10.

Because the CatGuard delivers online readings of cat fine levels, ship crews now have the required tool to actually manage cat fines on-board. The crew will automatically have observations available and can, when required, perform the required countermeasures. Afterwards, the improvements can be observed online.

Figure 42 shows 7 months CatGuard data from an installation in service of the separator input and the main engine inlet [9]. The average cat fines content in the heavy fuel oil supplied was relatively constant in the 30 mg/kg range in bunker reports, and as measured by CatGuard. The crew used the CatGuard to improve the separator efficiency and several permanent improvements to the fuel cleaning system were implemented on the ship in August. Thereby ensuring that the average cat fines content in the main engine was successfully reduced from around 15 mg/kg in June to around 5 mg/kg in average after August.

8.1.2 On-board kits for measuring cat fines in the fuel
Stand-alone on-board cat fines measuring equipment exist in the market, and we support the further development.

8.1.3 Fuel system check
Some of the fuels analyzing companies offer a fuel system check service. Such service may include, analyzing fuel samples from different positions in the fuels system, e.g. before and after the centrifuge and before the engine (see Section 9.8), and evaluating the actual fuel cleaning efficiency on board. The service may also include the company coming on board the ship checking and evaluating the actual fuel system, and making recommendations for improvements.
8.2 Cylinder condition

Successful optimisation of the lubrication and improvement of the cylinder condition are dependent on that the condition is followed closely and the operators act on the information obtained.

Main on-board analysis tools for checking the cylinder condition are:
- cylinder lube drain oil analysis,
- scavenge port inspections,
- wear measurements and
- liner surface examination

8.2.1 Cylinder lube drain oil analysis

During normal operation, fresh cylinder lube oil is injected into the cylinder and the used oil is drained from the bottom of the cylinder liner and discharged (once-through principle). See Figure 43.

The used cylinder lube oil (also called drain oil or scrape down oil) can be sampled from the engine through the scavenge bottom drain. Analysis of the drain oil can show whether the cylinder condition is within the normal range or whether action must be taken. Such actions could be: lowering the cylinder lube oil feed rate, lowering the cylinder lube oil BN, removing cat fines from the fuel or increasing the cylinder lube oil BN or the feed rate to protect against cold corrosion.

The analysis of the drain oil from the cylinder lube oil will indicate the cylinder condition mainly by the BN-value and the iron-content (Fe). The evaluation should be based on the combination of both BN and Fe in order to determine proper actions. We recommend to optimise the cylinder lube oil feed rate to secure the drain oil in the safe area. See Figures 44 and 45.

Evaluation of the corrosive level

The BN in the drain oil is an indication of the oils remaining ability to neutralize the acids. A low BN value indicates that the oil is close to exhaustion and thereby cannot protect the engine from the acid. A high value may indicate that the cylinder lube oil feed rate is too high or the BN in the applied oil is too high, and the risk of deposit build-up and bore-polish may increase.

Figure 43 Schematic of combustion chamber lubrication.
Evaluation of the wear

The iron concentration in the drain oil will reflect the wear of the piston rings and liners. A high number indicates high wear, and a low number could indicate low wear.

Different analysis methods measure different kinds of wear (Table 6). Some methods measure the total iron formed during the wear processes, as they measure the iron-element. Other methods measure the iron formed by adhesive or abrasive wear as e.g. from “normal wear”, wear from cat fines in the fuel, wear from micro-seizures and/or scuffing, as they measure the magnet flux formed by magnetic wear-particles. The wear particles from cold corrosion are iron oxides and are not magnetic. On-board methods for detecting this wear-form are based on chemical reactions.

<table>
<thead>
<tr>
<th>Wear types</th>
<th>Wear mechanism</th>
<th>Measuring method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total iron</td>
</tr>
<tr>
<td>Normal wear</td>
<td>Abrasive or adhesive wear</td>
<td>+</td>
</tr>
<tr>
<td>Cat fines</td>
<td>Abrasive or adhesive wear</td>
<td>+</td>
</tr>
<tr>
<td>Micro-seizures</td>
<td>Abrasive or adhesive wear</td>
<td>+</td>
</tr>
<tr>
<td>Scuffing</td>
<td>Abrasive or adhesive wear</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 6 Correlation between wear type and mechanism and different iron measuring methods.

Depending on the measuring method, different results may be obtained, and care must be taken to evaluate the results as different actions may be recommended. If the magnetic iron method shows low iron, it must be complimented by results of the remaining BN to evaluate whether the wear type is cold corrosion or e.g. normal low wear. If the BN is low, it could be cold corrosion, and the action should be to increase the cylinder lube oil feed rate or change to higher BN oil. But if the BN is in the safe area, everything is fine, and no action should be taken. If the BN is high, the engine might suffer from increased deposits and the action should be to lower the cylinder lube oil feed rate or change to a lower BN oil.

Wear from cat fines in the fuel will show high iron (Fe) in the drain oil, using methods for detecting total iron and magnetic iron.
Statistical evaluation of a high number of drain oil samples from many different engines in service do not show a direct correlation between wear likely originating from cat fines and amount of Aluminum (Al) in the drain oil.

### 8.2.1.1 Actions depending on results from cylinder lube drain oil

Normal levels of iron in the cylinder lube drain oil are 50-100 ppm in a well running engine. The amount of iron will increase when the engine is subjected to wear. Depending on the wear type, the drain oil will show different results. See Figure 46 and Section 9.1, 9.2, 9.3, 9.5 and 9.6.

**Figure 46** Results from drain oil analysis. Area 1: Cold corrosion. Area 2-3: Cat fines in the fuel. Area 4: Too much BN. Area 5: Safe area. See also [13].

Based on the results, different actions should be taken. A summary is shown in table 7.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Failure mode</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cold corrosion</td>
<td>The engine suffer from cold corrosion</td>
<td>Increase cylinder lube feed rate or change to higher BN oil.</td>
</tr>
<tr>
<td>2</td>
<td>Cat fines in the fuel &amp; too much BN</td>
<td>The engine suffers from abrasive wear from cat fines in the fuel, and might experience increased deposits from unused additives in the lube oil.</td>
<td>Check fuel centrifuge efficiency and decrease cylinder lube feed rate/change to lower BN oil. Increase fuel temperature and/or decrease flow through centrifuge.</td>
</tr>
<tr>
<td>3</td>
<td>Cat fines in the fuel</td>
<td>The engine suffers from abrasive wear from cat fines in the fuel.</td>
<td>Check centrifuge efficiency. Increase fuel temperature and/or decrease flow through centrifuge.</td>
</tr>
<tr>
<td>4</td>
<td>Too much BN</td>
<td>The engine might suffer from increased deposits from unused additives in the lube oil.</td>
<td>Decrease cylinder lube feed rate or change to lower BN oil.</td>
</tr>
<tr>
<td>5</td>
<td>Safe area</td>
<td>The engine wear is low and deposits from the cylinder lube should be low.</td>
<td>Keep the engine parameters.</td>
</tr>
</tbody>
</table>

**Table 7** Failure mode and corrective actions based on drain oil results.
8.2.1.2 On board equipment for cylinder lube drain oil

Operational and environmental parameters influence the wear of engine components. On-board equipment can therefore be of great value in the continuous process of protecting the engine and optimising the cylinder lube oil feed rate.

However, on-board measurement cannot stand alone. It is recommended that samples are sent for laboratory testing regularly, to ensure adequate correlation between the two types of measurements.

In Table 8 are listed examples of on-board equipment for cylinder lube drain oil analysis. Other equipment exists in the market, and we support the further development.

<table>
<thead>
<tr>
<th>Wear types</th>
<th>Wear mechanism</th>
<th>Measuring method</th>
<th>Measuring method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal wear</td>
<td>Abrasive or adhesive wear</td>
<td>DOTFAST</td>
<td>Analex/FWM</td>
</tr>
<tr>
<td>Cat fines</td>
<td></td>
<td>DOTFAST</td>
<td>Analex/FWM</td>
</tr>
<tr>
<td>Micro-seizures</td>
<td></td>
<td>DOTFAST</td>
<td>Analex/FWM</td>
</tr>
<tr>
<td>Scuffing</td>
<td></td>
<td>DOTFAST</td>
<td>Analex/FWM</td>
</tr>
<tr>
<td>Cold corrosion</td>
<td>Corrosive wear</td>
<td></td>
<td>CCT</td>
</tr>
</tbody>
</table>

Table 8 Examples of on-board equipment for cylinder lube drain oil analysis.

**DOTFAST**

The DOTFAST equipment measures the total iron concentration in the drain oil. The measuring principle is based on a chemical reaction and subsequent photometric reading. See Figure 47.

The equipment is developed by Chevron Lubricants, and can also be purchased through MAN Diesel & Turbo.

**Analex/FWM (Ferrous Wear Meter)**

The Analex or FWM (Ferrous Wear Meter) equipment measures the magnetic iron concentration in the drain oil. The measuring principle is based on magnetic flux from the magnetic iron particles. See Figure 48.

**LinerScan**

The LinerScan equipment measures the amount of magnetic iron in the cylinder lubricant drain oil on-line. The method used is magnetometry, where a sample is tested in a magnetic field, the inductance change and the change is a measure of the amount of magnetic material in the sample. It is installed on the cylinder drain oil pipe. See Figure 49.
The results may be included in our COCOS equipment, and the results may be stored together with the engine performance data, or the equipment may work on its own.

**Figure 49**  From Kittiwake LinerScan brochure showing installation on drain oil pipe and flow through LinerScan measuring device. Courtesy: Parker Kittiwake.

### 8.2.2 Scavenge port inspection

This visual inspection through the scavenge ports provides useful information about the condition of cylinders, pistons and piston rings. Measurements of piston ring coating (if present) and CL grooves also give valuable information. Regular inspections can detect if there are changes in the cylinder condition. It is generally advised to make such inspection twice a month.

When good and steady service conditions have been achieved, the running surfaces of the piston rings and cylinder liner will be worn smooth without scratches. The rings will move freely in the ring grooves, they will be well oiled, intact and not unduly worn. The ring edges will be sharp when the original roundings have been worn away, but without burrs.

**Visual observations of wear from cat fines**

Wear from cat fines may show as:

1. Normal, smooth surface on the liner and piston rings.
2. Usually, micro-seizures do not occur.
3. If wear is very high, seizures and possibly scuffing may occur.

In case cat fines attack is suspected, first step should be to increase the cleaning of the fuel. Further information and recommendations for actions depending on observations may be found in our Operation Manuals [10].

### 8.2.3 Wear measurements

As part of regular engine inspections, engine crew should measure liner, piston ring and piston ring groove wear. The wear measurements should be stored in the vessel maintenance system. It is recommended to analyse the wear in order to assess whether the lubrication and fuel cleaning processes are adequate. Furthermore, component lifetime can be assessed based on a number of measurements, and overhaul can be planned.
Wear from cat fines will show as either a sudden increase in the wear rates of liner, piston rings and ring grooves, or as a generally increased level over the normally expected levels. See schematic of liner wear in Figure 50. See also examples from service in Section 9.1, 9.4 and 9.7. In case cat fines attack is suspected, first step should be to increase the cleaning of the fuel.

Figure 50  Schematic of liner wear – with examples of wear from cat fines.

8.2.4 Liner surface examination
It is recommended to evaluate the liner surface condition during cylinder overhaul. A healthy liner surface appears visually dull with slight wear-marks. Liner surfaces subjected to wear from cat fines will show scratches, and when examined under microscope, the cat fines will appear in the graphite lamellas if the graphite lamellas are visible or as a totally scratched surface without graphite lamellas. See Figures 52-54.

A suspicion of whether sudden liner and piston ring wear is caused by cat fines can be examined by taking a replica of the liner surface. See Figure 51. Subsequent examination under microscope may show whether the surface suffer from cat fines attack, bore-polish, low wear, cold corrosion, seizures and scuffing or whether the liner surface is found normal. This service is offered by MAN Diesel & Turbo PrimeServ in Copenhagen [14].

Experience has shown that cylinder liners showing normal wear low wear, only show a limited number of cat fines in the graphite lamellas (less than 200 cat fines/cm²), while liners subjected to high wear from cat fines in the fuel show a high number of cat fines in the graphite lamellas.

In all cases where cat fines are found to be the cause of high wear, the first step to re-establish a normal, low wear situation must be to clean the fuel for the cat fines. Further actions to obtain a healthy situation could be:

1. In cases where the surfaces are found with cat fines in the graphite lamellas, but without seizures and scuffing, the liner surfaces will generally not require machining of the liner, and the piston rings may not need to be exchanged.
2. In cases where the surfaces are found totally scratched and seized, and the few visible graphite lamellas show cat fines, a light honing on the surface to open the graphite lamellas or in severe
cases wave-cutting and semi-honing of the liner may be necessary and the piston rings should be exchanged.

Figure 51. Photo of replica on the surface of a cylinder liner.

**Liner surfaces in replica examination**

Photos of replicas of liner surfaces in different tribology conditions from engines in service may be seen below in Figures 52-54.

Figure 52. Surface with normal wear. Replica showing wear pattern for a liner with normal low wear.

Figure 53. Surface with wear from cat fines. Replica showing wear pattern for a liner subjected to heavy wear from cat fines. Note the cat fines in the graphite lamellas (examples at red arrows), the heavy scratches and the protruding hard phases (in yellow circles).
9. Service experience

As described above, cat fines are found in marine fuel. High amounts are normally allowed in the fuel as bunkered, but such high level would cause extremely high wear in the combustion chamber, and the fuel must be cleaned before reaching the engine. Some examples of cases where the fuel have not been cleaned sufficiently are shown in Figure 55. The actual wear measured has been normed to mm/1000 running hours. It shows that the higher the amount of cat fines is in the fuel, the higher the wear. In some cases it reaches extreme levels.

In the following sections, actual cases of wear from cat fines in the fuel are described.
9.1 Case story 1: Clean the day tank
Cat fines damage is only rarely the result of running on off-spec fuel. The majority of fuels supplied fulfill the ISO 8217 specification requirements (see Section 3). Cat fines settle in the tanks and might enter the engine in high concentrations during rolling conditions or rough weather. Or if the bottom of the tanks are not cleaned on a regular or continuous basis the cat fines will enter the engine continuously. Such cases can result in severe cat fines attack and engine damage.

In this case, the ships service tanks where not cleaned regularly, and the cat fines settled in the bottom of the service tank were let directly to the engine causing high wear and also scuffing. When the service tanks were cleaned, the engine wear returned to normal, low levels.

Cylinder lube oil drain
A LinerScan equipment were installed on 4 cylinders on a 12K98ME-C engine as part of a cylinder lube oil test. The LinerScan equipment is able to measure the amount of magnetic iron in the cylinder lube drain. The amount of iron in the cylinder lube drain is a measure for wear of combustion chamber components (See also [13]), and the wear from cat fines results in magnetic iron particles (and also other wear particles). The iron content in the drain oil from well running cylinders is normally below 100 to 200 mg/kg (ppm). In case of a severe cat fines attack, the iron content may increase to 1,000 to 2,000 mg/kg (ppm). See also Section 8.2.1.2.

The actual ship set up can be seen in Figure 56. The overflow line is let merely from the top of the tank. It should be led to the bottom of the tank to enable continuously cleaning of the service tank. See [7]. In this ship set up also the dirt from the filter back-flushing were let back into to the fuel system. This is not either recommended. The filter back-flush should be led to the sludge tank.

![Diagram of LinerScan equipment](image)

During the testing, the amount of magnetic iron increased to high levels in the cylinder lube drain, and investigation started to find the failure cause.
In the entire period, the magnetic iron level in the cylinder lube drain was logged, and the results can be seen in Figure 57. The period can be divided in 6 cases:

1. Normal wear
2. Cat fines attack initiated
3. Severe cat fines attack
4. Cleaning of the service tank
5. Recovery period
6. Normal wear

Figure 57  A severe cat fines attack on a 12K98ME. Documentet by means of a Kittiwake LinerScan equipment, which measures the content of magnetic iron particles. Note that before the attack, the iron level was below 100 ppm - during the attack it peaked to more than 2500 ppm (which is the max. detection limit for the equipment).

As can be seen from the results in Figure 58, that if a cat fines attack is efficiently stopped by ensuring that the fuel, which is being led to the engine, is clean, the wear rate will return to normal within a short period. This means that as long as a cat fines attack is discovered in time, and the piston rings and liner are not worn out, overhaul of the units may not be necessary. Most important actions to take are to clean the settling and day tanks, and to improve the fuel treatment.
Figure 58. A severe cat fines attack on a 12K98ME. Documented by means of a Kittiwake LinerScan equipment, which measures the content of magnetic iron particles. Note that after cleaning of the tanks and ensuring clean fuel, the engine wear recovered within 6 days.

**Wear**

During the entire period the wear were monitored. In the cat fines attack, the liner wear rates increased to up to over 2 mm/1000 h, piston ring cermet coating wear rates up to 300 µm/1000h, and 5 cylinders scuffed and had to be replaced. After the cleaning of the service tanks, the wear rates returned to normal low levels. Wear rates can be seen in Figures 61 and 62. Photos of piston rings taken during the period of severe cat fines attack can be seen in Figure 59-60.

Figure 59. Piston ring with scuffed surface. Cyl. 4, 39136 h

Figure 60. Piston ring with heavy wear. Cyl. 7, CL-groove is reduced to 2 mm, i.e. 1 mm has been worn in 733 h.
Figure 61 Piston ring wear during the period. Note the high wear in the cat fines attack period. The remaining cylinders piston rings were exchanged during the period – either from wear out or scuffing.

Figure 62 Liner wear rates during the period. Note the high wear in the cat fines attack period. Liners in cyl. 1, 3, 4, 5 and 7 scuffed during the cat fines attack period.

**Cat fines found in cylinder liner surface**

The condition of the cylinder liner surfaces were also followed during the period. Cat fines embed in the soft graphite lamellas in the cylinder liner surface (see also Section 4 and 8.2.4). Figure 63 show examples from the same cylinder in 3 different periods:

- The initial cat fines attack, which show increased amount of cat fines embedded in the graphite lamellas (Figure 63a)
- The severe cat fines attack, which show very high amount of cat fines embedded in the graphite lamellas (Figure 63b)
- Normal wear, which show that the cat fines have been removed, and no more cat fines are let to the engine. (Figure 63c)
The case show that the “life-time” of the cat fines embedded in a liner surface is relatively short. When cat fines are found in the liner, it is a result of them being continuously fed into the engine with the fuel. When the fuel is fed clean to the engine, the cat fines embedded in the liner surface and piston ring surfaces will leave by themselves within a week.

9.2 Case story 2: Clean the fuel – also for small particles

The smaller the cat fines are, the more difficult they are to separate from the fuel in the separators. The minimum lubricating oil film thickness between the liner surface and piston rings at Top Dead Center (TDC) is down to 0.5 μm (see below). Consequently, very small particles captured between the piston ring and cylinder liner will contribute to the wear in the TDC area.

Oil film thickness

Oil film thickness in the combustion chamber has been calculated and also measured. A calculation example for S40ME-B engine type is shown in Figure 64. The calculation is based on in-house developed software. The oil film thickness has also been measured on board in a 12K90MC engine [15]. Results from the on board measurement can be seen in Figures 65-66. Both methods show that the oil film thickness at TDC is very small – down to 0.5 μm.

![Figure 64: In-house calculation of oil film thickness between liner surface and piston ring in an S40ME-B type engine. Note the oil film thickness down to 0.5 μm in TDC.](image)
Figure 65  Photo (left) and schematic showing position of the oil film measuring devises in the liner on board the 12K90MC [15].

Figure 66 Oil film thickness results from cylinder lube oil feed rate test on board the12K90MC. Load: 85%. [15]
Note that the oil film thickness is measured to 1.0 µm at TDC.
At cylinder lube feed rates below 0.6 g/kWh the oil film is reduced to below 1 µm in TDC. At feed rates higher than 0.6 g/kWh the oil film thickness stays constant at 1 µm - independent on the feed rate.

Small particle wear test on test engine
To verify whether small particles will wear the combustion chamber parts, MDT added small hard silicon oxide particles (1, 4 and 8 µm) to the scaveng air in the test engine in Copenhagen, 4T50ME-X, and measured the resulting wear by means of wear particles in the drain oil (Figure 67). Test parameters may be seen in Figure 68.
SiO₂ (quarts) particles were chosen for the test as they are almost as hard as cat fines, and they come in very defined shape and size distributions (Figures 69-71).

The results of the test are shown in Table 9. The iron in the drain oil samples was analysed by ICP (Inductive Coupled Plasma) after ashing and acid digestion of the sample. The results show normal level in the amount of iron in the cylinder lube drain oil when injecting 1 µm SiO₂ particles into the scavenge air and a significant increase in the iron when injecting 4 µm and 8 µm SiO₂ particles into the scavenge air.

Consequently, these results indicate that fuel entering the engine must also be cleaned of very small cat fines.
### 9.3 Case story 3: Cat fines amount -> Wear particles amount

A CatGuard (see Section 8.1.1) and a LinerScan (see Section 8.2.1.2) equipment were installed in a fuel system for a 12K98ME engine. See the ship set up in Figure 72. The CatGuard equipment is able to measure the cat fines content of fuel on line. The LinerScan equipment is able to measure the amount of magnetic iron in the cylinder lube drain oil. The amount of iron is a measure for the wear of the combustion chamber components (See also [13]), and the wear process from cat fines results in magnetic iron particles (and also other wear particles). See also Section 8.2.1.

For this engine, the results from the CatGuard and the LinerScan equipments were logged in the engine diagnostic system: COCOS-EDS, so that during operation of the engine, corresponding results of cat fines content in the fuel and magnetic iron in the cylinder lube drain oil can be followed.

Below in Figures 73-74 are results showing:

1. Figure 73: Red lines:
   - CatGuard: 10-12 ppm cat fines at engine inlet
   - LinerScan: 200-300 ppm magnetic iron in the cylinder lube drain oil.

#### Table 9 Small particle wear test results

<table>
<thead>
<tr>
<th>SiO₂ particle size</th>
<th>Method</th>
<th>Iron (Fe) measured in cylinder lube drain oil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analex</td>
<td>ICP (ashed)</td>
</tr>
<tr>
<td>Reference without SiO₂ particles</td>
<td>31-51</td>
<td>52</td>
</tr>
<tr>
<td>1 µm</td>
<td>63</td>
<td>60</td>
</tr>
<tr>
<td>4 µm</td>
<td>318</td>
<td>117</td>
</tr>
<tr>
<td>8 µm</td>
<td>381</td>
<td>415</td>
</tr>
</tbody>
</table>
2. Figure 74: Blue lines:
   ➔ CatGuard: 5-7 ppm cat fines at engine inlet
   ➔ LinerScan: 100-150 ppm magnetic iron in the cylinder lube drain oil.

![Figure 73](image1.png)

*Figure 73* Corresponding results from CatGuard: Cat fines and LinerScan: Wear. Note the red lines. From engine diagnostic system: COCOS-EDS.

![Figure 74](image2.png)

*Figure 74* Corresponding results from CatGuard: Cat fines and LinerScan: Wear. Note the blue lines. From engine diagnostic system: COCOS-EDS.

So, the results show that higher amount of cat fines in the fuel results in higher amount of iron in the drain oil, and thereby higher wear.

### 9.4 Case story 4: Clean the fuel - Testbed

During testing of a G45ME... engine, a special low-sulphur fuel was used. The fuel was regarded as a clean fuel, and it was not run through the fuel cleaning system. After the testing, the engine showed very high wear, and cat fines were found in the liners and piston rings. See Figures 75-76. The piston ring running surface was examined by SEM EDAX analysis to establish the particles to be cat fines (Al-Si-oxides). See Figures 77-78.

![Figure 75](image3.png)

*Figure 75* Cat fine found in replica of liner surface. Note the cat fine at the end of a wear track.

![Figure 76](image4.png)

*Figure 76* Cat fines found in replica of liner surface. Red arrow indicate cat fine. Note the many cat fines in graphite lamellas and wear tracks.
Figure 77 Piston ring running surface. Note the many cat fines. Same photo as used below in Figure 78 for element analysis.

Figure 78 Photos of piston ring running surface. SEM photo taken by Secondary Electron detector, and EDAX analysis of the same area applying mapping method with coloured illustration showing that the round particles are composed of Si, Al and O. There are also found iron particles (blue colour in illustration) which is wear particles from the liner surfaces smeared to the piston ring surface.
The cat fines amount in the fuel were later measured to be 30 ppm Al+Si, and the wear were as high as 0.25 mm in 100 operating hours, which is many times above the normal expected wear. See Figure 79.

![Figure 79 Expected normal liner wear per operating hours. Note the very high wear from the fuel with 30 ppm cat fines led to the engine.](image)

### 9.5 Case story 5: ULSFO must be cleaned – High cat fines amount in the fuel can be detected as high wear in the drain oil

Some of the new ULSFO (Ultra Low Sulphur Fuel Oil) contain cat fines. See also SL2014-593. Such fuel type was used on a 6S46MC-C engine. The ULSFO had 20 ppm cat fines (Al+Si), but the fuel was regarded as a distillate, and the crew did not have procedures in place to clean the distillate – and thereby the new ULSFO, so the ULSFO was let uncleared to the engine.

The crew was following the condition of the engine by cylinder lube drain oil analysis, and the results showed that when the ULSFO was used, the magnetic iron in the drain increased to very high levels (400-1000 ppm). The crew reacted to the results and started to clean the fuel, and after some time the amount of iron in the drain oil was reduced to normal levels again. See Figure 80.

![Figure 80 Drain oil analysis from a 6S46MC-C. Note the sudden increase in magnetic iron measured in the drain oil when changing over to a ULSFO (Ultra Low Sulphur Fuel Oil) which is containing cat fines (in the circle).](image)
9.6 Case story 6: Drain oil monitoring program
An engine under ExxonMobil cylinder condition monitoring (CCM) program normally showed low levels of iron in the cylinder lube drain. At some point, the iron increased to above 500 ppm iron, and showed BN level: 30-35 BN. See Figure 81a. ExxonMobil advised the crew to clean the fuel to reduce the iron level and thereby the wear. However, the crew thought the wear was due to cold corrosion and increased the cylinder lube oil feed rate. This resulted in increased BN in the drain oil, and also a somewhat reduced iron level, which is mainly due to the dilution effect when more lube oil is introduced. See Figure 81b. Eventually, the fuel was cleaned sufficiently and the iron level returned to normal levels. See Figure 81c. Optimising further could be done by reducing the cylinder lube oil feed rate back to previous low level to save money on cylinder lube oil.

![Figure 81a](image1.png) Results of drain oil analysis. Note the latest results with high iron and acceptable BN (in circle).

![Figure 81b](image2.png) Results of drain oil analysis. Note the latest results with lower iron but high BN (in circle).

![Figure 81c](image3.png) Results of drain oil analysis. Note the latest results with low iron – but still high BN (in circle).

Courtesy: ExxonMobil.

9.7 Case story 7: Cat fines in -> increased wear
A CatGuard (see Section 8.1.1) equipment were installed in a fuel system for a 12K98ME engine. See ship setup in Figure 82. The CatGuard equipment is able to measure the cat fines content of fuel on line. In this ship setup, the overflow line was let to the bottom of the service tank, and the back-flush from the filter was let to the sludge tank. This is in line with the recommendations, and is enabling cleaning of the service tank in service.
Figure 82  Schematic fuel system showing position and action for CatGuard and LinerScan equipment. Ship set up. Note the overflow line is let to the bottom of the tank to handle continuously cleaning of the service tank. See [7].

Figure 83  Shows 7 months CatGuard data from the separator input and the main engine inlet. The average cat fines content in the heavy fuel oil supplied was relatively constant in the 30 mg/kg range in bunker reports, and as measured by CatGuard. The crew used the CatGuard to improve the separator efficiency and several permanent improvements to the fuel cleaning system were implemented on the ship in August. Thereby ensuring that the average cat fines content in the main engine was successfully reduced from around 15 mg/kg in June to around 5 mg/kg in average after August.

Figure 83  Screenshot of 6 months of cat fines amount into the separator and into the main engine.

The liner and piston ring wear were measured in the same period, and the results are shown in Figures 84-85. Normal low level for liner wear rates are 0.05 mm/1000 h for this engine type, but in the period with 15 ppm cat fines in the fuel let to the engine, the liner wear rates increases to 0.2-0.3 mm/1000 h.
Likewise, the piston ring wear also increases in the same period. Both liner wear and piston ring wear returns to the normal low level, when the cat fines are lowered to 5 ppm.

![Liner wear graph](image1)

**Figure 84** Results of liner wear rates. Note the increased wear rate in the period with 15 ppm cat fines in the fuel let to the engine. The wear is stabilized at low level again in the period with 5 ppm cat fines in the fuel.

![Piston ring wear graph](image2)

**Figure 85** Results of piston ring wear. Note the increased wear in the period with 15 ppm cat fines in the fuel let to the engine. The wear is stabilized at low level again in the period with 5 ppm cat fines in the fuel.

### 9.8 Case story 8: Fuel cleaning - best in class and average

Marine fuels as bunkered must be cleaned in the ship fuel cleaning system before reaching the engine. The cleaning happens both in the separators but also by settling in the tanks and being captured in the filters.

**Best in class**

Best in class fuel cleaning systems are seen to remove more than 90% of the cat fines from bunkering over the settling tanks, the separator and finally the day tank before reaching the engine. Such an example can be seen below in Table 10.
In another case, the fuel remained in the settling tank for two months and the removal efficiency in the settling tank was as high as 42%.

A special analysis of cat fines from the drain of the service tank showed 24 ppm Al+Si. So, cleaning and recirculation of fuel from the service tank is always very important.

**Overall analysis – done by VPS**

Over the years, VPS has performed many fuel system checks for many different ship owners and many different ship types and fuel cleaning installations. Sampling of the fuel in different positions in the fuel systems has been performed by the crew on board. The average fuel cleaning efficiency can be seen in Table 11. The results are used to simulate the cleaning of a fuel with 80, 60, 50 and 40 ppm cat fines in the fuel as bunkered.

The calculation show that the average fuel cleaning system and operation of same is by no means sufficient to clean the fuels to the recommended level, and for the fuels with 60-80 ppm cat fines in the fuel as bunkered, it cannot clean to the required max. 15 ppm cat fines in the fuel before the engine.

It is clear that the average fuel cleaning systems and the operation should be enhanced considerably.

The results from best in class fuel cleaning and the results from the average fuel cleaning are entered in the figure for recommended level of cat fines entering the engine from [7]. See Figure 86. The best in class fuel cleaning are fully within the recommended area, while the average fuel cleaning are either not fulfilling the level of max. 15 ppm before engine or found in the yellow area.
9.9 Case story 9: Fuel cleaning: Increased temperature and reduced flow
In the same system as shown in Figure 82 in Section 9.7 a number of fuel cleaning tests were performed to get real life data for the effect of increasing the fuel temperature and decreasing the fuel flow through the separator. The temperature was varied between 98 and 115 C, and the flow through the separator was tested at 100%, 50% and 25% of rated capacity. Please note, that not all separator types are capable of operation above 100 C due to boiling of the water. In this test, the separator was not cleaned before the test. The results were measured by the CatGuard, and are shown in Figure 87.

Figure 86 Recommended level of cat fines entering the engine, SL2017-638. Note the best in class fuel cleaning fully within the recommended area, while the average calculated values are either not fulfilling the max. level of 15 ppm or found in the yellow area.

Figure 87 Cat fines content in and out of separator as function of fuel temperature and separator flow rate. Data based on CatGuard. Note the smaller content of cat fines out of the separator as fuel temperature increase and flow rate through separator decrease.
The fuel cleaning efficiency were calculated, and the results are shown in Figure 88. The results show, that when the fuel temperature increase and the flow rate through the separator decrease, the content of cat fines out of the separator decrease and the fuel cleaning efficiency increase.

![Figure 88: Separator cleaning efficiency as function of fuel temperature and separator flow rate. Data based on CatGuard. Note the cleaning efficiency increase with increasing fuel temperature and decreasing flow rate through separator.](image)

The fuel cleaning efficiency of this system is not very high, and it is expected that it is because of a dirty separator. When the discs in the separator are dirty, the space between the discs get smaller, and that increases the velocity of the fuel through the separator, leaving the cat fines less time to get out of the fuel.

9.10 Case story 10: Fuel cleaning: Increased temperature and reduced flow

In a similar setup as shown in Figure 82 in Section 9.7 a number of fuel cleaning tests were performed to get real life data for the effect of increasing the fuel temperature and decreasing the fuel flow through the separator. In this test series, the separator was cleaned before the test. The results were measured by the CatGuard and also in a lab.

The CatGuard data for fuel temperature of 98 and 110 C are shown in Figure 89. The results show a significantly better cleaning at the higher fuel temperature. Please note, that not all separator types are capable of operation above 100 C due to boiling of the water.
Figure 89  Cat fines content in and out of separator at two different fuel temperatures. Flow rate: 6000 l/h (75% of rated capacity). Data based on CatGuard. Note the smaller content of cat fines out of the separator at the higher fuel temperature. Data courtesy: GEA.

The test was further expanded to include both fuel temperatures at 98 and 110 C and separator flow rate of 100, 75 and 50% rated capacity. The results are shown in Figure 90, and the results show, that when the fuel temperature increase and the flow rate through the separator decrease, the content of cat fines out of the separator decrease and the fuel cleaning efficiency increase. The cleaned separator performs very well and cleans to very low cat fines levels.

Figure 90  Separator cleaning efficiency as function of fuel temperature and separator flow rate. Cat fines content in fuel entering the separator: 22-28 ppm Al+Si. Data based on lab. analysis IP 501. Note the cleaning efficiency increase with increasing fuel temperature and decreasing flow rate through separator. Data courtesy: GEA.

Data from CatGuard and lab results are compared, and the results can be seen in table 12 below. The data show a very good correlation between the CatGuard data and the lab results.
### Table 12  Data from CatGuard and lab results. Data courtesy: GEA.

<table>
<thead>
<tr>
<th>Position</th>
<th>Catguard, AI+Si, ppm</th>
<th>Lab, IP 501, AI+Si, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separator in</td>
<td>20-30 &lt;24.5&gt;</td>
<td>28, 22</td>
</tr>
<tr>
<td>Separator out</td>
<td>&lt;2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3-9 &lt;6.4&gt;</td>
<td>6</td>
</tr>
</tbody>
</table>

10. **Homogenisers**

Generally, MDT does not find installation of homogenisers necessary in the fuel system. If the operator chooses to install a homogeniser, it is recommended to install it after the separator and before the 10 µm filter in front of the engine. See Figure 91.

![Figure 91 Schematic fuel system cleaning diagram showing acceptable position of the homogenizer - after the separator and before the filter.](image)

![Figure 92 Schematic fuel system cleaning diagram showing unacceptable position of the homogenizer – before the separator.](image)

MDT does not recommend installing the homogeniser in front of the separator as this will significantly reduce the cleaning capability of the separator. This is also the recommendation from leading separator manufacturers. See Figure 92.

The homogenisation of the fuel will lead to low separation efficiency of both water and particles:

- Both freshwater and seawater will be emulsified with the fuel. This means that the water droplets will be too small to be removed by centrifugal separation. If the seawater is not removed, it will be led to the engine and after-engine systems, causing possible damage from the chlorides in the seawater and deposits from the salts.

  - Cat fines are said to be hydrophilic. This means that they are attracted to water. So, as the water cannot be removed, neither can the cat fines. Cat fines led to the engine will cause increased wear.

Furthermore, according to leading separator manufacturers, the fuel loss in well running fuel separators is generally found in the range of 0.005-0.010% of the fuel treated. So, it is difficult to see the business case to install and operate a homogeniser compared to the increased risk of engine damage.
11. Summary
Cat fines are found in marine fuel. High amounts are normally allowed in the fuel as bunkered, but such high level would cause extremely high wear in the combustion chamber, and the fuel must be cleaned before reaching the engine.

Summary – Fuel cleaning systems and operation:
Important points to achieve clean fuel – and increased reliability and low wear rates:
1. Install a best practise fuel cleaning system
2. Make high standard daily operational procedures
3. Check the results of the fuel cleaning
4. Act on the results obtained

Summary – Cat fines influence:
Important points regarding cat fines related failures:
1. Cat fines in fuel entering the engine will cause wear: The higher the amount of cat fines, the higher the wear will be
2. Cat fines accelerate corrosive wear
3. Cat fines accumulate in the service tank if the tank is not cleaned in service
4. Fuel cleaning is more important than fuel bunker cat fines content
5. Cat fines are found in both heavy fuel and ULSFO.
6. Cat fines are expected also to be found in fuels after 2020.
7. Cat fines in liner running surfaces prove unacceptable fuel cleaning
8. Cat fines disappear rapidly from liner surface if supply is stopped
9. Cat fines wear damages are mainly found in different positions for two-stroke and four-stroke engines

12. References
[4] CIMAC Recommendation 25: Recommendations concerning the design of heavy fuel treatment plants for diesel engines
[7] MAN Diesel & Turbo Service Letter: SL2017-638: Cleaning of Heavy Fuel Oil and Maximum 0.10% Sulphur Fuels – How to remove cat fines

[14] MAN Diesel & Turbo PrimeServ: Cat Fines – Surface Replica Service


