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ON COMBUSTION ENGINES

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CIMAC Guideline

Cold Corrosion in Marine Two Stroke Engines

By CIMAC Working Group 8 'Marine Lubricants'

The first edition of this CIMAC Guideline was approved by the members of the CIMAC WG Marine Lubricants at its meeting on September 28th 2017.

Content

1 Introduction

With the economic crisis of 2008 the phenomenon of cold corrosion has become a regular occurrence with many operators of large two-stroke marine engines due to engine operation at low load. Furthermore, cold corrosion may also occur as a result of engine design and tuning. As part of the economic environment, engine manufacturers introduced engines with improved fuel efficiency. These engines are characterised by having large stroke to bore ratios and are often described as super long stroke. This paper intends to explore the science behind cold corrosion; what it is and why it occurs. It will also aim to understand the hardware involved, fuel and operational effects. It will take into consideration monitoring of this issue, consider similar occurrences in history and provide guidelines.

All engines are different and must be treated individually, however some general advice can be given, see section 9 and Figure 1 below.

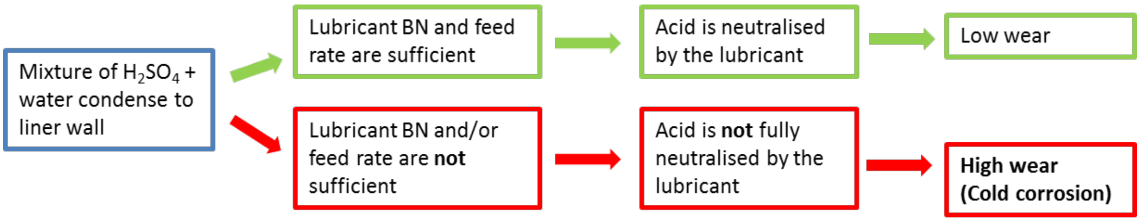


Figure 1: General recommendation to handle cold corrosion

Due to their design and general operating conditions, four stroke engines do not experience the same high level of cold corrosion; therefore this paper will not take these engines into consideration.

2 Wear Mechanisms

Wear of large diesel engine running components (cylinder liner and piston rings) is generally attributable to three primary mechanisms:

- Abrasive wear
- Adhesive wear
- Corrosive wear (Cold corrosion)

2.1 Abrasive Wear

Abrasive wear can be caused by hard asperities in the components rubbing against each other or by hard particles from contaminants such as catalyst fines (cat fines) from fuel oil. These hard particles embed themselves into the piston ring and/or liner surface and breach the oil film, thus abrading the surfaces and wearing them down in high speed.

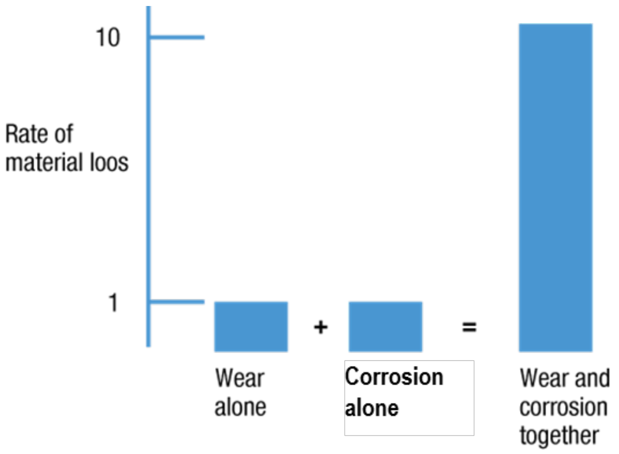
2.2 Adhesive Wear

Adhesive wear is due to a loss of oil film between piston / ring and liner. This leads to metal to metal contact and thereby friction and high temperature which may lead to localised bonding between the two mating surfaces (micro-welding) and subsequently may lead to scuffing of the surface.

2.3 Corrosive Wear (Cold Corrosion)

Corrosive wear occurs when there is a combination of a wear situation (abrasive or adhesive) and a corrosive environment. The rate of material loss can be very high; much higher than the sum of the individual contribution of wear and corrosion (see Figure 2). This is because loose corrosion products are easily removed by wear to continually reveal fresh metal beneath, which in turn can corrode quickly (see Figure 3).

Likewise, stable oxide films that would normally limit corrosion (in the absence of wear) are instantly worn away. Corrosive wear may be found in the combustion chamber, and is commonly referred to as "cold corrosion".



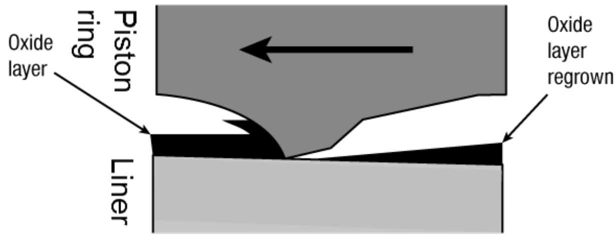


Figure 3: Schematic representation of oxide layer removal – exposing the surface to corrosion followed by contact between the piston ring and cylinder liner surface structure that triggers the corrosive wear

Figure 2: Illustrative example of material loss rate

Cold corrosion has been very much in focus in the last few years due to two main influences:

A. Slow steaming* as a result of the economic crisis in 2008 and over capacity in the shipping market,
B. Demands for better fuel efficiency leading to new engine designs and tunings

As cold corrosion can lead to very high wear rates, this paper will focus on the reasons for cold corrosion and ways to mitigate it.

** Slow steaming can be considered as continual operation below normal continuous service rating (NCSR) conditions. See also [13].*

3 Formation of Sulphuric Acid

Combustion of fuel oil containing Sulphur produces:

- carbon dioxide (CO_2)
- water vapor (H_2O)
- carbon monoxide (CO)
- particulate matter (PM)
- nitrogen oxides (NO_X)
- sulphur oxides (SO_X)

Calculation of the exhaust gas composition obtained during operation on high-Sulphur fuel showing the distribution between the different exhaust gas components may be seen below in Figure 4.

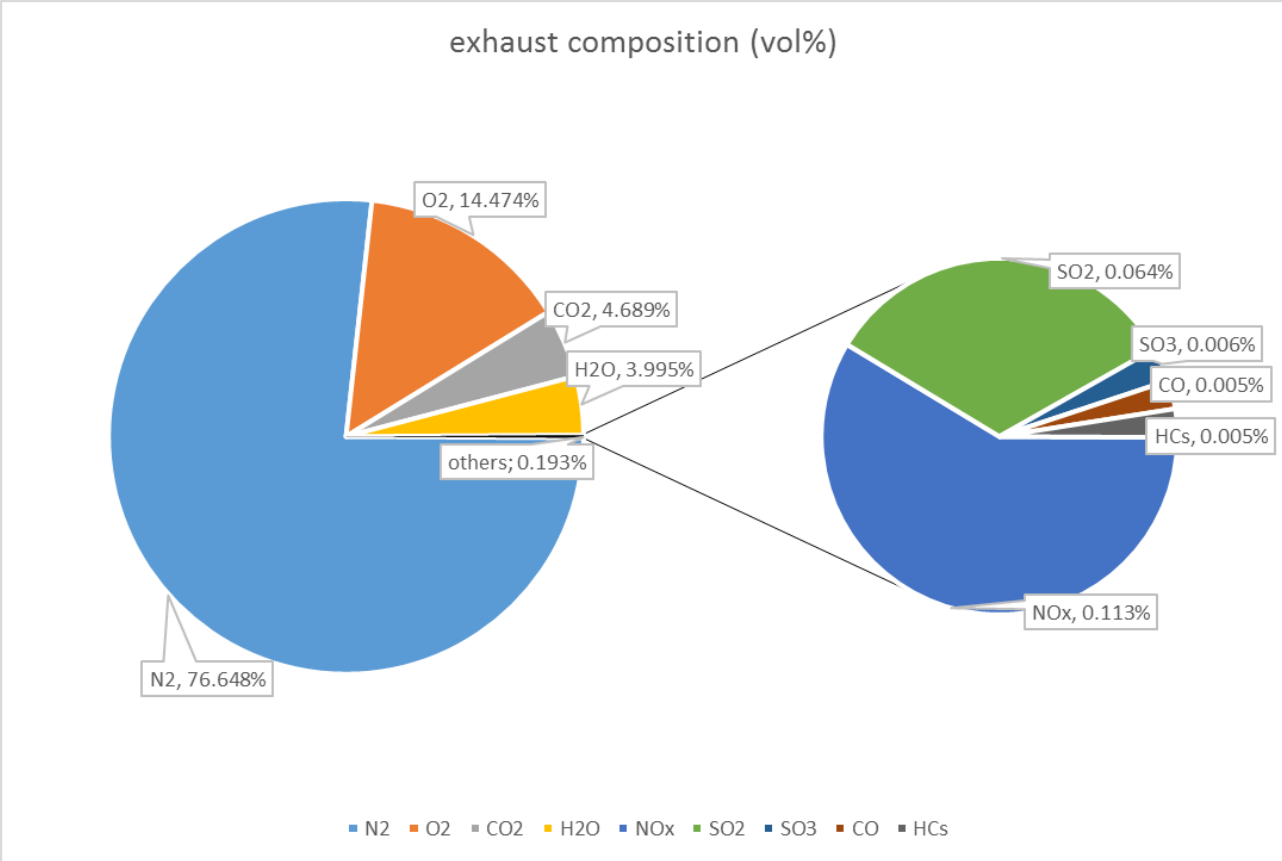


Figure 4: Exhaust gas composition calculation: total and excluding N_2 and O_2. *Courtesy: WinGD*

During combustion, all sulphur in the fuel is oxidised to sulphur dioxide (SO_2). This reaction is fast, hence it can be assumed that all sulphur is converted to SO_2. A small amount of the SO_2 is further oxidized to sulphur trioxide (SO_3). The formation of SO_3 is driven by the dynamic equilibrium between SO_2, O_2 and SO_3, which changes with concentration of these chemical components, pressure and temperature according to Le Chatelier's Principle. Depending on the engine design, tuning and operating conditions (load, fuel Sulphur, ambient conditions etc.) up to 10% of SO_2 are oxidized to SO_3 during combustion [2]. These reactions are shown below.

$$S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$$
$$SO_{2(g)} + ½O_{2(g)} \rightarrow SO_{3(g)}$$
$$SO_{3(g)} + H_2O_{(l)} \leftrightarrow H_2SO_{4(aq)}$$

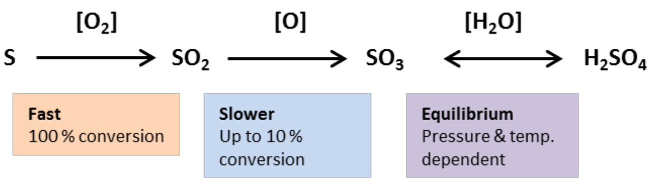


Figure 5: Reaction mechanism for the formation of sulphuric acid

The concentration of SO_2 in the exhaust gas can easily be estimated by the knowledge of fuel oil consumption, the amount of sulphur in the fuel and the airflow through the engine. The SO_3 concentration is more difficult to determine as this varies with the external factors already mentioned. However, there are methods available to measure the concentration of SO_3 in the exhaust gas [11, 15].

The gas mixture formed during the combustion results in a vapour-liquid-equilibrium system for SO_3, H_2SO_4 and H_2O. Below the dew point temperature of the gas mixture, the vapour phase is in equilibrium with a liquid phase, which consists of aqueous sulphuric acid.

The dew point is the temperature at which a vapour phase starts to condense into a liquid phase. When the temperature drops below the dew point, the vapour phase condenses - either as aerosols or as a film onto a surface.

The calculation of the dew point temperature of a mixture of $H_2O_{(g)}$, $SO_{3(g)}$ and $H_2SO_{4(g)}$ is more complicated than for a system consisting of pure $H_2O_{(g)}$ only. The dew point temperature of the H_2O-SO_3-H_2SO_4 vapour-liquid system is controlled by the partial pressure of each of the three components and the sulphuric acid concentration of the resulting liquid phase. However, extensive equilibrium data for such a vapour-liquid-equilibrium sulphuric acid system is found in e.g. [12].

Additionally various models have been proposed to calculate the sulphuric acid dew point of flue gases. Verhoff's dew point equation of SO_3 with H_2O predicts a large increase in dew point for small increases in the amounts of SO_3 [5]. The model predicts that at 180 bar a fuel with 3.5%m/m S will result in a dew point temperature as high as 280°C depending on SO_2 to SO_3 conversion.

The bulk gas temperatures in the cylinder are substantially higher than the dew point temperature of aqueous sulphuric acid. Hence, no condensation is expected in the gas volume. However, since the cylinder wall always has the lowest temperature, condensation of aqueous sulphuric acid on the liner surface occurs. During the scavenging process condensation at air / exhaust interface may be possible as well.

Lower liner temperatures are associated with slow steaming and modified engine design. Higher pressures are associated with engine efficiency improvements. Both factors increase the likelihood of the onset of cold corrosion.

4 The Role of the Lubricant

Cylinder lubricants are specially formulated to perform in the specific environment of the two-stroke combustion chamber. The lubricant is consumed in a lost lubrication system. The generic purposes of a cylinder lubricant are to protect the cylinder liners, pistons and piston rings from the harmful effects of combustion-products and to provide an oil film between piston rings and cylinder liners.

To achieve this, the cylinder lubricant is required to:

- Spread uniformly over the cylinder liner surface and form a stable oil film
- Provide a gas seal between the liner and the piston rings
- Neutralise acids formed from the products of the combustion process
- Minimise deposit formation on piston surfaces and ring grooves
    - Deposits on piston surfaces may disturb the oil film
    - Deposits in the piston ring grooves may lead to ring sticking or breakage
- Flush out particles formed during combustion from the combustion chamber as well as wear particles
- Prevent corrosion of the cylinder liner and other combustion chamber components while the engine is stopped
- Be compatible with the different methods used by engine manufacturers to introduce lubricant into the combustion chamber

Traditionally cylinder lubricants have been designed for heavy fuel oil (HFO) operation but now other fuels such as distillate fuels and gas are becoming more widely used. As engine development proceeds and the range of fuels burned increases, the temperature and pressure conditions to be endured by lubricant and engine components will likely become both more severe and more varied. Cylinder lubricants will be required to maintain performance under these varying conditions.

Correct engine operation ensures that the optimum supply of the cylinder lubricant to the critical ring/liner interface is maintained. Detailed advice on oil feed rates and maintenance to ensure the necessary protection of the engine, is given in the engine manufacturers instruction manuals.

The selection of a cylinder lubricant depends on the type and quality of the fuel, the mode of engine operation and the economic criteria applied by the owner. This could result in multiple cylinder lubricants being required in the operation of the engine over time.

Furthermore, it is recommended to only use cylinder lubricants that have successfully undergone the engine OEM validation process (refer to OEM information).

A general recommendation for selection of cylinder lube oil depending on fuel sulphur content may be seen in Figure 6 below. A minimum feed rate must be obtained for pure lubrication, and when the Sulphur in the fuel increases more Sulphuric acid condense on the cylinder wall, and more neutralising ability (mainly BN) is necessary to protect the liner wall against corrosion.

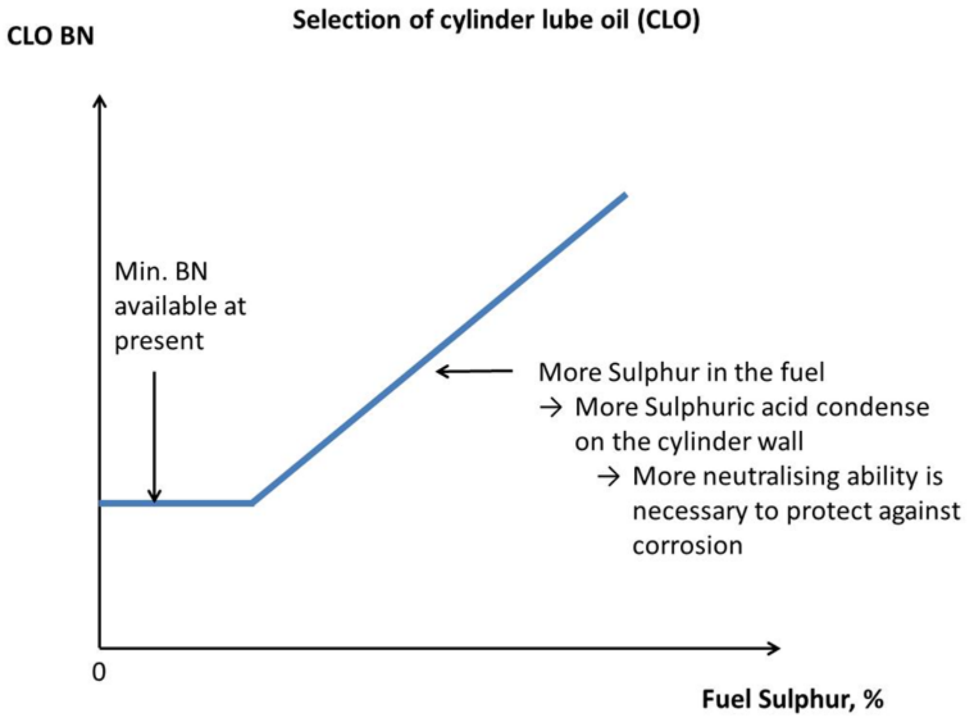


Figure 6*:* General recommendation for selection of cylinder lube oil (CLO) depending on fuel sulphur content [13].

5 In Cylinder Cold Corrosion

Corrosion can only take place when the acid molecules reach the liner wall – without being neutralised by the lubricant.

High alkaline lubricants are used to neutralize the sulphuric acid to avoid cold corrosion of piston rings and cylinder liner surfaces. Calcium carbonate ($CaCO_3$) is commonly used as additive in cylinder lube oil. It neutralises the acid according to the following reaction:

$$H_2SO_{4(aq)} + CaCO_{3(s)} \rightarrow CaSO_{4(s)} + H_2O_{(l)} + CO_{2(g)}$$

If the sulphuric acid is not neutralized, corrosion of iron occurs according to the following reaction:

$$Fe_{(s)} + H_2SO_{4(aq)} \rightarrow FeSO_{4(s)} + H_{2(g)} \quad [6]$$

A generally accepted hypothesis proposes the following four successive steps to describe transport of acid to the metal components [10]:

A. formation of sulphur trioxide in the combustion gas
B. condensation of water or aqueous sulphuric acid on the oil film/liner surface
C. neutralisation of the acid by the alkaline additives in the lubricant
D. reaction of remaining acid at the metal surface leading to corrosion

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 and corrosion resistance. Figure 7 below show an example of liner material micro structure and the different phases. Table 1 below show examples of hardness of the different phases.

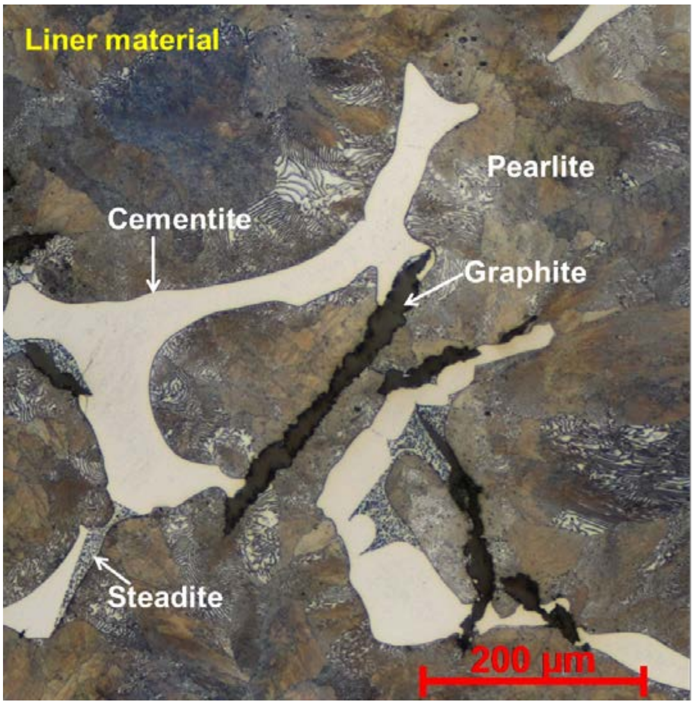


Figure 7: Polished and etched microsection of grey cast iron liner material, showing the different phases in the base material. Courtesy: MAN Diesel & Turbo.

Micro-structure phases in cast iron	Corrosion willingness	Knoop hardness, 100 g load
Graphite: C	+	15-40
Pearlite: Cementite + Ferrite	+++	300-390
Cementite: Fe_3C	+	1000-1300
Steadite: Fe_3P	+	600-1200
Ferrite: Fe	++++	215-270

Table 1: Corrosion willingness and hardness of phases in cast iron.
Corrosion willingness: Courtesy: MAN Diesel & Turbo. Hardness: MAN Diesel & Turbo & [14]

Experience show that the sulphuric acid corrodes the softer phases of the cast iron at a faster rate than the hard cementite, and also that it attacks in the boundary between the different phases. This is leaving the hard cementite standing out from the matrix, and also the cementite grains loosened from the matrix. See schematic below in Figure 8.

Such corroded surfaces are extremely vulnerable to mechanical load. Depending on whether the remaining hard phase protrudes from the base matrix or not, the piston ring, which is passing over it, can chop it off or not. Such chopped-off hard particles will disturb the lubrication between ring and liner and can easily embed in, for example, the piston ring base material to start acting abrasively. On the other hand, corrosion can also act between the boundaries of single grains (inter-crystalline corrosion) and loosen hard phase particles until they fall out of the matrix. See Figure 8.

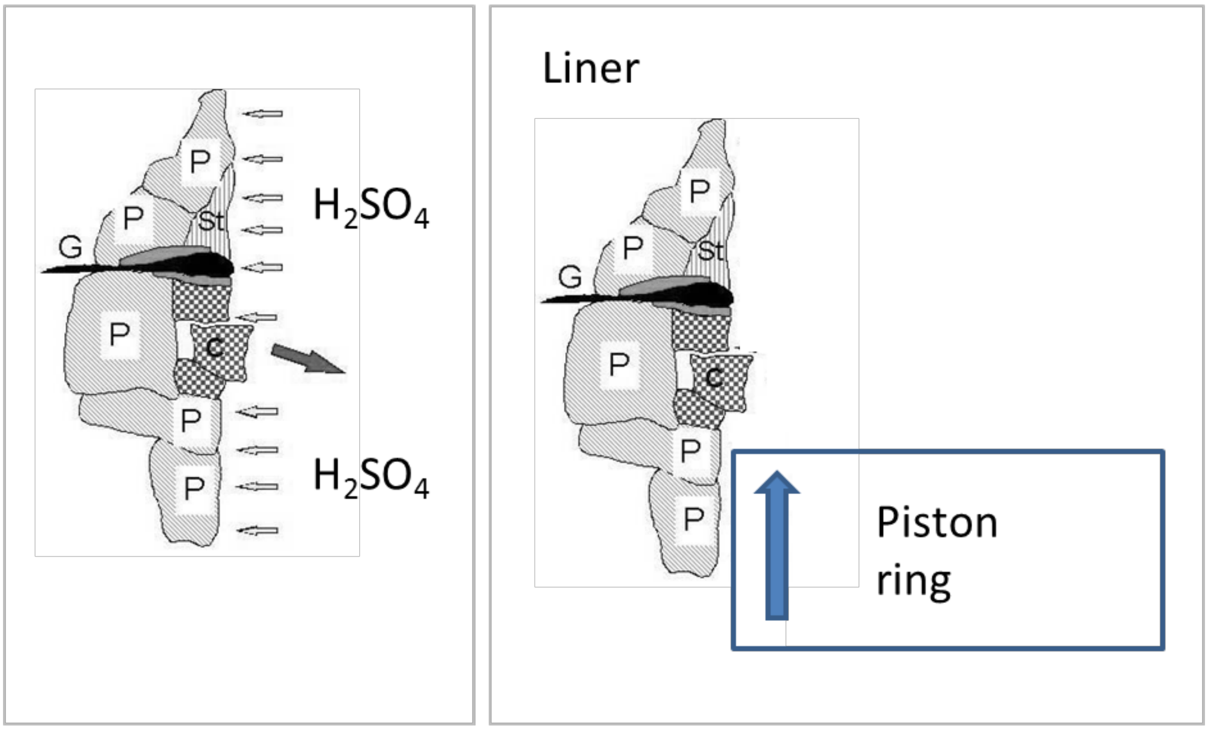


Figure 8: Schematics of H_2SO_4 acid corroding grey cast iron (left) and piston ring hitting and breaking the hard cementite grain during operation (right). P: Pearlite, St: Steadite, G: Graphite, C: Cementite, [8]: Courtesy:WinGD

Photos of liner surfaces in different tribology conditions from engines in service may be seen below in Table 2 and Figure 9.

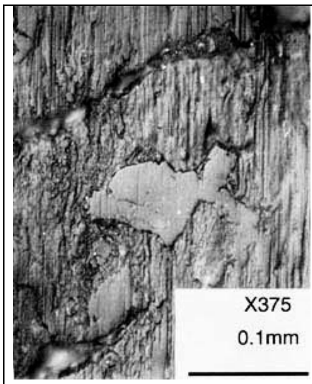
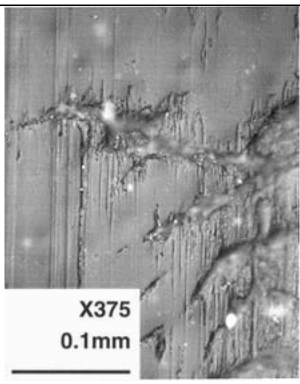
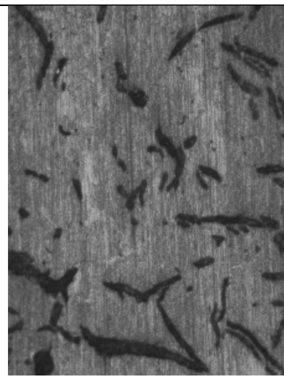
			
A: Corroded and abraded liner surface with protruding hard phase.	B: Scarred liner material with missing hard phase after heavy acid attack. Grooving is well visible.	C: Corroded liner surface with missing hard phase and heavy grooving. Smeared surface without proper structure.	D: Liner in good running condition.

Table 2: Images of different liner conditions [8]. Courtesy: WinGD

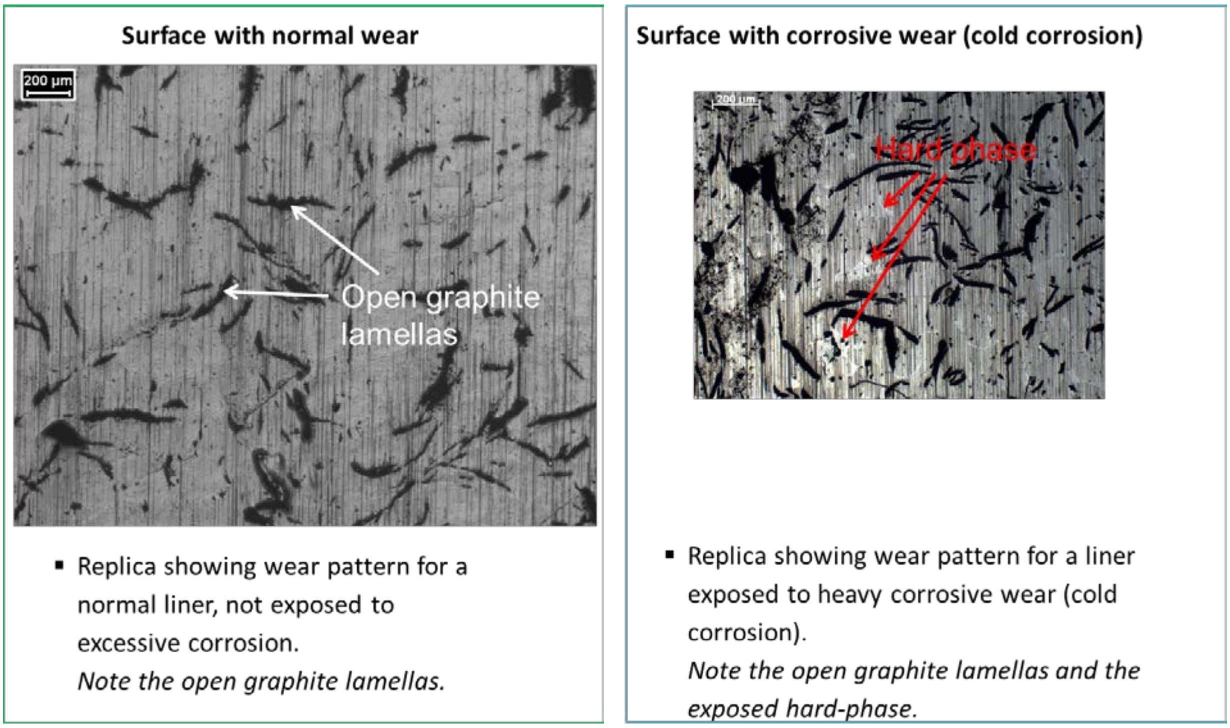


Figure 9: Replica images of different liner conditions. Courtesy: MAN Diesel & Turbo.

5.1 Induced cold corrosion by lube oil degradation on test rig

To get a better understanding of the basic mechanisms, lab tests were performed [9]. Tests with sulphuric acid and water aiming to degrade the lube oil film and to induce a relevant damage on a real cylinder liner surface in a relatively short time are costly and difficult to control, when carried out in the field, i.e. on an engine installed in a vessel. But it is quite possible to do it in a laboratory-scale by using the CPT method (CPT Cameron Plint, TE77 Testing equipment), suitably modified for water and sulphuric acid admission during the test cycle. Twelve test cases were carried out in total, which are summarised in Table 3 and figure 10.

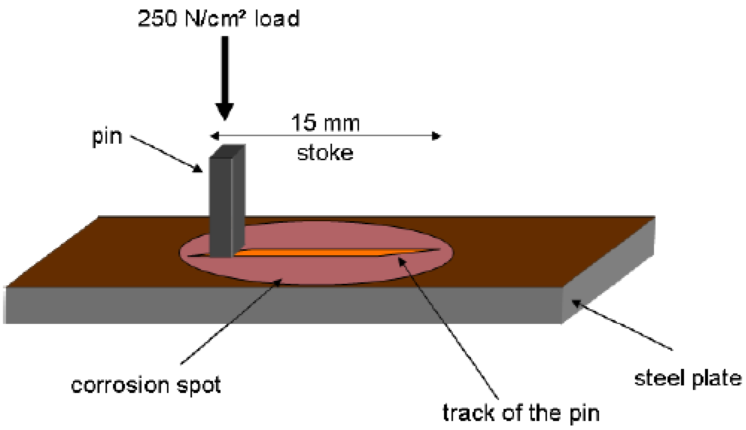


Figure 10: Schematics of Cameron Plint TE77 test conditions. [9]

The entity of the cases aimed at representing possible mechanisms that could occur in a real lube oil film, while the engine is operated in a tropical area, and if fuels with a high sulphur content are used. Therefore, the commercially available "Shell Alexia 50" cylinder lube oil with base number (BN) of 70 mg KOH/g alkaline equivalent was used in all here described tests, as this product is frequently used for cylinder lubrication of low-speed two-stroke diesel engines in commercial operation. A shortcoming of the regular CPT machine is that it is not prepared to work under pressurised conditions, which is particularly important when monitoring processes in combination with water or sulphuric acid that have a much lower evaporation temperature than lube oil under atmospheric conditions. Furthermore, the mean sliding speed of the pin is limited to 3 m/s, which is quite below the mean piston speed of about 9 m/s, which modern low-speed two-stroke diesel engines are using. However, main wear happens in the TDC area, where piston speeds are considerably reduced.

Test Case	Water content	Test bath	Temp.	Time (min.)
1	21%	Emulsion	80°C	60
2	21%	Emulsion	60°C	60
3	0.18%	Saturated oil	80°C	60
4	21%	Emulsion	100°C	60
5	0.18%	Saturated oil + 3% of sulph. acid at 33% concentration	80°C	60
6	21%	Emulsion + 3% of sulph. acid at 33% concentration	80°C	60
7	0.18%	Saturated oil	100°C	60
8	0.18%	Saturated oil + 3% of sulph. acid at 33% concentration	130°C	60
9	0.18%	Saturated oil + water injection	100°C	60
10	0.18%	Saturated oil + 3% of sulph. acid at 33% concentration	130°C	60
11	21%	Emulsion + 3% of sulph. acid at 33% concentration	130°C	120
12	0.05%	Pan evaporation process	200°C	60

Table 3: Test cases run on the Cameron Plint TE77 Test rig. (Emulsion: Water in oil). [9]

The mentioned emulsion samples, which are water-in-oil emulsion samples, as well as the samples with water-saturated lube oil, were prepared in laboratory before the test run, i.e. in these cases the oil bath on the base plate was consisting of these samples. The water-saturated oil was prepared using the hygroscopicity of the lube oil that makes the oil capable to absorb some water from the environment, e.g. from water vapour available in humid air. Tests showed that the highest achievable water content for this particular lube oil by vapour absorption is 0.3% in weight.

In case 12 of Table 3 the “pan evaporation process”, which was assumed to happen on the cylinder liner surface, when water droplets are impacting on it, was simulated by spraying water over the base plate, when the pin was sliding over it and to heat the base plate in a controlled way up to 200°C during the test cycle. Thus, the fine water droplets that were sprayed onto the oil film, "exploded" due to the fast occurring evaporation as they got into contact with the hot surface.

The temperature of the oil film was adjusted by the temperature control of the CPT base plate. If the temperature exceeded 130°C, the water content of the samples evaporated, be it saturated oil or be it emulsion. Therefore all tests have been carried out at temperature $T \leq 130°C$ except case 12, where the aim was not to study the influence of water on the oil properties, but the physical removal of oil by evaporating water from the base plate. Duration of the tests was usually 60 minutes, except for case 11, where it took 120 minutes to find any surface damage on the base plate during the testing time.

All CPT cases were evaluated in terms of wear and depth of the scratch due to the sliding pin. The weight loss and the scratch depth on the plate were measured after each test case. Furthermore the base plate surface was investigated in the area of the wear scratch by a scanning electron microscope (SEM) in order to elaborate the differences in damage depending on the test case. The weight loss of the base plate is shown in Figure 11 as milligrams of material loss because of the abrasive and corrosive effects as a function of the different test conditions.

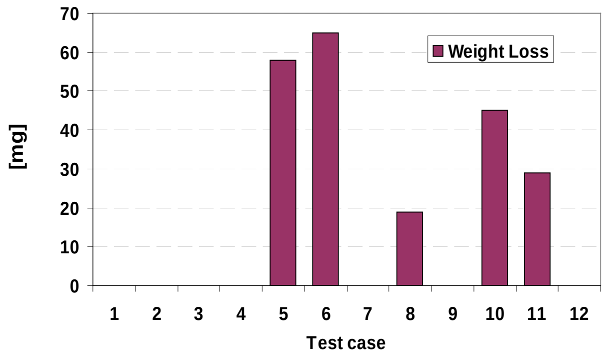


Figure 11: Weight loss of the Cameron Plint, TE77, test machine base plate surface for each case of the test conditions. Note that merely conditions including H_2SO_4 show wear. [9]

The test results show that water-in-oil emulsion, water-saturated oil, water injection and even the "pan evaporation process" *do not* affect any wear on the base plate surface. Measureable wear is related to only the cases with water *and* additional sulphuric acid in the lube oil. See Figure 12.

Five exemplary cases are highlighted in terms of wear scratch appearance: case 4 and 12 show practically or completely undamaged surfaces. In these cases, only water was added on the lube oil film. From this result, the authors conclude that the pan evaporation process had – as carried out in this test campaign – *no detrimental* effect on the lubrication performance of the system. But the SEM pictures related to test cases 5, 6 and 8 show indeed relevant signs of wear. These three cases with addition of sulphuric acid cover a very wide range of water amount in the sample from 0.18% to 21% and also a relevant range of surface temperature from 80°C up to 130°C, which is equivalent to typical cylinder liner surface temperatures of a low-speed two-stroke diesel engine below mid-stroke. From this result, the authors claim that sulphuric acid is most probably the very prerequisite condition to cause wear between piston rings and cylinder liner surface with the currently used materials for the sliding partners.

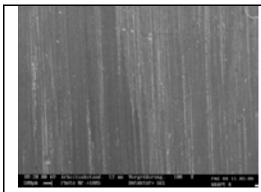
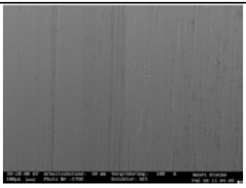
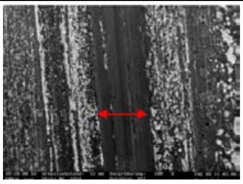
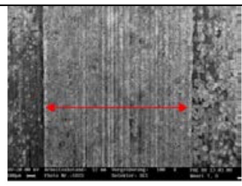
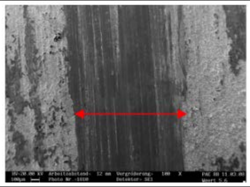
				
Test case 4 - no H_2SO_4	Test case 12 - no H_2SO_4	Test case 5 - with H_2SO_4	Test case 6 - with H_2SO_4	Test case 8 - with H_2SO_4

Figure 12: Images of CPT base plate (liner) without and with wear scratches when using lube oil samples with water only or with water and sulphuric acid. From scanning electron microscope (SEM) with magnification factor of 100X

6 Engine Design

Engine design also plays a role in controlling cold corrosion. Different strategies are implemented by the different engine designers to reach a good tribology situation in the combustion chamber. One strategy is to have components with pre-defined geometries [16]. Differences in hardness and metallurgy – and of course the lube oil – prevent contact and seizures during normal operation. Another strategy is a “controlled-wear” strategy, where the tribology situation is controlled by adequate surface roughness and wear-shaped geometries, which enable a good lube oil film to form which prevents contact and seizures during normal operation. Both strategies are vulnerable to loose hard particles which could arise from the corrosion process (see Section 5) or from fuel related cat fines.

6.1 Effect of liner wall temperature:

Liner surface temperature varies dependent on engine design, rating, load and over the stroke. It should ideally be maintained above the dew point temperature of water or aqueous sulphuric acid for the entire engine operating range. Below is an example of improved liner wear after liner temperature optimisation [8]. The liner temperature was increased to well above the water dew point temperature and this reduced the wear significantly. See Figure 13 and 14.

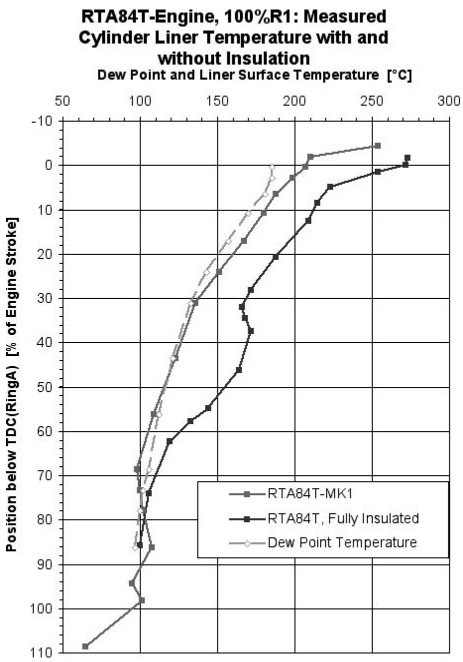
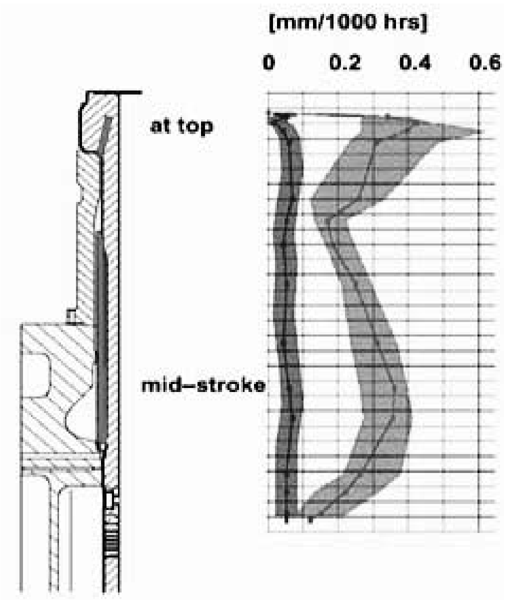


Figure 13: Effect of insulation on cylinder liner surface temperature and the impact on wear. The dew point temperature is of pure water [8].



Lighter area represents higher wear with cold cylinder liner. Darker area represents insulated cylinder liners with elevated surface temperatures and low wear figures.

Figure 14: RTA84T Liner wear improvements as a function of temperature increase. [8]

6.2 Cylinder oil delivery systems

Cylinder oil delivery systems must perform, so that:

- Oil must be delivered and distributed to the liner wall at the right time and quantity.
- Oil must be distributed effectively on the liner wall in the right area for more effective control of cold corrosion.
- Oil refreshing rate must be at a level that maintains the neutralisation capabilities of the resident oil film.

7 Engine configuration and its impact on the corrosive level

The engine performance is tuned to meet the required NOx limits at the most optimal fuel oil consumption. This tuning is set individually for different engine types, and may further be adapted due to demands of high fuel efficiency in certain load ranges. This is for example the case for part load optimisation.

7.1 General considerations

As described in Section 3, the corrosive level of an engine is influenced by three effects:

1. formation of SO_3,
2. condensation of aqueous sulphuric acid on the cylinder liners and
3. neutralisation reaction in the cylinder lubrication oil.

This means that the corrosive level of an engine is mainly affected by:

- Dew point temperature of aqueous sulphuric acid.
- Temperature of the cylinder liners.
- Degree of SO_2 to SO_3 conversion.

These three points are strongly influenced by changes in the engine performance layout. Such changes can originate from different tuning options, which are available in the market. Examples of these are turbocharger cut-out, various bypass solutions and influencing the combustion chamber pressures via engine settings. However, all of these tuning options affect the same parameters, which are:

- Scavenge air pressure.
- Compression pressure.
- Maximum firing pressure.
- Scavenge air temperature.
- Air excess ratio in the cylinder.
- Total air amount in the cylinders
- In extreme cases the scavenging efficiency.

From this is clearly seen that by changing any of the engine settings it is very likely that the corrosive level of the engine also is affected. This highlights the importance of carefully balancing the cylinder lubrication oil (feed rate and BN) with the actual engine performance layout.

7.2 Effect of turbocharger cut-out

An example is presented, how turbocharger cut-out may affect the corrosive level of an engine.

Slow-steaming ship operation led to activities to reduce main engine fuel consumption at low part load operation. One way to achieve such savings is to blind a turbocharger on engines with two or more turbochargers.

As a two-stroke engine works flow-wise rather like an orifice than a pump (as a four-stroke engine does), increasing scavenging air pressure and therefore reducing volume flow does not only influence engine efficiency positively, but restricts the scavenging process of the engine. In detail: if one turbocharger out of two, three or four turbochargers working in parallel is taken out of operation (both flow paths, compressor and turbine, are blinded), the flow distributed originally over e.g. two turbochargers is now going through one turbocharger. It means that the turbocharger in operation works on double the power than before, assuming that the engine load is kept constant.

A turbocharger of certain geometry has a fixed operating map that is mainly influenced by compressor geometry, diffusor geometry (after compressor), turbine inlet casing geometry, nozzle ring geometry and turbine blade geometry. This one turbocharger is now working on double power as explained above. Based on the fixed operating map, this one turbocharger tends now to run on a higher speed to absorb the higher power given by double amount of exhaust gas.

The compressor of such TCs, however, is built so that it delivers a higher pressure at its outlet, if higher shaft speed is applied. Therefore, higher scavenge air pressure is delivered, which leads to a better engine efficiency, as both engine compression and maximum firing pressure are elevated compared to the regular operating regime. Higher air pressure means also higher air density.

The enthalpy flow (transferred power) of a fluid stream is defined by the mass flow multiplied by the inner energy of the fluid and energy conservation applies, the power in our case is merely constant, but the fluid pressure is higher than in regular operation. In order to comply with energy conservation, the volume flow must be reduced in the same proportion as the fluid density is increased as can be easily seen from the ideal gas law: $pV=mRT$. As the mass flow is constant due to unchanged engine load, R is a constant and we can assume the air temperature in the scavenge air receiver to be not much different than in regular operation, $pV=mRT=constant$. If p (pressure) is double, V (volume flow) must be half to fulfil the equation.

Furthermore, the flow geometry of the engine is unchanged for both operating regimes, therefore the flow areas of inlet ports and exhaust valves as well as their opening and closing times are given and fixed. As the volume flow is significantly reduced due to the increased density as a consequence of the higher scavenging air pressure for turbocharger cut-off operation compared with regular operation, the liners are not filled anymore completely with fresh air, but some exhaust gas is remaining in the cylinder after scavenging. Therefore also more SO_3 and water are remaining, thus potentially more sulphuric acid is ready to form and to corrode the cylinder liner.

Similar effects like described above may occur also when applying other measures often used to achieve fuel consumption saving by reducing the air flow through the engine's combustion chambers as e. g. turbochargers with variable turbine geometry, increased geometric compression ratio or late exhaust valve opening (nonexhaustive enumeration).

8 Engine Operation and Service Experience

Quote from an operator:
"Of course the fuel sulphur level has a major impact of cold corrosion but also engine operation parameters have a great impact on cold corrosion as well as ambient conditions. Engines operating at high humidity areas have been more challenged than engines operating in dry areas. Another parameter influencing is engine load, due to the correlation of liner wall temperatures and engine load. Lower load gives lower liner wall temperatures and therefore higher amount of condensed water/acid on the liner wall.

In order to neutralize the different amount of sulphuric acid, either the amount of lubricant can be adjusted or the concentration of neutralizing BN additive. At high sulphur levels, experience has shown that a higher BN, can have better performance than increased amount of lubricant with lower BN. Experience is also showing that the sensitivity to cold corrosion is increased at higher fuel sulphur levels, so in order to optimize the cylinder condition the operator found the relation between fuel sulphur and BN may not be linear."

It has been observed that vessels leaving ports in regions of high humidity experience high levels of iron in the drain oil. This is believed to be a kind of running in process due to surface corrosion of the piston ring and liner. The additional water in these areas may have an impact on the lubricant film by causing emulsions and reducing the ability of the lubricant to effectively neutralise acids.

8.1 Case stories – Service Experience

Case story 1: Increase cylinder lube feed rate

An engine of the type: MAN B&W 12S90ME-C9.2 was set into service lubricated with a 70 BN oil. It was in 2013 before the introduction of the 100 BN oils. The ship crew decreased the cylinder lube feed rate without the recommended port inspections and follow up, and the engine experienced heavy wear within the first 2000 operating hours. When the cylinder lube feed rate was increased, the wear rate decreased to the normal, low level. See Figure 15.

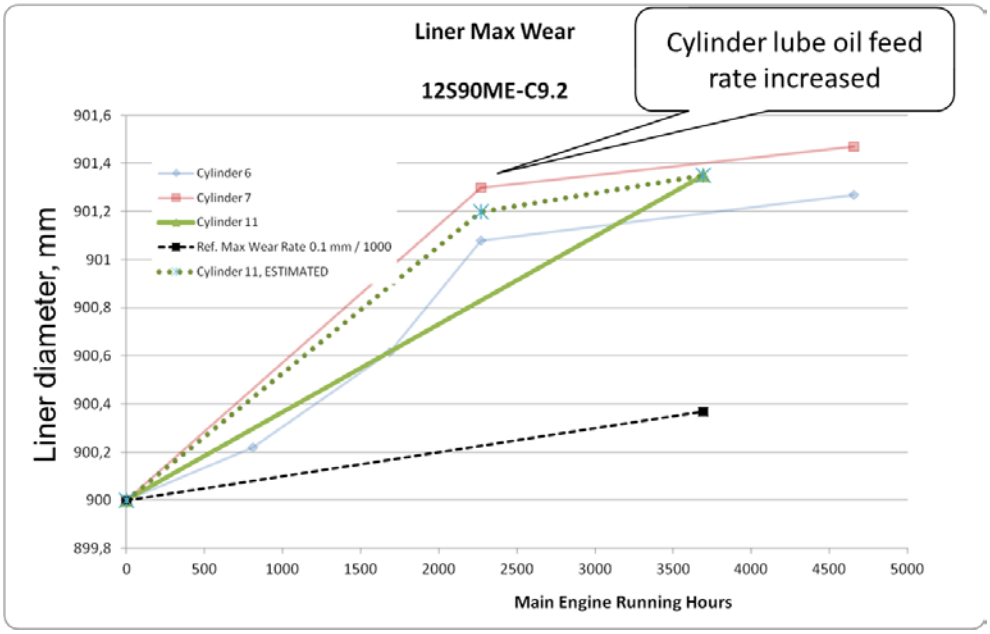


Figure 15: Wear data from new engine. Engine type: MAN B&W 12S90ME-C9.2.
Note: When the cylinder lube feed rate is increased, the wear rate decreases to the normal, low level.

Furthermore, one of the signs of insufficient protection from the cylinder lube oil against cold corrosion is deposits on the piston ringlands between the piston rings. When the feed rate was increased, the cylinder lube oil was able to clean up the ringlands and remove the deposits. See Figure 16.

Same engine as opposite picture. Port inspection, cyl. 3. 1687 running h. Cylinder lube oil: 70 BN, low feed rate, ACC=0.26. *Note: The cylinder lube feed rate is too low -> high wear and dirty ringlands*

Same engine as opposite picture. Port inspection, cyl. 3. 2883 running h. Cylinder lube oil: 70 BN, high feed rate, ACC=0.40. Note: The cylinder lube feed rate is increased to sufficient level -> low wear and the lube oil has cleaned the ringlands.

Figure 16: Effect of feed rate on piston cleanliness

Case story 2: Operation on higher BN cylinder lube oil – wear data

It was expected that cylinder lube oils with higher concentration of neutralising additives would be more effective in protecting against cold corrosion. In order to test this hypothesis, the cylinder lubrication system was split on an engine in service and half of the engine was lubricated using a 70 BN oil and the other half was lubricated using a more concentrated 100 BN oil.

The two different lube oils were used two different feed rates:

- 70 BN oil: High feed rate: FR = Fuel Sulphur% * ACC_{70}. ACC_{70} = 0.45
- 100 BN oil: Low feed rate: FR = Fuel Sulphur% * ACC_{100}. ACC_{100} = 0.30

The test showed that the 100 BN oil can be used at 33 % lower feed rate than the 70 BN oil, and produce lower wear rates. See Figure 17. This led to the successful introduction of the 100 BN cylinder lube oils.

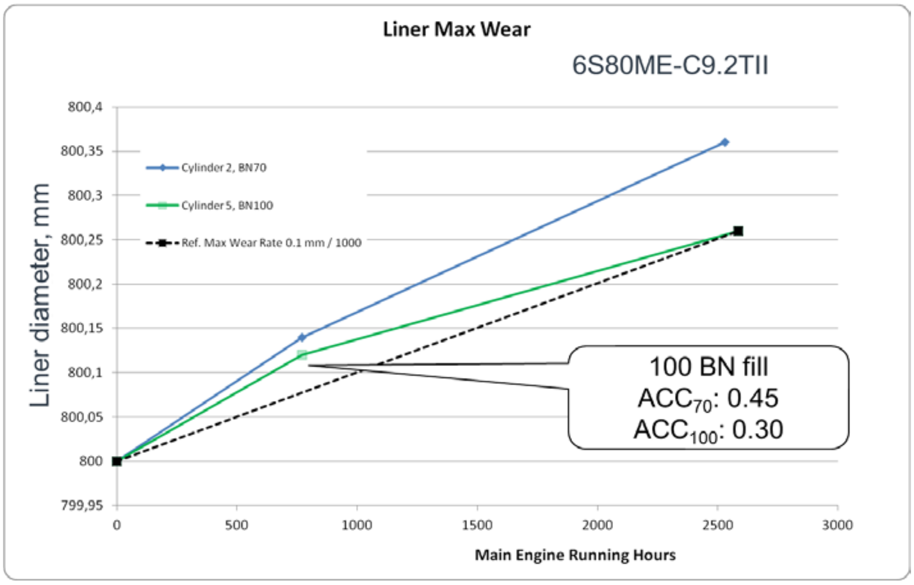


Figure 17: Wear data from new engine. Engine type: MAN B&W 6S80ME-C9.2.

Note: The 100 BN oil can be used at lower feed rate than the 70 BN oil, and produce lower wear rates.

Case story 3: Operation on higher BN cylinder lube oil – drain oil data

Different engine types, engine configuration, ambient conditions, operating pattern, cylinder lube oil types and BN etc. influence the corrosive level of the engine. To evaluate the corrosive level of a particular engine and cylinder lube oil, a cylinder lube feed rate sweep test can be performed. In such sweep test, the engine is operated for 24 h on decreasing feed rates and the drain oil is analysed to establish the corrosive level. An overview of the test can be seen in Figure 18.

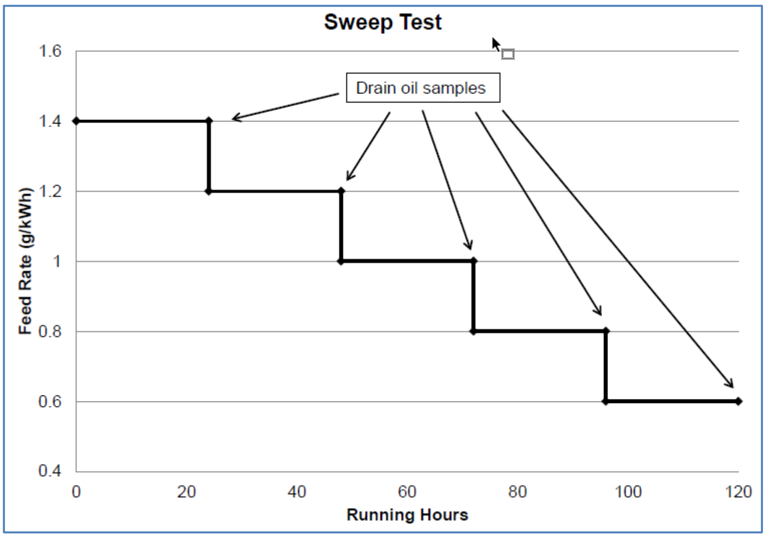


Figure 18: Overview of sweep test procedure.

As for the case story 2 above, 70 BN and 100 BN cylinder oil were tested on an engine with split lubrication system: Half the engine was lubricated with 70 BN oil and half was lubricated with 100 BN oil. A cylinder lube sweep test was performed, and the drain oil was analysed for iron and remaining BN. See also Section 10. The data show that the remaining BN is approximately 30 BN higher for the 100 BN than for 70 BN at equal feed rate, and that the iron in the drain increases to unacceptable level at up to 40% higher feed rate for the 70 BN oil. The conclusion is, that the 100 BN oil is able to protect the engine against cold corrosion at much lower feed rate than the 70 BN oil. See Figure 19.

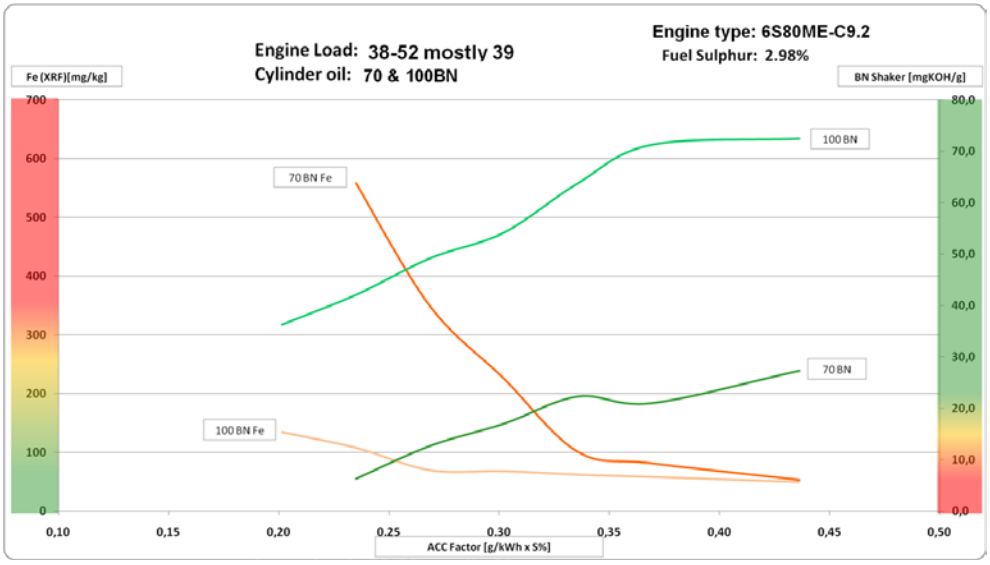


Figure 19: Drain oil data from engine with split lubrication system: Half of engine is lubricated with 70 BN oil and other half is lubricated with 100 BN oil. Engine type: MAN B&W 6S80ME-C9.2. Feed rate = ACC factor * Fuel Sulphur.
Note: When the BN in the cylinder lube is higher, the feed rate can be lower and still protect the engine.

Case story 4: Effects of Turbocharger Cut-out [source BP]

As described in Section 7.1, slow steaming operation has been further optimised for lower fuel consumption on engines with multiple turbochargers by blanking a turbocharger. The volume of air flow is reduced and there is a chance that cylinders will have incomplete scavenging of exhaust gases. If air flow is reduced in this way, it is conceivable that the distribution of scavenging air may not be even across the engine, with cylinders adjacent to the running turbochargers receiving air preferentially. This uneven air distribution has been shown in some cases to cause excessive corrosive wear in cylinders close to the cut out turbocharger, and has been identified via drain oil analysis: cylinders with air starvation have reduced residual base number in the drain oil and increased corrosive iron content.

Case A:
10 cylinder engine, centre t/c cut out, 45% load, 3.1% sulphur fuel, 0.75 g/kWh.

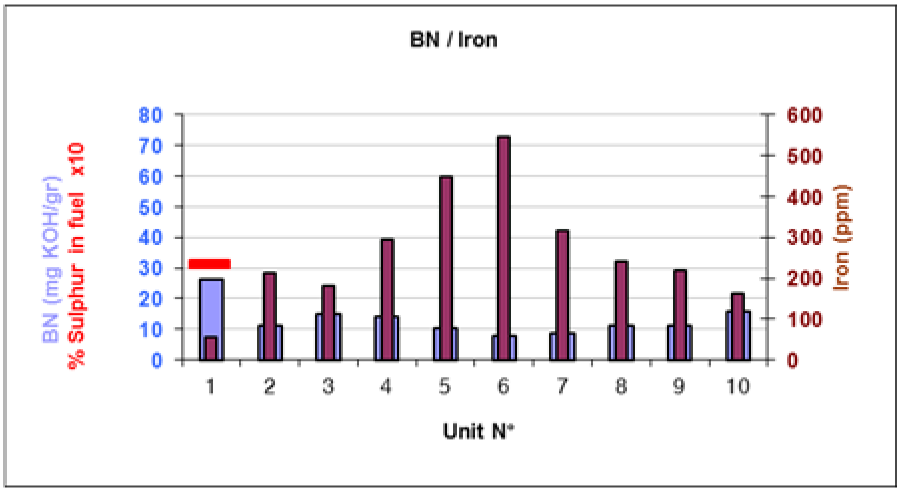


Figure 20: Comparison of [Fe] and residual BN

Case B:
8 cylinder engine, two turbochargers, one at each end, with one cut out. Ships engineers were mis-led by on board use of a magnetic iron detector which did not see the corrosive iron. Lab analysis highlighted the problem. See also Section 10.

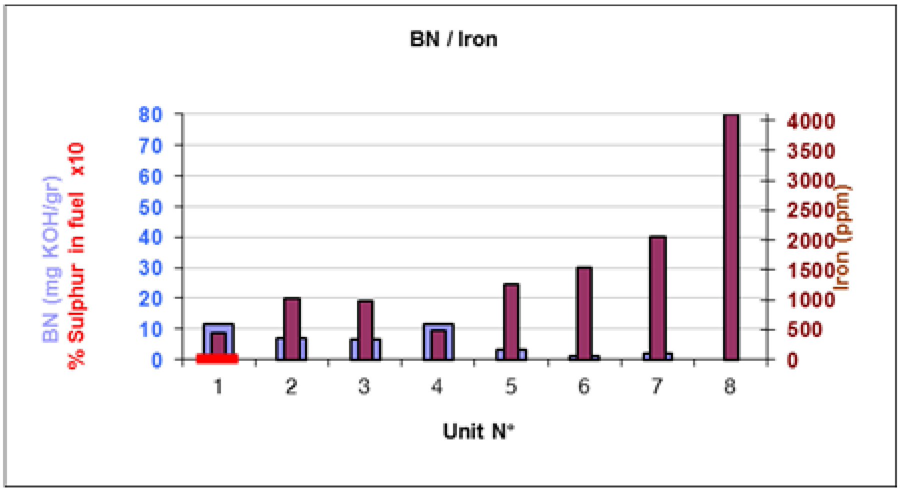


Figure 21: Comparison of [Fe] and residual BN

Turbocharger cut-out does not always mean there will be high wear, as many factors have an influence, such as fuel sulphur, load, oil feed rate, BN of the cylinder oil etc. This case also highlights the importance of taking drain samples from all cylinders across the length of the engine so rogue cylinders are not missed.

Case story 5: Optimised Feed rate with high BN Cylinder Oils [source ExxonMobil]

The subject vessel was a tanker operating in the Middle East and Asia with a fuel profile of 2.8-3.2% fuel sulphur. The vessel was equipped with a 7 cylinder Wärtsilä (WinGD) RT Flex 82T main engine of 32000KW. Operating on 70 TBN cylinder oil the engine required a high feed rate of 1.3g/kWh but still showed signs of corrosive wear.

Typically the liners had black marks and the ring pack showed signs of deposits from exhausted cylinder oil additive. Cylinder oil scrape down analysis showed the residual BN to be <20 and the iron content to be typically 150 ppm. The switch to a 100 BN cylinder lubricant was discussed with the owner who was initially reluctant. The OEM guidelines were used to reinforce the need for a higher BN oil and the switch was made to the 100 BN cylinder oil.

After switching the engine lubrication strategy was adjusted in line with the latest scrape down oil analysis results. This allowed the engine cylinder oil feed rate to be reduced significantly while still maintaining a higher residual TBN and lower iron level in the scrape down oil.

Overall final figures were 0.8g/kWh with residual BN circa 35 BN and iron below 100 ppm. Overview of the test can be found in Figure 22. The pictures in Figure 23 show the cylinder condition after optimization on the 100 BN oil. Now the engine is showing optimal cylinder condition with no black marks or ring pack/land deposits. As well as reducing engine wear the reduced oil consumption also brought a reduced overall operating cost despite the higher BN oil having a higher purchase cost.

Vessel	1 – Owner Approval in progress
Engine	Wartsila RT Flex
Operation	70TBN oils on 2.8-3.3% S HFO Feed Rate 1.3g/kwh Engine load 30-40%
Results	High liner and ring wear, black streaks and cold corrosion Avg. Residual BN - <20BN Avg. Total iron - > 150ppm

After Optimization:
Feed rates reduced to 0.85g/kwh on MobilGard 5100. Brings feed rate below WinGD max recommended of 1.2g/kwh (SL RT161)
Avg. Residual BN 35 ave.
No black marks and ring /liner under control, ring pack clean.

Figure 22: Overview of test parameters and results during test: 70 BN -> 100 BN oil. Engine type: 7RTFlex82T.

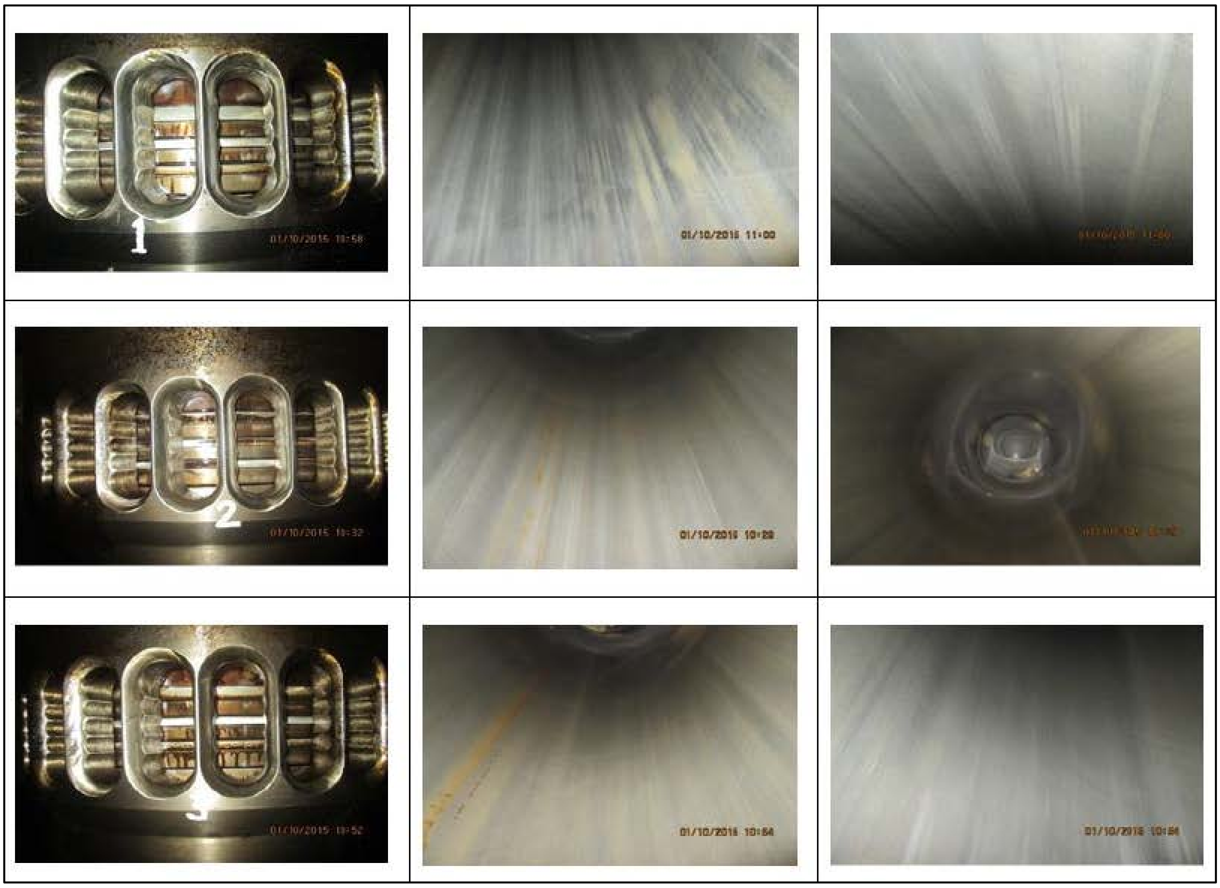


Figure 23: Cylinder condition on 100 BN oil after optimizing the feed rate to 0.85 g/kWh. Engine type: 7RTFlex82T.

Case study 6: Direct comparison of BN70 and BN 100 cylinder lube oil [source TOTAL Lubmarine]

An engine of type Wärtsilä 14 RT-flex 96C-B using a CLU4 Pulse Lubrication System fitted in a 13800 TEUs container ship was used for over 4300 h to compare the commercialized BN70 and new BN100 Total Lubmarine cylinder lube oil (CLO). The ship has been sailing between China and Europe via the Suez Canal, operated at loads between 16% and 63% MCR. The fuel used was RMK 700 HFO with 1.0% to 3.5% sulphur and DMA fuel with less than 0.10% sulphur when sailing in the European emission control area (ECA).

Before starting the comparison test the whole engine was lubricated with the BN 70 CLO. During the tests the cylinder units 1 to 7 were lubricated with the BN 100 CLO whilst the cylinder units 8 to 14 were lubricated with the BN 70 CLO. During the operation in the European ECA the whole engine was lubricated with the BN 100 CLO.

Engine inspections were carried out at the start of test and at the end of test on 2 reference units on BN 100 side to enable quantification of the wear of the liner and of the piston ring coating. Along the test, drain oil samples have been taken from each cylinder unit and analysed to monitor, among other things, the iron content and the residual BN.
The following table shows the results of wear measurement measured on the reference units at the end of the test (over 4300 h).

	BN 70 CLO	BN 100 CLO	Variation BN100/B70
Average ring coating wear rate	12 µm/1000h	8 µm/1000h	- 30%
Average liner wear rate	0.03mm/1000h*	0.015mm/1000h	- 50%

Table 4: Wear rate comparison at different BN

* average reference value based on engine data from the ship operator

It shows that under the same operating conditions, the BN100 CLO has performed in a better way than the regular BN 70 CLO. However it must be pointed out that the wear measured with the BN70 CLO is much lower than the limits set by the engine manufacturer. In other words the BN 100 CLO brings here additional operating safety margin and allows possible lower lube oil feed rate than the BN 70 regular CLO.

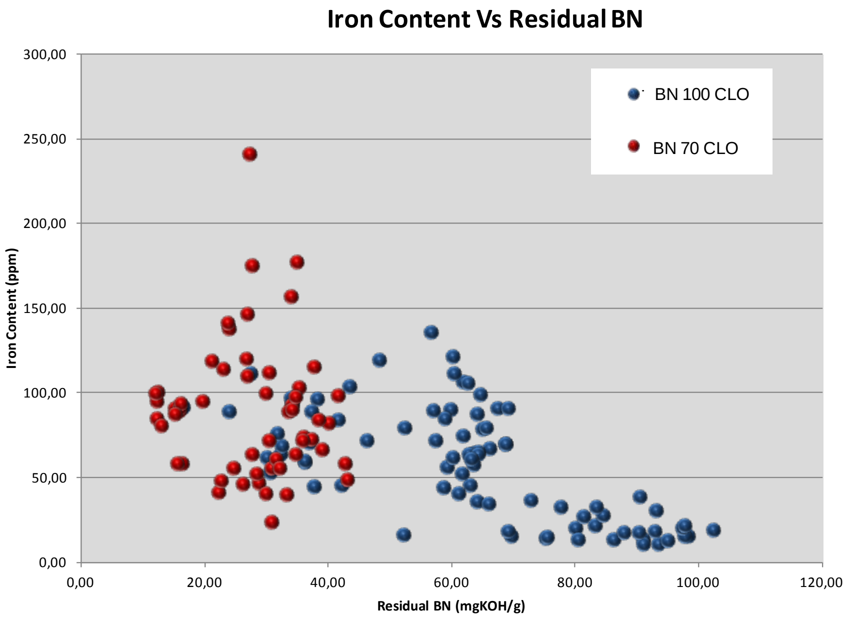


Figure 24: Iron content versus Residual BN for BN 70 and 100 CLO

The graph above shows the iron content and residual BN measured from the drain oil samples taken along the test. It can be seen clearly that the residual BN is higher when using the BN 100 CLO, also the BN reserve is higher and the risk of corrosion is lower. In the meantime, the trend to have a lower level of iron is in favour of the BN 100 CLO. The set of blue dots concentrated in the area 80-100 mg KOH/g corresponds to the period of time during which the ship was sailing in ECA, where also the iron content was also the lowest.

The following table summarizes the various values measured. The chromium content gives a view on the ring coating wear behaviour. All the items are in line with engine manufacturer recommendations.

	BN 70 CLO	BN 100 CLO
Average Fe (max. Fe)	80 ppm (240 ppm)	50 ppm (135 ppm)
Average residual BN (min. BN)	32 mg KOH/g (14 mg KOH/g)	62 mg KOH/g (34 mg KOH/g)
Average Cr (max. Cr)	9 ppm (19 ppm)	8 ppm (15 ppm)

Table 5: Comparison of wear metals and Residual BN for 70 and 100BN CLO

Case story 7: Comparison between 70 – 100 – 140BN oil in a corrosive environment [source Chevron Marine Lubricants]

New engines have a much higher tendency to develop cold corrosion inside the cylinder than the older, less efficient installations. To mitigate the effects of this corrosive environment, several methods are possible. The easiest way is to increase cylinder lubricant feed rates. This, however, is not always the most economical strategy. After a certain increase, it makes more sense to switch to a higher BN lubricant. This will provide the same corrosion protection with less injected product.

For the ship operator, the biggest advantage of switching to a higher BN lubricant is the associated cost savings. Higher BN lubricants can deliver the same amount of protective alkalinity in the cylinder at a lower cost. The included graphs show the results of a field test executed by Chevron.

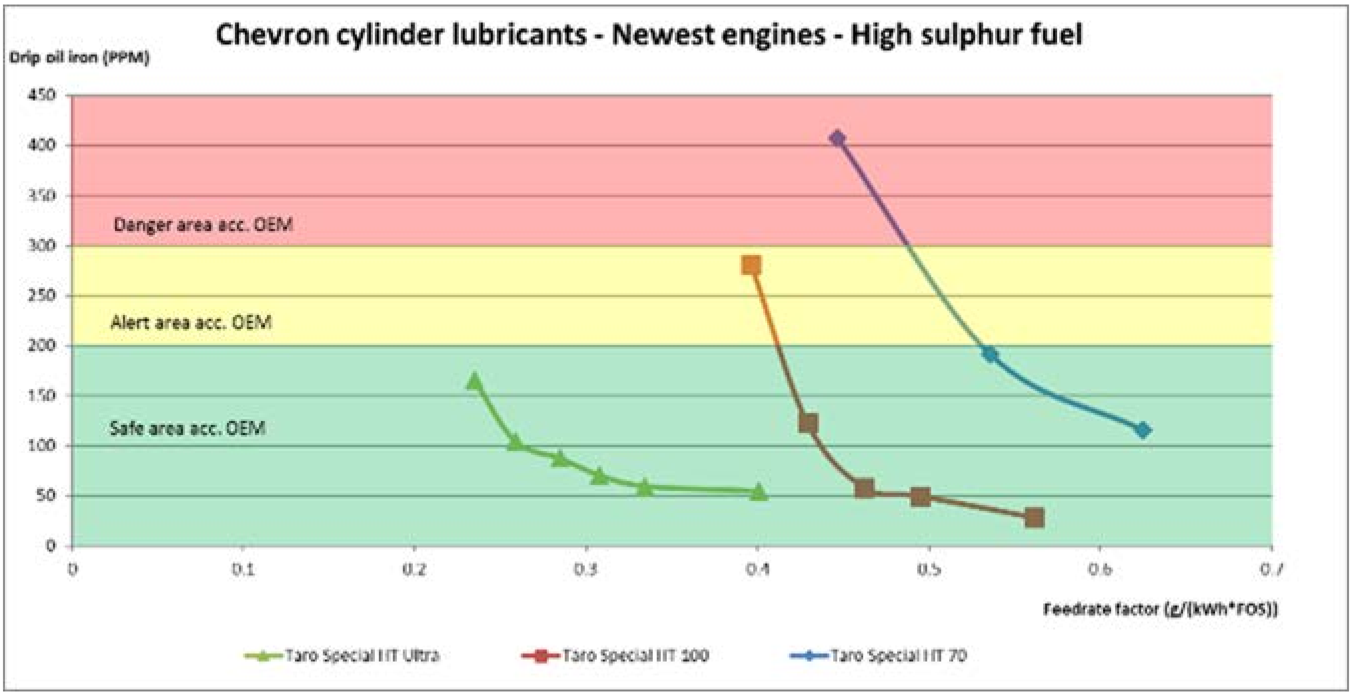


Figure 25: Comparison of drip oil analysis results of a 70BN, 100BN & 140BN cylinder oils show feed rates being reduced during field testing. Changing from 70BN to 100BN oil brings feed rates to manageable levels. Using Chevron Taro Special HT Ultra (140BN), wear metals stay below OEM limits while operated at historical minimum feed rates.

Case story 8: Optimising lubrication with 140 BN cylinder oil in super long stroke marine engine [source Shell Marine]

The current generation of highly fuel efficient super-long stroke and ultra-long stroke two stroke diesel engines have a larger liner surface area than the previous generations. Therefore, the cylinder oil on this larger liner surface is exposed for a longer time to the combustion gases because of lower engine speeds. This puts a larger stress on the cylinder oil, specifically in respect of acid neutralisation performance.

Increasing the cylinder oil feed rate to protect the cylinder liner against corrosive wear when using a 100BN cylinder oil has proven to be suboptimal for certain engine types in terms of lubricating feed rates as a significant proportion of the oil fed is sub utilised. The reason is that the oil film has a limited thickness and the transport of cylinder oil additives has therefore limitations.

Increasing the BN in the fresh cylinder oil from 100BN to 140BN increases the amount available additives in the oil film and enables the oil film to transport more additives over the liner surface to protect it against cold corrosion. Thus, a higher cylinder oil BN presents 2 advantages in highly corrosive engines: increased protection against corrosive wear and reduces lubrication needs because of lower and more effective cylinder lubrication.

The graph in Figure 26 show the results of a field test executed by Shell comparing feed rate needs for a 100 BN vs 140 BN to maintain similar drain oil analysis results.

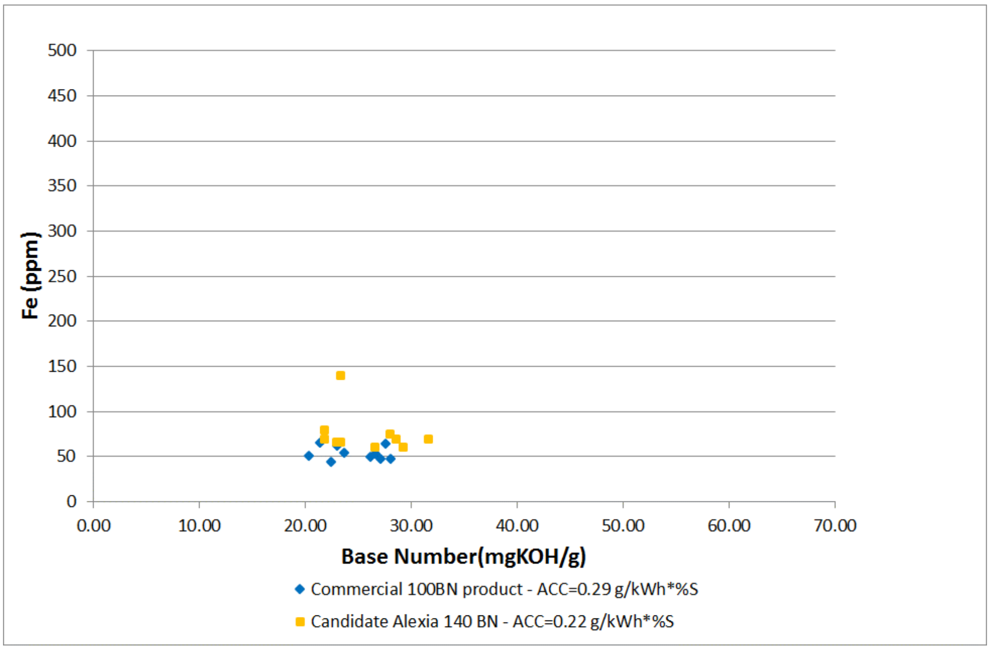


Figure 26: Comparison of drain oil analysis results of a 100BN versus a 140BN cylinder oils show feed rates being reduced, BN and Iron maintained at a safe level.

9 Guidelines

OEM bulletins provide up to date guidelines to reduce cold corrosion and maintain optimum engine operation. Please refer to OEM guidelines for specific details.

All engines are different and must be treated individually, however some general advice can be given. See below and Figure 27:

- Higher BN oils provide better protection against cold corrosion.
- Feed rates should be optimised by analysing piston underside drain oil.
- Liner cooling water temperatures should be kept at the upper limit.
- Higher sulphur fuels bear the highest risk.
- Some engine types benefit from low scavenge temperature and some from higher temperature.
- Scavenging equipment must be kept in good working order.
- Lubricant oil quills or injectors must be kept in good working order to maintain correct oil distribution.
- Drains (scavenge air, water mist catcher, receiver, and piston underside) must be kept clean and open.

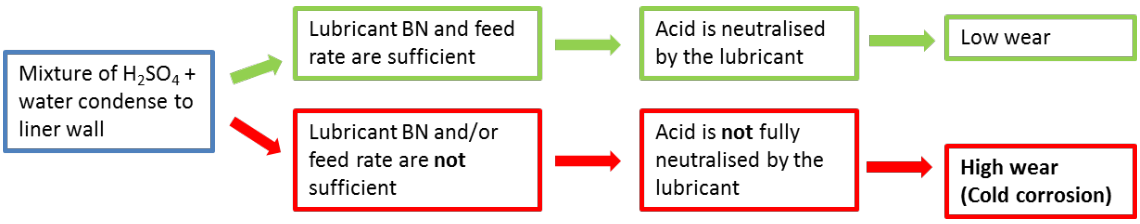


Figure 27: General recommendation to control cold corrosion.

Cylinder lube oil BN and feed rate

It is important to match the cylinder oil BN to the fuel sulphur content. Generally, it is recommended to:

- Use high-BN lube oil to high-Sulphur fuel, and
- Use low-BN lube oil to low-Sulphur fuels.

Today, cylinder lube oils can be acquired with different amounts of BN. At time of publishing the range is: 15-140 BN.

A general recommendation for selection of cylinder lube oil depending on fuel sulphur content may be seen in Figure 28 below. A minimum feed rate must be obtained for pure lubrication, and when the Sulphur in the fuel increases more Sulphuric acid condense on the cylinder wall, and more neutralising ability (mainly BN) is necessary to protect the liner wall against corrosion. Supplying more BN to the surface can be done by either increasing the BN in the oil or by increasing the feed rate. Generally, the feed rate may be reduced or increased by the ratio between the BN in the oils. An example is shown in Figure 28.

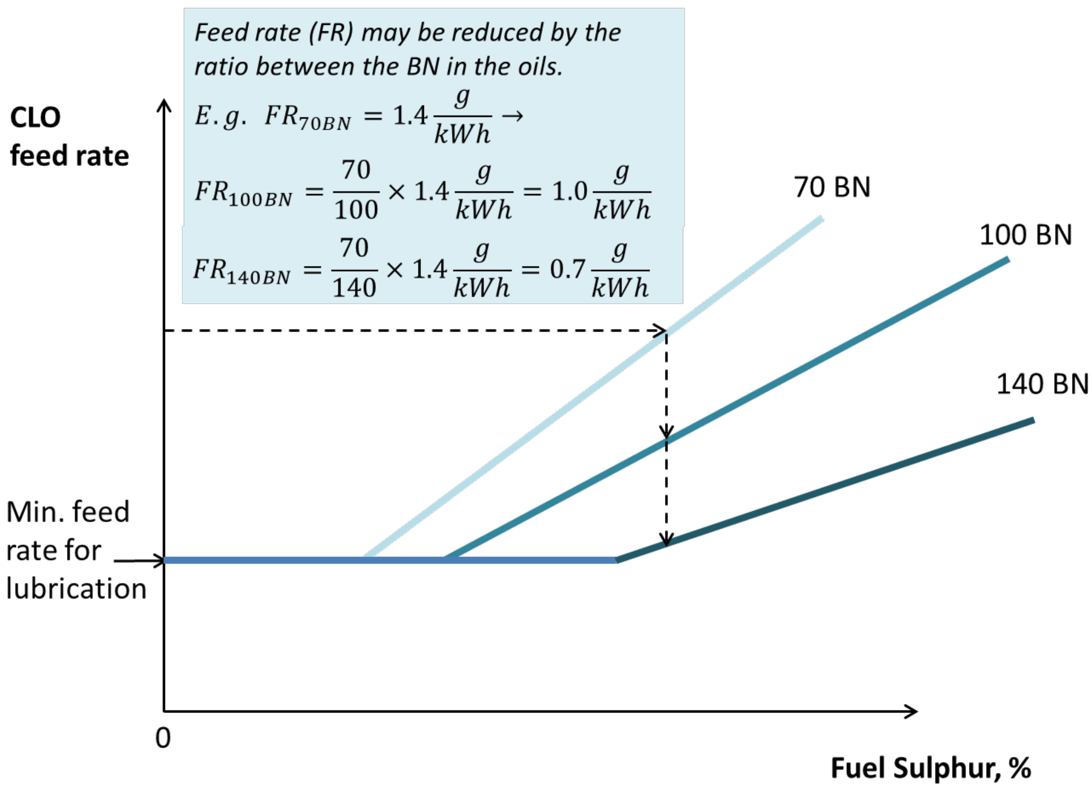


Figure 28: General recommendation to control cold corrosion.

Switching fuels

When switching fuels it is important to allow time for the new lubricant to reach the cylinder liner versus the time for the new fuel oil to reach the engine. It is preferable to have a higher BN than necessary rather than operate the engine with too low BN. It is advisable not to run low BN oils with high sulphur fuel as corrosion may occur immediately.

It is recommended that the vessel should have two cylinder oil day tanks to swiftly change lubricant type as required. Pipe volume must be considered when switching lubricants.

Scavenge air

Scavenge air temperature has an effect on cold corrosion. Low scavenge air temperature improves engine efficiency as a result of higher scavenge air amount, compression and firing pressures, and it may also lower the cold corrosion rate. However the low scavenge air temperature increases the amount of condensed water produced in the cooler with the potential of water carry over to the combustion chamber. Introduction of water to the liner may induce limited lubrication and possibly subsequent seizures and scuffing. So, when operating with a low scavenge temperature, it is very important to make sure that the cooler and water mist catcher is able to drain all free water. Conversely, high scavenge air temperature reduces amount of condensed water produced. Higher scavenge air temperatures increases the volume of air for a given mass and this may improve scavenging of exhaust gas.

Start - stop
The practice of pre and post lubrication is important to help minimise cold corrosive conditions during engine stand-still and restart.

10 Monitoring

Please also refer to the “CIMAC Recommendation for the Lubrication of Two-Stroke Crosshead Diesel Engines” [13].

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. Modern engine design and the variable operating patterns of speed and fuel sulphur level make slow speed two-stroke diesel engine monitoring a necessity. Without regular analysis using both on-board and laboratory methods the operator is often unaware of the effectiveness of applied cylinder lubrication. If too much oil is applied, resources are wasted and excess unused base from the lube oil may cause wear. If too little oil and/or too low a base number are used, cold corrosion will result. Variable operating loads and fuel sulphur confuse the picture further depending on where the vessel is operating as also ambient conditions influence the cold corrosion.

Main on-board analysis tools for checking the cylinder condition are:

- drain oil analysis,
- scavenge port inspections and
- wear measurements

10.1 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 29.

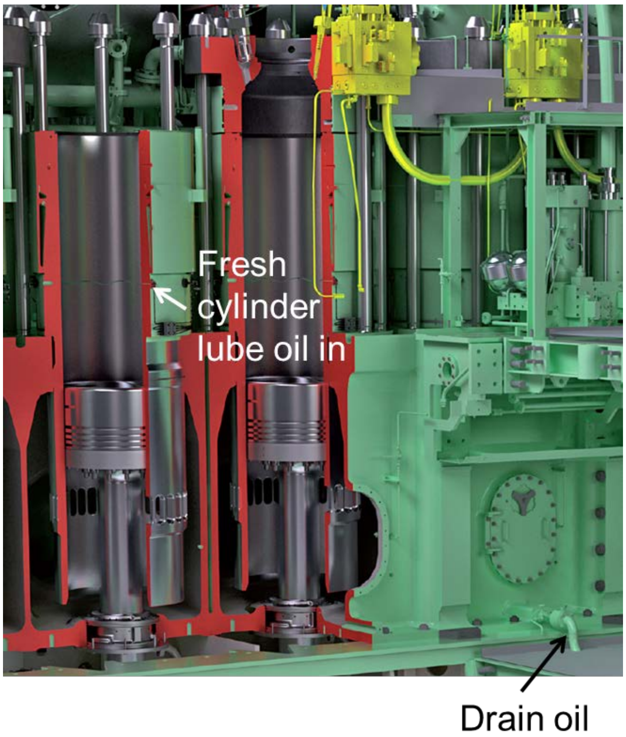


Figure 29 Scavenge drain oil

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. Once readings have been obtained the engine manufacturers lubrication guide should be consulted to ensure the engine is operating in the recommended range or if any feed rate or change of cylinder oil base number is required. Figure 30 below gives good guidelines on actions depending on the results of the drain oil analysis. It is recommended to optimise the cylinder lube oil feed rate to secure the drain oil in the safe area.

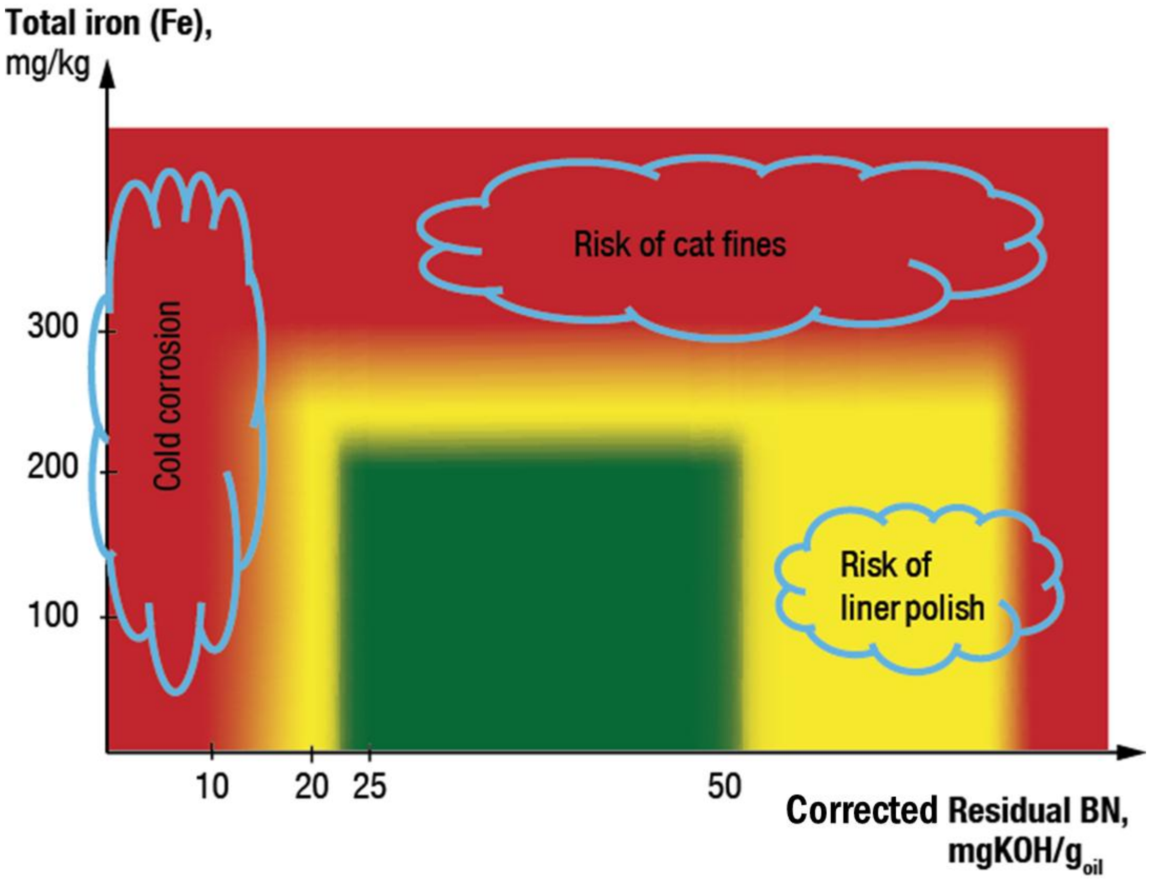


Figure 30: Scavenge Drain Oil analysis interpretation: (1) green area: keep current operation procedures; (2) "Cold Corrosion": increase cylinder oil feed rate and/or switch to a higher BN cylinder oil; (3) "Risk of Cat fines": check fuel centrifuge operation and cleanliness of the fuel; (4) "Risk of liner polish": consider to reduce cylinder lube feed rate or switch to a lower BN cylinder oil

On-board equipment

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.

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 acids produced. 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, the analysis of Fe will provide further guidance.

The on-board test is usually a simple test using gas evolution from a reaction with any BN remaining in the scrape down oil sample. The lab test is a titration method.

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 elemental iron. 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 magnetic 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. Results from both the ferro-magnetic iron and the corroded iron should be added together to provide the total iron reading.

<table>
<tr><th rowspan="2">Wear types</th><th rowspan="2">Wear mechanism</th><th colspan="3">Measuring method</th></tr>
<tr><th>Total iron</th><th>Magnetic iron</th><th>Corrosive iron products</th></tr>
<tr><td>Normal wear
Cat fines
Micro-seizures
Scuffing</td><td>Abrasive or adhesive wear</td><td rowspan="2">+</td><td>+</td><td>-</td></tr>
<tr><td>Cold corrosion</td><td>Corrosive wear</td><td>-</td><td>+</td></tr>
</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.

Lab testing

Lab services will provide BN, iron (both corrosive and abrasive) and other elements and physical properties of the drain oil. Laboratory data are not immediately available due to the time taken to get samples from vessel to laboratory, although it will provide definitive full analysis which give greater understanding of engine condition and verification of the accuracy of on-board test results.

Other metals: Some components may contain other metals that may be indicators of cold corrosion. Refer to specific OEM documentation.

10.2 Inspections

Scavenge port inspections

Irrespective of drain oil collection and analysis, visual port inspections by qualified and experienced crew should be carried out following OEM photographic examples of liner and ring condition. Indications of cold corrosion would be dirty ring lands, abnormal ring surface conditions and black liner patches. Regular inspections can detect if there are changes in the cylinder condition.

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.

11 Outlook

The marine industry continues to face a challenging environment of progressive legislation aimed at reducing ship emissions. All emissions reduction techniques will to some degree have an impact on ship and engine design and operation. Below is a summary of potential impacts coming from some of these solutions.

Most fuels that are new to the marine market have inherently low sulphur content and so not relevant to the corrosion aspects broadly covered in this paper. Other acidic species may be formed (e.g. nitric, formic) however in the combustion environment of a large two stroke engine that would be insignificant, and there would be sufficient base (alkalinity) present in the cylinder oil to provide adequate neutralisation.

11.1 Dual Fuel engines

All engines designed to run on gases, LNG, Methanol, Ethane, LPG etc. will also run on liquid fuel, and in any ratio of the two. The liquid fuel can be distillate, ULSFO or high sulphur heavy fuel. Therefore cylinder oils must be selected as appropriate for the sulphur content in fuel used in the engine during operation.

11.2 Scrubbing of Exhaust gas

Scrubbing of the exhaust gas and use of high-Sulphur fuels are allowed in most parts of the world – also beyond 2020. However local legislation may enforce tighter legislation than IMO guidelines. When using a scrubber, the high-Sulphur fuel is no longer regulated by the IMO max. cap of 3.5% S, and Sulphur content could increase significantly above 3.5% in some locations which means cold corrosion is likely to continue into the future.

11.3 EGR - Exhaust Gas Recirculation

With EGR exhaust gas is recirculated into the combustion chamber, reducing the combustion temperature and thereby the formation of NOx. The EGR used in marine are normally fitted with their own internal scrubber, so the exhaust gas is scrubbed for SOx before introduced into the combustion chamber again. Initial experience using high-Sulphur fuel suggests that EGR does not appear to influence the cold corrosion in the combustion chamber.

11.4 SCR – Selective Catalytic Reaction

The catalyst in the SCR requires a minimum operating temperature, and to achieve this it might require additional heat input from exhaust gas during low load. Initial experience suggests that SCR does not appear to influence the cold corrosion in the combustion chamber.

11.5 High-BN Lubricants

Recent occurrences of cold corrosion have led to the reintroduction of 100 BN or higher cylinder oils to the market in recent years. All indicators mentioned in this paper would suggest that higher BN oils offer additional protection with regards to cold corrosion.

12 Recent History

From the mid 2000's the shipping industry has been impacted by various increasing levels emission legislation aimed at controlling exhaust gas and other pollutants. In addition the shipping industry has continued through a financially challenging period since 2008 as a result of ship overcapacity.

The legislation impacting engine exhaust emissions has been phased to reduce sulphur content of fuel aimed at controlling sulphur dioxides, improve fuel economy and associated CO_2 emissions through Energy Efficiency Design Index (EEDI) and reduce Nitrogen Oxide emissions.

The legislative compliance drive to improve fuel economy and associated CO_2 reduction along with industry financial pressure has resulted in engines with much higher BMEP and peak pressures over a wide operating load range. These factors have and will continue to impact the level of cold corrosion seen in current and future engines where sulphur levels remain significant in the fuel used.

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