CHALMERS
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# Lubrication Failure

## An analysis of lubrication failure insurance claims on main and auxiliary engines

Master's thesis in Maritime Management

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CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS 2021

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Cover: Severely damaged crosshead bearing. Published with permission from the Swedish Club.

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# Abstract

Failures on main and auxiliary marine engines due to issues with engine lubrication is a costly and frequently occurring type of engine failure. This thesis investigates main and auxiliary engine damages caused by lubrication failure, using data acquired from the Swedish Club on insurance claims over the past 11 years. The objective was to identify common causes of lubrication failure and preventive measures with the potential of reducing the frequency of engine damages caused by lubrication failure. The most frequently occurring cause of damage was identified to be water-contaminated lubricating oil, followed by faulty lubricating oil filters and incorrectly performed maintenance procedures. Different root causes of failure were also established, where the most common one was lack of maintenance, followed by previously performed maintenance. To prevent engines from sustaining damage due to lubrication failure, it is vital that maintenance is properly and timely performed. Likewise important is to maintain and monitor the engine lubricant condition. A well functioning engine lubricant condition monitoring scheme enables early detection of engine and lubricant issues. This can be accomplished by regularly performing engine oil analyses and by installing equipment which measures the oil condition in real-time.

Keywords: Lubrication failure, marine diesel engine, lubricating oil, oil contamination, water-in-oil

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Andreas Olsson, Gothenburg, May 2021

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# 1
# Introduction

The Swedish Club is a mutual provider of marine insurances, with its headquarters located in Gothenburg, Sweden. By being mutual, they are owned and are under the direct control of the members i.e., the assured. This ensures a common interest of the insurer and the member (The Swedish Club, 2020b). In a mutual association like The Swedish Club, the members collectively share their risks. The premiums paid by each member in return for insurance cover need to cover the expenses resulting from all members' claims. Any financial excess, less the club's administrative expenses are either returned to the members or set aside in reserve funds to be used in the future (Attard, Fitzmaurice, Gutiérrez, & Belja, 2016). As a result, a decrease in the cost of claims will be reflected upon the premiums that the members pay for their insurance cover. The Swedish Club provides a wide range of marine insurances. In terms of the number of vessels insured, their Hull & Machinery (H&M) insurance is their largest category of insurance, with a total of 4.194 vessels insured (The Swedish Club, 2020c). The H&M insurance is a property insurance that covers the ship owner's economic interest in a vessel, its machinery, and equipment (Johansson, 2013). This includes cover for damages to main and auxiliary engines.

There are many potential ways in which an engine could sustain damages resulting in an insurance claim. To keep track of the type of damages and their occurrence, The Swedish Club are using "loss codes" internally, which forms a basic categorization of the immediate cause of damage resulting in a claim. The loss code attributed each claim is the result of an investigation to determine the extent and cause of damage. Usually, this investigation is carried out as a survey by an independent surveyor. Statistics from The Swedish Club on claims from their H&M insurance reviles that the most common loss code on claims between 2009-01-01 and 2020-11-27, next to claims with an unknown cause of damage, is lubrication failure. This category of claims represent 13% of all H&M claims. Claims from lubrication failure also represent the highest cost amongst all machinery and equipment claims (The Swedish Club, 2020a). The vast majority of claims in this category are from damages inflicted on main and auxiliary engines. Claims on main and auxiliary engines from lubrication failure during this period have an average cost of approximately US$ 550.000 (The Swedish Club, 2020a). This covers only the loss of property, but an engine failure may also result in an inability for operators to operate their vessels. Thus, should an engine failure lead to down-time, this will result in further economic strain. Considering the high frequency and the high costs involved in lubrication failure claims, there are strong incentives from both insurers and the insured to reduce their occurrence.

## 1.1 Objective

The thesis will be aiming at identifying common causes of lubrication failure on main and auxiliary machinery on vessels insured with The Swedish Club. Measures to prevent or reduce the frequency of these failures will be investigated. Ultimately, the purpose of this study is to come up with recommendations on preventive measures to reduce the risk of lubrication failure, which The Swedish Club can circulate to its members.

## 1.2 Research questions

- What are the common causes of lubrication failure on main and auxiliary engines with vessels insured with The Swedish Club?
- What preventive measures can be implemented to reduce the risk of lubrication failure on main and auxiliary engines with vessels insured with The Swedish Club?
- What indicators can be used to detect an increased risk of lubrication failure on main and auxiliary engines?

# 2
# Theory

Within this theory chapter, the theory essential for assessing investigated failures will be presented. This includes topics such as tribology, lubrication, lubricating oils, and engine wear.

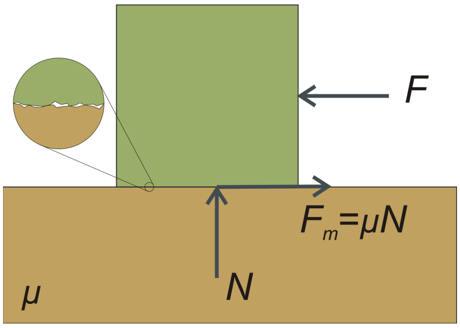
## 2.1 Tribology

Tribology is derived from the Greek word *tribos* meaning "rubbing", hence the word tribology can be translated into "the science of rubbing" (Bhushan, 2013). A common definition of tribology is "the branch of science and technology concerned with interacting surfaces in relative motion and with associated matters". This definition includes the science of friction, wear, and lubrication as well as bearing design. (Hutchings & Shipway, 2017). Practically all modern mechanical systems involve moving components (Hutchings & Shipway, 2017), this is especially true for internal combustion engines which consist of numerous moving parts designed to transform chemical energy into mechanical energy (IFPEN, n.d.). When surfaces move or slide over each other they will be subject to friction and wear. Friction is in many applications sought for, for example in clutches and breaks, while in other applications low friction is preferred. Low friction will reduce the energy required to overcome frictional forces, increasing the efficiency of systems in motion, and will also reduce the rate of wear and consequently, the need for maintenance (Hutchings & Shipway, 2017).

### 2.1.1 Friction

Friction can be described as the force opposing relative movement between bodies. It is present in all relative movement between materials, such as solid surfaces, layers of fluid, and gases. The amount of friction encountered in the interaction between two bodies is often described using the coefficient of friction, which is a numeric value, usually denoted with $\mu$, representing the ratio between the normal and frictional force (Hutchings & Shipway, 2017). This is visualized in figure 2.1.
A low coefficient of friction will represent low friction between bodies, whereas a high value will represent high friction. When a solid body move over another, it is the interaction between irregularities in the surface topography of the bodies that give rise to friction. Such surface irregularities are also known as asperities. The friction between two bodies will convert kinetic energy primarily into thermal energy, thus, the majority of the energy required to overcome frictional forces will be converted

**Figure 2.1:** Frictional force



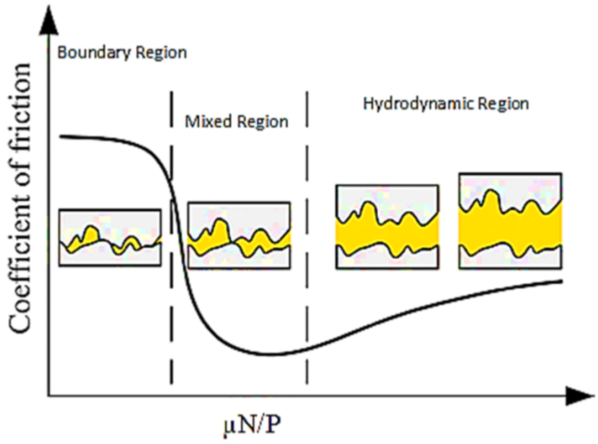

*Note.* The force F required to overcome the frictional force $F_m$ is determined by the normal force N and the coefficient of friction $\mu$ between the two bodies. Reprinted from Wikimedia Commons, by Keta, 2007, (https://upload.wikimedia.org/wikipedia/commons/f/f7/Marruskadura.svg), Licence: CC BY 2.5

to heat. Using materials with low coefficients of friction will not only result in less frictional losses and higher overall efficiency but will also reduce thermal stress and wear of friction surfaces (Hutchings & Shipway, 2017). The friction between surfaces can be dramatically reduced with lubrication, which will be discussed in section 2.1.2.

### 2.1.2 Lubrication

Lubrication and lubricants are widely used to improve the performance of various applications with moving components. Apart from reducing friction, lubrication serves the purpose of reducing wear, protecting against corrosion, and providing cooling for lubricated components (Hutchings & Shipway, 2017). In tribology, there is a distinction between different regimes of lubrication, which depend on the specific features of a lubricated system. These can for example be load, temperature, speed, and lubricant properties (Wang & Wang, 2013). A Stribeck's curve, as seen in figure 2.2, can be used to visualize the relationship between the coefficient of friction and the lubrication parameter, where the latter is dependent on viscosity, sliding velocity, and bearing load. The curve extends from the boundary to the hydrodynamic lubrication regimes, and clearly shows that the coefficient of friction is a non-linear function of the lubrication parameter. The coefficient of friction is highest in the boundary region, significantly reduced in the mixed region, and will increase with the film thickness in the hydrodynamic region (Patil, Patel, & Patil, 2019). Since the coefficient of friction will be higher in the boundary and mixed lubrication regimes, this will result in higher frictional losses and more importantly in increased wear of friction surfaces (Hutchings & Shipway, 2017). Different regimes of lubrication will be further discussed in the following subsections.

**Figure 2.2:** Stribeck's curve




*Note.* Stribeck's curve describes the relationship between the coefficient of friction and the lubrication parameter, Reprinted from Experimental Analysis of Oil Film Pressure and Temperature on EN31 Alloy Steel Journal Bearing, by H. S. Patil, D. C. Patel, C. S. Patil, 2019, *American Journal of Materials Engineering and Technology*, 7(1), 7-11, Licence: CC BY 4.0

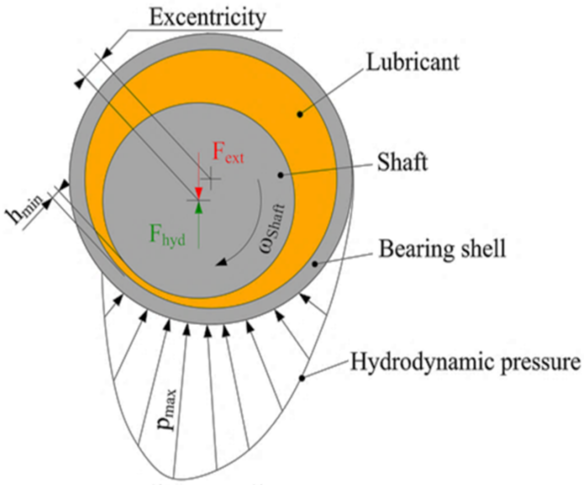
#### 2.1.2.1 Hydrodynamic lubrication

Under hydrodynamic lubrication, sliding surfaces are separated by a fluid film of lubricant. It is the pressure within the fluid film that is responsible for supporting the load under hydrodynamic lubrication. The fluid film pressure is a result of viscous forces within the fluid lubricant acting as a result of surface motion. There are two prerequisites to achieve hydrodynamic lubrication. The lubricated surfaces must be conformal, meaning that their dimensions must be precisely matched, only leaving a small gap over a large area. Secondly, the gap between the lubricated surfaces must converge for the fluid film to generate hydrodynamic pressure. For instance, a shaft supported by a journal bearing will be slightly smaller than the bearing supporting it. As it rotates, the rotational movement will be slightly eccentric in relation to the bearing. The eccentricity creates convergence in the oil film enclosing the shaft. This results in a wedge of lubricant with enough hydrodynamic pressure to separate the shaft from the bearing. This is illustrated, although somewhat exaggerated, in figure 2.3. To create a sufficient hydrodynamic pressure, the sliding velocity, being the relative motion between the surfaces cannot be too low (Hutchings & Shipway, 2017).

#### 2.1.2.2 Hydrostatic lubrication

Hydrostatic lubrication is in many ways similar to hydrodynamic lubrication, where the lubricated surfaces are separated by a load-carrying fluid lubricant film. The difference between the two is that in hydrostatic lubrication, the lubricant film pressure is generated externally by various hydraulic systems (Mang & Dresel, 2017). The advantage of this is that the load-carrying film separating the friction surfaces can be maintained regardless of the friction surfaces sliding velocity. Thus, the

**Figure 2.3:** Hydrodynamic journal bearing

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full separation between friction surfaces can be maintained during start and stop operations, where the sliding velocity generated under hydrodynamic lubrication would otherwise be insufficient (Totten, 2017).

#### 2.1.2.3 Boundary lubrication

Lubricated systems enter the boundary regime when there is a collapse or breakdown of the fluid lubricating film separating the surfaces under hydrodynamic lubrication. As the hydrodynamic film collapses, the entire load will be supported by direct contact between the friction surfaces. This results in a dramatically increased friction and rate of wear. Lubricated systems may enter the boundary regime when stationary, under high loads or when the sliding velocity is not sufficient to maintain hydrodynamic lubrication. In certain applications, the sliding velocity will be zero at times, for example between a cam and follower or a piston reaching the end positions in a cylinder liner. This will also be the case during start and stop operations of lubricated systems. To protect friction surfaces from excessive wear in the boundary lubrication regime, it is common to formulate lubricants with additives to improve its lubricating properties under boundary lubrication conditions (Hutchings & Shipway, 2017). This is further discussed in section 2.2.8.

#### 2.1.2.4 Mixed lubrication

The mixed lubrication regime describes lubrication that takes place between the boundary and hydrodynamic lubrication regimes. Under mixed lubrication, the load is shared between the hydrodynamic film and asperities in the friction surfaces. As the film thickness decreases, due to high loads or low sliding velocities, the likelihood of asperity contact between friction surfaces will increase. As a result, an increasing proportion of load will be supported by the interaction between surface asperities instead of being supported by the lubricant film (Totten, 2017).

## 2.2 Lubricating oil properties and formulation

The main ingredient in lubrication oil is often referred to as base oil. To formulate a complete marine lubricant, the base oil is mixed with one or more chemical additives depending on the specific performance requirements of the lubricant (Carter & Green, 2010). However, certain properties cannot be modified with any known additive, and those need to be managed during the refinement process of the base oil stock. Such properties include, for example, thermal conductivity, volatility, vapor pressure, and flashpoint. Since the '90s, new refining technologies have emerged which has resulted in base oil stocks with improved properties (Srivastava, 2014). Most marine lubricants used today consist of paraffinic base oil. Traditionally, naphthenic base oils were more common. Paraffinic oils come with many advantages, such as a higher viscosity index, improved oxidation resistance, and lower volatility, which has lead to the preferred use of this over the naphthenic base oils. In addition to mineral-based paraffinic base oils, there are synthetic alternatives available for certain marine applications. The use of these is however limited (Carter & Green, 2010). Since marine engines operate in conditions with stable temperatures, marine lubricants consist of mono-grade viscosity base oils (Jao & Verhelst, 2013). The viscosity grade in marine lubricants ranges from SAE 20 to SAE 60, where SAE 30 and SAE 40 is the predominating grade used for trunk piston engines. For crosshead engines, a system oil with grade SAE 30 and cylinder oil with grade SAE 50 is common (Carter & Green, 2010).

The chemical or physical properties of base oils can be modified with the use of additives (Harrington, 1992). Such additives can either add new properties to the oil or enhance existing ones (Ahmed & Nassar, 2011). According to Carter and Green (2010) the most common additives used in marine lubricants include alkaline detergents, dispersants, antioxidants, corrosion inhibitors, anti-wear/extreme-pressure additives and pour point depressants.

### 2.2.1 Viscosity

The kinematic viscosity or just 'viscosity' is the most important parameter of lubricating oil. Viscosity describes the flow resistance of a fluid and is determined by measuring the time required for a fluid to flow through a defined capillary at a specific temperature. Viscosity is commonly defined either at 40°C or at 100°C and is expressed in $mm^2s^{-1}$ or cSt (centistoke). The viscosity determines the internal friction, oil film thickness between bearing surfaces and load-carrying capability of the lubricating oil (CIMAC, 2011). A lubricating oil's viscosity is not constant but will change with temperature, pressure, and shear rate. An increase in temperature will result in a decrease in viscosity, while an increase in pressure will result in increased viscosity. The shear rate, being the velocity of the lubricated surfaces in relation to each other, will also impact viscosity depending on the fluid characteristics of the lubricant. The thickness of oil films generated by a lubricant is usually proportional to its viscosity, hence a higher viscosity lubricant would theoretically result in better separation of lubricated surfaces. A higher viscosity lubricant will however require more power to be sheared, which will result in power losses and excessive heat generation which can potentially lead to component failure (Stachowiak, 2005). When selecting a lubricant, it is important to make sure that the viscosity of the lubricant is sufficient to meet the operational requirements even under the most severe conditions. As too high viscosity will lead to power losses and additional requirements on cooling, the viscosity should always be kept at a minimum while still meeting the anticipated operational requirements of the machinery (Harrington, 1992). Another oil characteristic related to viscosity, and of relevance for engine lubrication is VI, short for viscosity index. The viscosity index describes how an oil's viscosity will change with temperature, where a high VI translates into oil with a viscosity less sensitive to changes in temperature and where low VI oils viscosity is more sensitive to changes in temperature (Stachowiak, 2005). When engine oil is entering an engine, it will be cold and will gradually heat up as it makes contact with hot surfaces. Thus, the viscosity will change and therefore an engine oil with a high VI is preferred (CIMAC, 2008).

### 2.2.2 Thermal stability

When lubricating oils are heated above a certain temperature they will start to decompose. As this happens, molecular rearrangement or breakdown of the oil into lighter molecules, such as ethane, methane and ethylene will take place (Stachowiak, 2005). This can cause an increase in oil viscosity but also limit oil additives' ability to perform their functions (Livingstone, Wooton, & Thompson, 2006). A lubricant's resistance to molecular arrangement or breakdown at elevated temperatures under conditions without oxygen presence is described with the lubricant's thermal stability. This property is of high importance when lubricating marine diesel engines, since the lubricating oil will be exposed to high temperatures as it passes through the engine (CIMAC, 2008). There are currently no additives to improve an oil's thermal stability, which is solely determined by the grade of refinement of the oil (Stachowiak, 2005).

### 2.2.3 Oxidation stability

In the presence of air, lubricating oils will be subject to oxidation. This occurs continuously but is greatly accelerated at elevated temperatures and in the presence of wear metals, water or other contaminants (Machinery Lubrication, n.d.). During this process, molecular arrangement or breakdown of the oil will occur. The oxidation stability of an oil describes its resistance to such molecular rearrangement or breakdown in exposure to elevated temperatures and air. When oil is oxidizing, byproducts such as sludge, acidic compounds, and lacquers will be formed. In addition, oxidized oil will become more viscous. The consequences of oxidation may lead to a reduction in oil flow through an engine, and acidic compounds formed will contribute to corrosive attack on engine components. The rate of oxidation is dependent on, apart from temperature, the degree of refinement of the oil and the presence of metallic catalysts which can originate from wear or oil contamination. Oxidation stability can be controlled in the refining process and may be further increased by the use of oil additives (Stachowiak, 2005). Additives used to control a lubricant's oxidation stability are referred to as oxidation inhibitors. These will help in preventing oxidation of the base oil (Machinery Lubrication, n.d.).

### 2.2.4 Alkalinity and detergency

The alkalinity of an oil is defined by the lubricant BN, short for base number. This is a measure of the lubricant's alkalinity reserve, which reflects its ability to neutralize acids (CIMAC, 2011). Such acids are primarily introduced by acidic compounds found in marine fuels, but may also be formed as oil oxidizes (ATC, 2016). To control the BN of a lubricant, alkaline detergent additives are used. The amount of additives used will determine the lubricant BN, and consequently its ability to neutralize acids. A high BN translates into a lubricant containing more alkaline detergent additives with a higher capability of neutralizing acids whereas a low BN lubricant contain fewer such additives (CIMAC, 2011). As alkaline detergents react with acids, the lubricant will gradually undergo BN depletion. The rate of BN depletion is primarily influenced by the content of sulphur present in the fuel and by engine oil consumption (CIMAC, 2011). Benefits of alkaline detergent additives is that they help in protecting engines from rust and corrosion, but also help in maintaining engine cleanliness (Carter & Green, 2010). The use of alkaline detergents will affect the lubricant detergency. It is this property that helps in maintaining engine cleanliness. Precursors to deposits are often insoluble in oil but will be attracted to detergents. This will keep oil insoluble particles in solution, preventing the build-up of deposits on engine surfaces (ATC, 2016). According to Talley and Larsen (1943), the detergency of a lubricant will help in carrying away soot and combustion products as well as the lubricants own decomposition products before these can accumulate into deposits.

### 2.2.5 Dispersancy

The dispersancy of a lubricant describes its ability to maintain particles and combustion products dispersed and in liquid suspension. This ability will help in maintaining engine cleanliness. By keeping impurities dispersed in liquid suspension, buildup of sludge and deposits on tank bottoms and engine surfaces can be prevented. Additionally, impurities can be transported and be removed in a lubricating treatment system (CIMAC, 2008; Jao & Verhelst, 2013). The dispersancy of a lubricant can be controlled by the addition of various dispersant additives (Carter & Green, 2010). Dispersants are especially efficient in keeping fine diesel engine soot particles in suspension (Machinery Lubrication, n.d.). These may otherwise agglomerate and cause thickening of the oil (ATC, 2016).

### 2.2.6 Demulsibility

An oils ability to break emulsions of oil and water, i.e. its ability to separate from water is indicated by its demulsibility (Srivastava, 2014). The demulsibility of engine lubricants is what enables the removal of water emulsions in a separator (Jao & Verhelst, 2013).

### 2.2.7 Corrosion inhibitors

Given the nature of marine diesel engines and their application, it is likely that their lubrication oil at some point will be contaminated by water. While this is usually taken care of by a separator, corrosion inhibitors add additional protection against corrosion to the lubricant. They work by creating a water-repelling or hydrophobic film on metal surfaces, which prevents direct contact with water (Carter & Green, 2010).

### 2.2.8 Anti-wear and extreme pressure additives

Extreme pressure and anti-wear additives are two categories of lubricant additives closely related to each other (Frene, Nicolas, Degueurce, Berthe, & Godet, 1997). They both work in an almost identical way, where they reduce wear by forming a protective film on friction surfaces in the mixed and boundary lubrication regimes (Kolm et al., 2005). The protective film is created as the additives react chemically with the metal surfaces. This chemical reaction is initiated by heat generated when two surfaces make contact. The protective film is sacrificial and hence operating for too long under boundary lubrication conditions can cause a depletion of additives (Machinery Lubrication, n.d.). The main difference between the two additives in terms of functionality is at what temperature the additives will be activated. Anti-wear additives are activated at a lower temperature than extreme pressure additives (Ahmed & Nassar, 2011), where the latter is commonly used in applications with high loads, such as in gearbox lubricants (Machinery Lubrication, n.d.).

## 2.3 Marine engine lubrication

Lubrication in marine engines serve many purposes, apart from reducing friction between moving parts and limiting wear, it act as a coolant, where circulating oil dissipates frictional heat and heat from engine parts exposed to high temperatures. Additionally it provides protection against corrosion, neutralizes acids, and acts as a sealant (Kuiken, 2008). There are two types of engines commonly used in the marine industry, low-speed two-stroke crosshead engines and medium/high-speed four-stroke trunk piston engines (Kuiken, 2008). These engines place different requirements on lubrication. Crosshead engines commonly utilize two separate lubricating oil systems with different purpose and demands on the lubricant, whereas trunk piston engines utilize one common lubricating system with a single lubricant (Srivastava, 2014). In trunk piston engines, cylinder liners are lubricated by splashing oil, this splashing oil is provided by oil releasing from big end bearing surfaces as the engine rotates. On some engine designs, additional cylinder liner lubrication is provided by lubricating holes in the lower part of pistons or cylinder liners. While some of the lubricating oil will find its way past the piston ring pack and into the combustion space where it will be combusted, the majority will be returned to the crankcase by the action of the oil scraper rings.

Crosshead engines utilize a different principle for cylinder liner lubrication. The cylinder liner lubrication system is separated from the main engine lubrication system. Used cylinder lubricating oil is prevented from reaching the crankcase by stuffing boxes which acts as seals between the crankcase and the scavenging air space. Lubrication is achieved by timely injecting lubricating oil through quills located in the cylinder liner into the piston ring pack as this moves past the quills. The cylinder lubricating systems on these engines can be described as a "total loss" system, as used oil is either combusted or ends up in the scavenging air space. The advantage with this lubricating system design, is that cylinder lubricant can easily be changed depending on operational requirements (Morton, Jackson, & Prince, 2013).

Morton et al. (2013) further suggests that the main objectives of cylinder liner lubrication are to:

- To provide an oil film that separates sliding surfaces
- To provide a seal between cylinder liners and piston rings, preventing blow-by of combustion gases
- To provide cooling for hot surfaces
- To protect cylinder liners, pistons and piston rings from corrosive attack by neutralizing corrosive combustion products
- To prevent piston seizure by removing deposits and simultaneously keeping the engine clean
- To prevent abrasive wear by softening deposits

### 2.3.1 Fuel and alkalinity

The quality of fuel used will directly impact the requirements on engine lubrication. Traditionally heavy fuel oils with high concentrations of sulphur have been used in the maritime industry (Jao & Verhelst, 2013). Following environmental concerns of sulphur emissions, the sulphur content of marine fuels have been limited in steps by regulations imposed by the IMO. In 2012, the sulphur limit was changed to 3,5% by mass from a previous limit of 4.5%. This was further limited to 0,5% since 1 January 2020 (Fanø, 2019). In addition to global regulations on sulphur emissions, more restrictive local regulations further limits the sulphur content of fuels in certain areas of the world. These areas are referred to as Sulphur Emission Control Areas or SECAs. Currently, these include areas such as the Baltic Sea, the North Sea, North America, and certain areas in the Caribbean Sea. The sulphur limit in these areas have since 1 January 2015 been set to 0,1% by mass. Vessels trading in and out of SECAs must comply with the regulations by either changing over to a low sulphur compliant fuel or by utilizing an exhaust gas cleaning system to remove sulphur from the exhaust gases (Mallidis, Despoudi, Dekker, Iakovou, & Vlachos, 2020). As low-sulphur fuels come at a higher cost, the exclusive use of low-sulphur fuel on vessels trading in and out of controlled areas is uncommon. Instead, different grades of fuel are used to comply with different local and global sulphur restrictions (Jao & Verhelst, 2013).

Low and high sulphur fuel comes with different demands on engine lubrication. A low sulphur fuel will reduce an engine's exposure to acids, and therefore reduce the potential for corrosive wear. Likewise, high sulphur fuel will expose the engine to acids and increase the potential for corrosive wear (Brice & Bown, 2019). This is why the alkalinity (BN) of lubricants is so important. As mentioned in 2.2.4, the alkalinity of a lubricant determines its ability to neutralize acids. The BN can directly be translated into the content of alkaline detergents present in the lubricant and thus, the lubricant's ability to neutralize acids and protect the engine from corrosive wear. During the combustion process, sulphur contained within the fuel is converted to sulphur oxides. As these oxides make contact with the colder cylinder liner walls, they will condense and react with water, which is also a byproduct of the combustion process. This will result in the formation of highly corrosive sulphuric acid on the cylinder liner walls. The alkalinity of the lubricant will protect the engine by neutralizing such acids (CIMAC, 2011).

According to Morton et al. (2013), it is vital to tune cylinder lubrication based on operational requirements. This includes for example engine load, where a higher load would require a higher amount of lubrication. The other important parameter is the fuel used and its sulphur content. Insufficient cylinder lubrication can lead to an accumulation of combustion products and in severe cases metal-to-metal contact, commonly referred to as "scuffing". It may also lead to corrosion damages if the lubricant alkalinity is not enough to neutralize all acidic combustion products. By increasing the cylinder lubricant dosage or changing to a higher alkalinity oil, such corrosion damages can be avoided. Likewise, over-lubricating can also cause issues. Apart from a higher lubricant consumption, piston rings can be prevented from rotating by excessive hydraulic pressure (Morton et al., 2013). Over-lubricating or alternatively the use of a too high BN cylinder lubricant paired with a low sulphur fuel can potentially lead to an accumulation of excess base additives on piston crown lands. These deposits are abrasive and can result in scuffing or polishing of cylinder liners (Brice & Bown, 2019; Jao & Verhelst, 2013).

According to Jao and Verhelst (2013), alkaline detergents used to modify lubricant alkalinity could potentially also cause issues. Cylinder and medium-speed engine oils contain high concentrations of different alkaline detergents. The mix of additives could cause instability issues which may result in the formation of deposits. These can potentially lead to blockages of filters, lubrication feed lines, and quills. This is generally more of a problem with engine oils with a high BN, as lower BN oils contain less over-based additives and are less likely to undergo additive instability.

Apart from sulphur content, the quality of fuel can impact lubrication in other ways. As refineries attempt to maximize the yield of light distillates with the use of additional refinement processes such as cracking and visbreaking, the quality of heavy fuel oils has deteriorated over time, with aggravated combustion properties and an increased concentration of asphaltenes and other contaminants (Carter & Green, 2010). Asphaltenes are heavy aromatic molecules, kept in suspension by their outer molecular structure. During the cracking process, parts of these outer molecular structures are damaged which leads to a decreased solubility in paraffinic media, such as lubricating oil. The lubricating oil can potentially be contaminated by asphaltenes either from leaking fuel pumps or from incomplete combustion. As asphaltenes generally have a low solubility in lubrication oil, contamination can lead to coagulation of asphaltenes which will form sticky asphaltic particles in the lubricating oil. These particles will adhere to internal engine surfaces and cause blackening of the engine crankcase. This is especially true for medium-speed trunk piston engines, where there is no separate cylinder lubricating system, hence the likelihood of combustion products or fuel contaminating the engine lubricating oil is increased. Asphaltic particles can lead to the blocking of filters and oil scraping rings, which can impact lubrication performance and cause lubricating oil consumption to increase. Additionally, they may lead to the formation of deposits on piston cooling surfaces, which will act as an insulating layer, decreasing the efficiency of lubricating oil piston cooling. This will result in an elevation of combustion chamber temperatures. High temperatures and the presence of vanadium and sodium, elements that can be found in heavy fuel oil can in turn lead to hot metal corrosion. This can potentially result in corrosion damages and the formation of holes in piston crowns (Jao & Verhelst, 2013).

### 2.3.2 Compatibility

Engine lubricants will be subject to oxidation and contamination with combustion products during its service. According to Jao and Verhelst (2013), the main contaminants are soot particles, nitration and oxidation products, partially combusted fuel and calcium salts. These contaminants may coagulate and form deposits, which may cause blocking of filters (Jao & Verhelst, 2013). To prevent contaminants from coagulating and forming deposits, lubricants are designed with detergent and dispersant additives (Štěpina & Veselý, 1992). The formulation of additives determines the contaminant particle size in suspension. In automotive engines, where the engine oil is frequently replaced, the formulation of additives is designed to keep very fine particles in solution. These fine particles will not interfere with lubricating oil filters while still keeping the engine free of deposits. The lubricant condition is in such applications maintained by performing frequent replacements of the lubricant. Marine diesel engine lubricants come with different requirements in terms of dispersion of particulate impurities. It is uncommon to frequently replace engine lubricant, primarily because of the high quantities of lubricants used in marine diesel engines. Instead, the engine lubricant condition is maintained by utilizing separators to remove water and impurities. Thus, particles in suspension must be small enough to not cause blocking of filters while at the same time being sufficiently large to enable the separation of these under centrifugal force. To maintain this balance, marine lubricants are formulated with different ratios of additives, where they contain higher amounts of detergent additives and lower amounts of dispersant additives in comparison to automotive lubricants (Jao & Verhelst, 2013).

### 2.3.3 Water resistance and separability

As ships operate under high humidity conditions, marine engine oils must be resistant to water. The high humidity can cause water condensation in engine crankcases which will contaminate the lubricating oil. Likewise, the oil can be contaminated by accidental spills and internal cooling water leakages (Jao & Verhelst, 2013). It is therefore important that the lubricant, even in the presence of water, is still able to lubricate the engine. The need for water resistance also applies to the additives used in the lubricant. If additives with poor water resistances are used, water contamination can potentially lead to additive losses (CIMAC, 2008). There must be a fine balance between a lubricant's ability to emulsify and demulsify. In the event of water contamination, a lubricant must emulsify with the water to prevent free formation of water occurring inside the engine. When treating the oil in a purifier, the oil is in constant contact with water. To ensure proper water separation, the lubricant must not emulsify with water as it passes through the purifier while at the same time, it must demulsify under centrifugal force (Jao & Verhelst, 2013). According to CIMAC (2008), it is also important that a lubricant maintains its ability to be filtered as it is contaminated with water. CIMAC (2008) further explains that certain filter designs does not function if the lubricant contains water.

## 2.4 Lubricating oil treatment

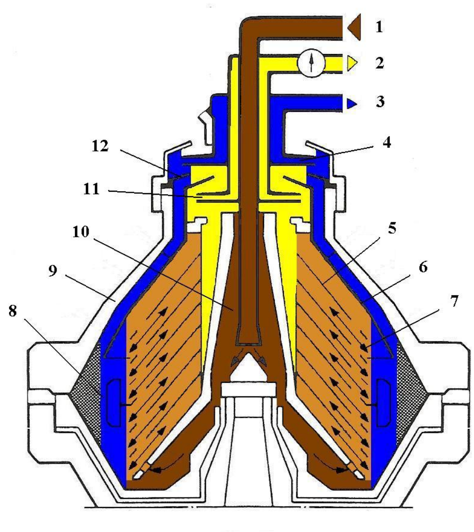
Lubricating oil treatment systems are necessary to maintain a lubricant's condition and to protect the engine from harmful particles. Typically, marine diesel engine lubricating oil treatment systems consist two major components, the cleaning system, and the protection system. The purpose of the cleaning system is to maintain the condition of the lubricating oil by cleaning it from contaminants. Keeping contaminants at an acceptable level, will ensure that the lubricant retains its properties and consequently its ability to perform its functions. This is typically done with a separator. Protection systems consist of filters and serve to protect engines from harmful particles. Filters belonging to the protection system are therefore typically installed in the full flow system, just before the engine lubricating oil inlet. While filters may be sufficient on small engines, large engines typically use a combination of filters and centrifuges (CIMAC, 2005).

### 2.4.1 Centrifuges

The separation of contaminants from lubricating oil in a centrifuge is accomplished by utilizing centrifugal force. As oil passes through a centrifuge, the centrifugal force will push contaminants such as solid material and water towards the periphery of the centrifuge bowl. The more dense contaminants will settle at the centrifuge bowl wall while water will accumulate between these and the lubricating oil. These contaminants are discharged as sludge and the cleaned oil is returned to the engine. The separation of contaminants under centrifugal force is heavily dependant on the difference in density between contaminants and the oil as well as the contaminant particle size. To increase separation efficiency, oil is preheated before entering a

centrifuge. It is typically recommended to operate centrifuges at 95°C. Preheating the oil will result in a decreased oil viscosity which facilitates contaminant separability. There are two types of centrifuges commonly used in marine applications, the purifier and the clarifier (CIMAC, 2005).
Purifiers are apart from separating particles designed to continuously separate water from the oil. This is achieved by a water seal in the outer periphery of the separator bowl. This water seal is connected to a continuous water outlet, hence, as water contamination in oil is separated and enters the water phase, excess water will overflow to the water outlet. Particle contaminants will settle at the bowl periphery and will be periodically emptied as the separator performs a discharge maneuver by opening the bowl. Before such maneuver, the oil is fully or partially displaced by water, depending on the purifier design. This is done to minimize the loss of oil during sludge discharges (CIMAC, 2005). The use of water in purifiers introduces the risk of water ingress into engine lubricating oil. It is therefore important to ensure that purifiers are operating as intended and that they are properly maintained (CIMAC, 2011). The principle of a purifier and its internals are visualized in figure 2.4.

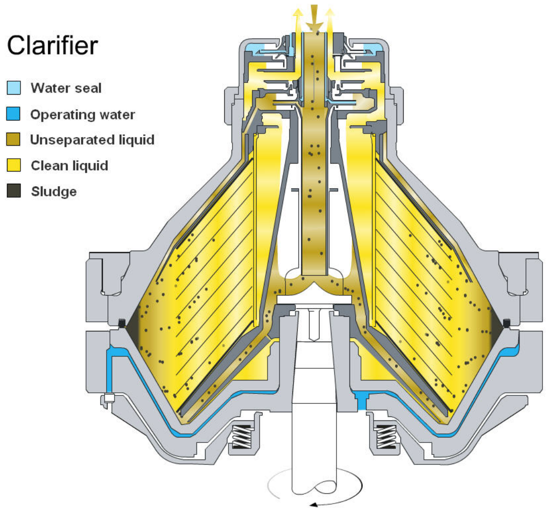
**Figure 2.4:** Purifier principle




*Note.* Reprinted from Wikipedia, by Bengtsson M., 2007, (https://sv.wikipedia.org/wiki/Oljeseparator#/media/Fil:Purifier_principles.JPG), Licence: CC BY-SA 3.0

Clarifiers lack the water seal and continuous outlet of water present in purifiers. Water separated in a clarifier will accumulate together with solid contaminants at the bowl periphery and it is the discharge mechanism that is responsible for discharging separated water. To avoid overfilling the bowl with water, and consequently contaminating the oil outlet, clarifiers are equipped with water monitoring devices to detect water in the oil outlet (CIMAC, 2005). Figure 2.5 illustrates the principle of a clarifier.

**Figure 2.5:** Clarifier principle




*Note.* Reprinted from Wikimedia Commons , by Alpls., 2011, (https://commons.wikimedia.org/wiki/File:Clarifier.jpg#/media/File:Clarifier.jpg), Licence: CC BY-SA 3.0

### 2.4.2 Filtering

Centrifuges do not operate on the full flow circuit of an engine lubricating oil system, thus, even though they are capable of removing particles from the oil, the presence of harmful particles in the full flow system is still likely. To protect engines from such particles, filters are used in the full flow circuit before the engine lubricating oil inlet. Filters work by filtering the oil through a mesh, where particles greater in size than that of the mesh will be retained in the filter. The performance of a filter is therefore largely dependant on its mesh size. There are various filter technologies available on the market and often, a combination of filter technologies is used in series (CIMAC, 2005).

## 2.5 Engine oil analysis

Marine diesel engines require high quantities of engine oil to be operated. As the cost of completely replacing the engine oil on a regular basis would be high, this practice is uncommon. Instead, techniques such as filtering and purification of the engine oil are utilized to maintain its condition. To ensure that the engine oil is suitable for further use and to safeguard machinery, it is common for shipowners to participate in oil analysis programs, where lubricant samples are sent for laboratory analysis on a regular basis (Jao & Verhelst, 2013). According to CIMAC (2011), tests typically carried out under such routine analyses include tests of the lubricant viscosity, water content, base number, insolubles, flash point, and element analysis. Additional analyses such as soot, oxidation, and particle quantifier index could also be included depending on the lubricant analysis provider (SIGNUM, n.d.)(Shell, n.d.). The tests included in routine analyses are designed to give as much information about the condition of the lubricant with as few tests carried out as possible. In addition to tests performed during routine analysis, supplementary tests can be carried out as needed to provide a better overview of the lubricant condition (Carter & Green, 2010). Lubricant analyses can, apart from providing information about the lubricant condition, help in detecting and preventing issues with engines at an early stage. They can also provide useful information when the causes of engine problems are investigated. Often, the report attached with the analysis results will also provide recommendations on course of actions to be taken by the crew (CIMAC, 2011).

To provide any useful data on the condition of the lubricant, analyses need to be carried out on a regular basis. This allows the analysis results to be plotted as a function of time or operating hours. By plotting the results over time, the detection of trends, as well as the deviation from these will be possible. As every engine has its own unique operating parameters, it will also have its own unique trend in lubricant characteristics which could be considered "normal". To detect any deviations from the "normal" trends, it is vital to first establish a baseline representing the specific engine and lubricant "normal". Engine manufacturers and lubricant suppliers typically recommend analyses to be carried out on a frequency not exceeding 3 months. Engine manufacturers and/or oil suppliers typically set up threshold limits for every oil characteristic. These limits act as warnings and may indicate a varying degree of engine or lubricant issues. They are typically expressed as "caution" and "urgent" or "action". Depending on the severity of warnings, intervention by the crew may be required (CIMAC, 2011).

### 2.5.1 Interpretation of lubricant analyses

The following sections will provide information useful for interpreting typical tests performed during routine lubricant analysis. Potential causes of abnormal lubricant analysis results will also be elaborated upon.

#### 2.5.1.1 Viscosity

The viscosity of a lubricant has a direct impact on bearing temperatures, the lubricants' spread-ability, and the quantity of oil that the lubrication system is able to deliver to engine components. The viscosity of a lubricant varies during its service life. The main factors which have an influence on the viscosity are contaminants, oxidation, and thermal degradation of the lubricant. A too low lubricant viscosity is potentially more adverse for an engine than a too high viscosity. As the viscosity decreases, the load-bearing capacity and film thickness of the lubricant decreases, which can cause bearings to seize. Likely causes of a decrease in viscosity are contamination with light fuels, cleaning agents, or a mixture with low viscosity lubricants. On medium-speed engines, an increase of lubricant viscosity will result in decreased cooling to the piston and piston-crowns as well as decreased lubrication of cylinder liners, piston rings, and other engine components. A continuous increase in viscosity will generally indicate a degrading lubricant. This may in turn be the result of various different processes. Mixture with other viscosity grade lubricants will, as mentioned earlier, have an impact on viscosity. The cylinder oil used on two-stroke crosshead engines is normally of a higher viscosity grade than the system oil. Hence, contamination of system oil with cylinder oil, due to leaking stuffing boxes will cause an increase in system oil viscosity (CIMAC, 2011). CIMAC (2011) mentions other processes such as oxidation, nitration, sulphation, insoluble content, soot content and water contamination as possible reasons for an increase in lubricant viscosity. These processes and possible causes will be described in more detail in sections 2.5.1.4 to 2.5.1.9. It is worth mentioning that a too low lubricating oil level can indirectly impact the lubricant viscosity. If the quantity of oil is decreased, the processes mentioned above will become accelerated (CIMAC, 2011).

#### 2.5.1.2 Base number

As described in section 2.2.4 the base number of a lubricant is a measure of its alkalinity reserve which directly describes the lubricants ability to protect against corrosive attack. During the combustion process, sulphur contained within the fuel is converted to sulphur oxides. As these oxides make contact with the colder cylinder liner walls, they will condense and react with water, which is also a byproduct of the combustion process. This will result in the formation of sulphuric acid on the cylinder liner walls, which is highly corrosive. The alkalinity of the lubricant will neutralize these acids (CIMAC, 2011). As neutralization occurs, alkaline additives will be consumed and result in the formation of magnesium or calcium sulphates, depending on which additives are used in the lubricant. These will be part of the insoluble particles suspended in the oil (CIMAC, 2011). As earlier described in section 2.2.4, the BN of a lubricant will gradually be depleted. Fresh trunk piston engine lubricants will see a rapid BN depletion until it reaches a point of equilibrium. This usually happens when less than half of the original BN has been depleted (Carter & Green, 2010). The BN will remain at the point of equilibrium provided the lubricating oil consumption and the fuel sulphur content remains stable. If the BN would decrease too much, the lubricant will lose its potential to neutralize acids which increases the risk of corrosive wear, which will otherwise become visible on bearings, cylinder liners, and piston rings (CIMAC, 2011). Engine operators must ensure as BN stabilizes, it still meets the minimum requirement of BN recommended by the engine manufacturer. If this is not the case, oil can be topped up with a higher BN oil, or alternatively, the engine can be permanently operated with a higher BN oil (Carter & Green, 2010).

In two-stroke crosshead engines, there is a significant difference in the BN of system oil and cylinder oil. System oil normally utilizes a lubricant with a BN below 10 (CIMAC, 2011), whereas a BN of 70 is common in cylinder oils. However, this is heavily dependent on the sulphur content of the fuel and the cylinder oil feed rate (Woodyard, 2009). When system oil is contaminated with scavenging drain oil, its BN will increase. The increase of BN is dealt with by topping up with fresh system oil, hence balancing out the BN. On average, system oil in operation will have a BN of about 15. However, a too high system oil BN may result in difficulties separating water from the oil, hence, most engine manufacturers set a caution threshold at 25 with a recommendation to partially replace the system oil when BN reaches 30 (CIMAC, 2011).

#### 2.5.1.3 Elemental analysis

Elements detected in lubricating oil can originate from different sources. Certain elements are commonly used in lubricant additives, whereas others originate from the wear of engine components or from combustion products. Contaminants such as fuel and water may also result in an increased amount of specific elements. Since different grades of lubricating oil use different additive compositions, the concentration of individual elements can be used to identify the lubricant as well as detecting contamination/mixture with other lubricants. Engine components are manufactured from various alloys containing different elements at various concentrations. The presence of such elements, commonly called wear elements can indicate wear of engine components, such as bearings, cylinder liners, and piston rings. If the content of wear elements in lubricating oil were to suddenly increase, this might indicate an abnormal wear situation. In two-stroke crosshead engines, the large volume of lubricating oil will cause significant dilution of wear elements, hence modest changes in wear element concentrations should be investigated. A common method used for determining elements is Plasma Emission Spectrometry. This method is somewhat restricted, as particles above a certain size (5-7µm) will not be detected. As a result, in situations with abnormal engine wear, the actual element content in oil might be higher than what is detected. In such situations, other non-routine analyses will be required to fully assess the presence of wear elements in the lubricant (CIMAC, 2011). SIGNUM (n.d.) describes common sources of elements, visualized in figure 2.6. It is possible to further narrow down the source of elements or combination

**Figure 2.6:** Common sources of elements in engine lubricant.

| Source | | Fe | Cr | Mo | Cu | Pb | Ag | Sn | Al | Ni | V | Si | B | Na | Mg | P | Zn | Ba | Ca |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trunk piston engine | Liners, pistons, rings | X | X | X | | | | | X | | | | | | | | | | |
| | Bearings | | | | X | X | X | X | X | | | | | | | | | | |
| Crosshead engine | Liners, pistons, rings | X | X | | X | X | | | | | | | | | | | | | |
| | Bearings | | | | X | X | | X | X | | | | | | | | | | |
| | Stuffing box | | | | X | | | X | | | | | | | | | | | |
| Gears | Reduction gear | X | X | | X | X | | X | X | | | | | | | | | | |
| | Other | X | X | | X | X | | | | | | | | | | | | | |
| Water | Sea water | | | | | | | | | | | | | X | X | | | | |
| | Cooling water | | (X) | | | | | | | | | (X) | X | X | | | | | |
| Lubricant additives | | | | | | | | | | | | X | | | | X | X | X | X |
| Fuel | | | | | | | | | X | X | X | X | | (X) | | | | | |
| Air | | (X) | | | | | | | (X) | | | X | | | | | | | |

X indicates great impact whereas (X) indicates less impact on element concentrations. Recreated from SIGNUM (n.d.).

of elements to specific engine components, provided the elemental composition of these are known (Cutler, 2018). Elemental analysis is also used to detect contamination with fuel. In such cases, it is primarily the levels of Vanadium and Nickel that are of interest, because of the abundance of these in marine heavy fuel oils. In scavenge drain oil, the presence of these elements will likely originate from combustion products. As this oil can potentially contaminate system oil through leaking stuffing boxes, the presence of Vanadium and Nickel in system oil can only be used to roughly indicate potential fuel contamination. Analysis of lubricant asphaltene content will likely provide a better indication of fuel contamination in such cases (CIMAC, 2011).

#### 2.5.1.4 Water content

There are many potential sources of water contamination of engine lubricating oil. Jao and Verhelst (2013) describes the environment in which ships operate as humid, which can result in water condensing inside engine crankcases. This humid air is the primary source for water detected in scavenging drain oil (CIMAC, 2011). Water content may also be the result of leaks from water-cooled engine components as well as accidental spills (Jao & Verhelst, 2013). Water contamination of engine lubricants, even in small quantities, can have catastrophic consequences. According to Wright (2008), water is the second most harmful contaminant found in lubricating oils next to particles. Water can exist in lubricating oils in three different forms, dissolved, in emulsions or as free water, where free and emulsified water is the most destructive. As lubricating oil is contaminated with water, the oil film strength is weakened. This results in components being more susceptible to friction wear processes. Lunt (2011) suggests that water contents of 0,1% can reduce the expected bearing lifetime by up to 75%. This is supported by Zhao, Tie, Guo, and Li (2020) who also suggests that the coefficient of friction increases with water content. Water contamination could potentially also lead to an increase of lubricant viscosity if emulsions with water and lubricating oil are formed (CIMAC, 2011). Other consequences of water contamination are according to CIMAC (2011) reduced load carrying capacity, increased potential for cavitation damages and corrosive attack on bearings. Free water will also have the ability to displace the lubricant film, which essentially defeats the lubrication otherwise provided by the lubricating oil. Wright (2008) further describes how water contamination does not only impact lubricated components, but will also impact the rate of oil oxidation. The rate of oxidation in water contaminated oil can increase tenfold, especially in presence of wear elements such as lead, tin, and copper, which according to SIGNUM (n.d.) are elements commonly found in marine diesel engine bearings. The presence of water will also enable microbial growth, which can further increase the rate of oxidation as bacteria decompose oil and form acids (Wright, 2008). Additionally, water contamination may lead to additive depletion. Many additives used in oils are sensitive to water and will form insoluble sludge in contact with water which can be removed from the system by a separator. For instance, this could result in a drop in oil BN (CIMAC, 2011). According to Halme, Gorritxategi, and Bellew (2010), emulsified water can bind to sludge, dead additives, soot, and oxidation products. As this is circulated within the engine and lubricating system, the flow of oil to bearings can be restricted and filters may become blocked. Considering how harmful water is, it is commonly agreed that a water-in-oil content above 0,2% should be avoided in marine engine applications (CIMAC, 2011).

#### 2.5.1.5 Insolubles content

The content of insolubles is important to control to ensure satisfactory lubrication of marine diesel engines. It reflects the level of contamination as well as the degree of oil degradation. While particles are included in the insolubles, the majority of insolubles will be made up of degradation products and contaminants that are either dissolved or dispersed in the oil and thus will not be considered to be particles (CIMAC, 2011). Insolubles present in marine diesel engine lubricants are derived from combustion products of lubricant and fuel, depleted lubricant additives, debris such as wear metals, contamination of fuel or water, and contaminants in the intake air (Carter & Green, 2010). A high presence of insolubles will impact the heat transfer capabilities of a lubricant. This will reduce the lubricant's ability to cool the engine. With the increasing content of insolubles, the lubricant viscosity will also increase. It may also lead to the formation of deposits inside the engine and in filters (CIMAC, 2011). High concentrations of insolubles may also indicate poor combustion, faulty or insufficient operation of centrifuges or filters, and the overall mechanical condition of the engine (CIMAC, 2011). According to Carter and Green (2010), examination of the fuel and fuel combustion systems should be performed if sudden increases of insolubles are detected.

#### 2.5.1.6 Oxidation

The level of oxidation of engine lubricants will indicate the level of oil degradation. When lubricants oxidize, their lubrication properties will deteriorate and will for instance result in an increase of viscosity (CIMAC, 2011). The process of oxidation will be accelerated by elevated temperatures (Stachowiak, 2005) and by the level of contamination with fuel or wear elements with catalytic properties (CIMAC, 2011).

#### 2.5.1.7 Nitration

Nitration occurs as lubricants reacts with nitrogen oxide. This can result in depletion of oil additives, deposit formation, and as mentioned in 2.5.1.1, an increase of viscosity (CIMAC, 2011). Nitration occurs mainly as the oil is contaminated by $NO_x$ rich blow-by gases, which according to CIMAC (2011) mainly is a concern on gas engines. According to SpectroScientific (2017) $NO_x$ gases will interact with the lubricating oil and form nitrates and nitrous compounds which leads to thickening of the lubricant. They further suggest common causes of nitration which are: "inefficient exhaust of the combustion products, improper air-to-fuel ratio, low operating temperature, and leaking piston seals".

#### 2.5.1.8 Sulphation

Sulphation occurs when sulphuric acids are neutralized by alkaline detergents present in the lubricant or when such acids react with the base oil (SpectroScientific, 2017). The degree of sulphation is inversely proportional to the BN depletion of the lubricant (CIMAC, 2011). Apart from having an increasing effect on lubricant viscosity, sulphation can lead to sedimentation and the formation of sludge and varnish (SpectroScientific, 2017).

#### 2.5.1.9 Soot

The are various running conditions of an engine that may result in soot. Soot originates from the combustion process and can be the result of poor combustion. Soot could also be the result of a too high lubricating oil consumption, causing it to burn and form soot particles. Poor combustion can be caused by worn out fuel nozzles or insufficient fuel injection pressure, where the latter is common when running an engine with conventional fuel pumps at reduced load. Insufficient air due to defective turbochargers or clogged air filters will also impact the combustion and the likelihood of soot formation. Soot contamination will lead to an increase of lubricant viscosity (CIMAC, 2011), and can according to Lunt (2011) additionally result in an increased rate of wear of engine bearings, and blocking of oil passages and filters.

#### 2.5.1.10 Asphaltenes

Asphaltenes detected in engine lubricant originate from contamination with residual fuel. This analysis can indicate the proportion of fuel present in the lubricant(CIMAC, 2011). As described in 2.3.1, asphaltenes can coagulate on contact with lubricating oil and form sticky deposits that will adhere to engine surfaces. This can in turn result in blackening of crankcases and decreased engine cooling performance. Sticky asphaltic deposits can lead to other engine issues, as these may result in clogging of oil scraper rings and blocking of fuel injection pumps (CIMAC, 2011).

#### 2.5.1.11 Flash point

The flash point refers to the lowest temperature at which a flame or spark is capable of igniting vapors from a lubricant. Changes in lubricant flash point is mainly influenced by contamination by fuel. Light distillate fuels will decrease the lubricant flash point, whereas residual fuels may have no apparent impact (CIMAC, 2011).

#### 2.5.1.12 Particles quantifier index

The particle quantifier index or PQ index is a measurement of the amount of ferrous debris present in a sample. This analysis is not sensitive to particle size, hence a high PQ index might indicate the presence of few large particles alternatively large amounts of small particles, or a combination of these (Totten, 2017). Due to its insensitivity to particle size, it enables the detection of metal-to-metal contact and fatigue failures that cannot be detected with spectrographic methods used in elemental analyses. By testing for the PQ index, it is possible to for example detect wear of bearings and indication of piston scuffing at an early stage. If such wear conditions are left undetected, they might otherwise result in catastrophic engine failure (SIGNUM, n.d.). The PQ index can also be used to evaluate the efficiency of centrifuges and filters (CIMAC, 2011).

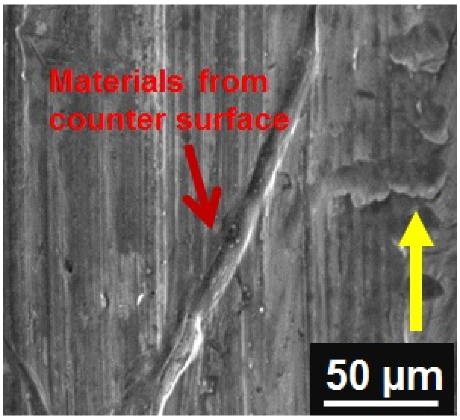
## 2.6 Wear

The process of wear involves the removal, deformation or damaging of material. This can be caused by mechanical means such as abrasion or erosion, but can also be the result of chemical attack i.e. corrosion (Totten, 2017). Different types of wear as well as bearing and cylinder liner wear will discussed in the following sections.

### 2.6.1 Sliding wear

The wear that occurs when two surfaces slide over each other is known as sliding wear and is commonly also described as adhesive wear. This kind of wear occurs when friction surfaces in sliding contacts adhere to each other, resulting in the transfer of material from one surface to the other. Severe cases of sliding wear can be further classified into "scoring", "scuffing" and "galling". Scoring describes wear resulting in the formation of grooves and scratches which are formed in the direction of sliding. Such grooves and scratches could also be the result of abrasion by hard particles. Scuffing describes the wear that occurs in the absence of adequate lubrication between sliding metal surfaces. The results of scuffing can be observed by changes in the surface texture of the scuffed component. Severe cases of scuffing is often referred to as galling. Galling is the result of local welding of the sliding surfaces, associated with severe damage to the sliding surfaces. The word is often used to describe damages resulting from low speed sliding with absent lubrication. Typical damages resulting from galling are extremely roughened surfaces and the displacement of large fragments of surface material. This could result in seizure of the sliding surfaces, which consequently can lead to catastrophic failure of machinery (Hutchings & Shipway, 2017).

**Figure 2.7:** Micrograph of adhesive wear

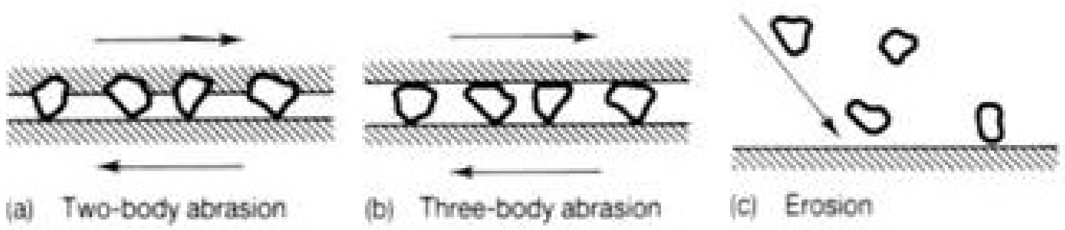



*Note.* Reprinted from Wikimedia Commons , by Noim210, 2012, *Wikipedia: Wear* (https://en.wikipedia.org/wiki/Wear), Licence: CC BY-SA 3.0

### 2.6.2 Abrasive wear

Abrasive wear is the removal or displacement of surface material, caused by hard particles or by counter-face protuberances as these are forced against, and move along a surface. Wear caused by protuberances or particles stuck to a surface can be classified as "two-body abrasive wear". In abrasive wear by loose particles or "three-body abrasive wear", a third interacting body is introduced, being the loose particles. A better way of describing the wear process is to use terms such as rolling or sliding abrasion. In two-body abrasive wear, fixed particles or protuberances slide against the wear surface, hence the wear occurring will be sliding abrasion. In three-body abrasive wear, free particles can either by rolling or sliding against a surface, depending on the size of the gap between the moving surfaces. This is visualized in figure 2.8.

**Figure 2.8:** Abrasive and erosive wear types



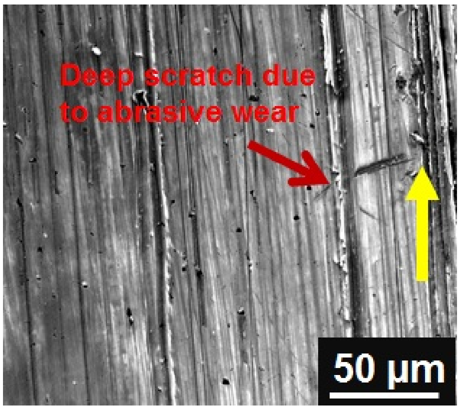

*Note.* Two- and three-body abrasion and erosion visualized. Adapted from Tribology - the friction and wear of materials, Wear - introduction, by University of Cambridge, n.d., (https://www.doitpoms.ac.uk/tlplib/tribology/wear.php), Licence: CC BY-NC-SA 2.0 UK

Hard particles contributing to abrasive wear can be external contaminants entering the lubricating oil, products of oxidation or component wear. The latter can originate from sliding wear of components. When such hard particles find their way into and in between moving surfaces, they will accelerate wear by abrasion. Sliding abrasion can also occur when friction surfaces have different characteristics in terms of hardness and roughness. The main factors having an influence on the rate of abrasive wear are particle/protuberance size, shape, and hardness (Hutchings & Shipway, 2017).

### 2.6.3 Erosive wear

Erosive wear or solid particle erosion is just like abrasive wear, caused by hard particles. The difference is that particles cause wear by striking and rebounding from a surface instead of sliding against it. Hence, it is the forces exerted on a surface by decelerating particles that cause erosive wear (Totten, 2017). Erosive wear is illustrated in figure 2.8.

**Figure 2.9:** Micrograph of abrasive wear




*Note.* Reprinted from Wikimedia Commons , by Noim210, 2012, *Wikipedia: Wear* (https://en.wikipedia.org/wiki/Wear), Licence: CC BY-SA 3.0

### 2.6.4 Fretting wear

Fretting wear is caused by oscillatory movement between contact surfaces, which are often a result of vibrations. Fretting can also be caused by cyclic stress of the contacting surfaces, which can be the result of for example misalignment or load variations across a contact. Severe cases of fretting can lead to fretting fatigue, where fatigue cracks are formed on the exposed area (Totten, 2017).

### 2.6.5 Corrosive wear

Most metals will react with corrosive substances to form oxides. This can be the result of reactions with oxygen in the air or by other more aggressive substances such as sulphuric acid. This can in turn lead to roughening of attacked surfaces and the formation of pits or cracks. As oxides form on the surface of metals, these surfaces will be weakened and will be subject to increased wear by friction processes. Corrosive wear is the removal of such corrosive products by friction wear. As oxide layers are worn down, they will expose new metal which can further be attacked by corrosive substances. Thus, a corrosive environment can rapidly increase the rate of wear (Totten, 2017).

### 2.6.6 Bearing wear and failure modes

There are numerous ways in which a bearing can fail. Harrington (1992) describes common failure modes of bearings in marine diesel engines and the type of wear that can be expected. Failures caused by normal wear are usually defined as bearing clearances exceeding the maximum allowable limit. Normal wear of bearings includes sliding and abrasive wear by particles resulting from adhesion between surface asperities, whereas abnormal wear is dominated by abrasive wear by particles not originating from surface asperity adhesion. Abnormal wear could for instance be the result of lubricant contaminated with corrosion products, sand or aluminum oxides (Harrington, 1992). Bearings may also fail due to corrosion, which as discussed in XXXXX is a phenomenon which occurs in acidic environments and will accelerate the rate of wear. If lubricating oil is contaminated with fuel, this could result in the formation of weak acids in the engine crankcase. These acids will attack copper lead bearings, where the lead will be removed from the bearing surface, exposing nearly pure copper. This will result in elevated bearing temperatures, which causes new lead to rise to the bearing surface. The process is repeated until the bearing lead is depleted and will eventually result in bearing failure. As the bearing fails, scoring can take place on engine crankshaft pins (Morton et al., 2013). Another type of wear resulting from corrosion is when bearing housings or shells are attacked by rust. Rust or iron-oxide particles will be released and suspended in the oil. As these particles are carried by the lubricant to the friction surfaces of bearings, they can score the surface and become embedded in the bearing metal. In turn, this can lead to the scoring of shaft journals. This type of wear can be identified by the presence of grooves or score marks on shaft journals and iron-oxide particles embedded in the bearing metal surface. Another corrosion product that is harmful to engine bearings is tin-oxides. These are formed on bearing metal surfaces in the presence of water, even in small quantities. These particles can cause serious damage to shaft journals as they can be hard enough to score and create grooves on journal surfaces (Harrington, 1992).

Bearings may also fail due to failure of the bearing surface material. Such failures are described as bond failures, and are caused by bearing surface material seperating from the bearing back metal. This can happen to poor or brittle bonds as these are exposed to high loads and vibrations. Bond failures are easily distinguished as machining marks become visible on bearing backs after surface separation occurs. The causes of bond failure can in most cases be traced back to deficiencies in the manufacturing process (Harrington, 1992).

Failure of bearings due to overload or misalignment can be identified by a smeared, wiped, or polished bearing surface. Smeared surfaces refer to surfaces where a flow of metal has occurred in a localized area. Surface smears at the bearing ends might indicate misalignment. More severe cases of surface smear, where a significant flow of metal and overheating of bearing surfaces has occurred are known as surface wipes. Wipes occurring centered on or across a bearing surface is often the cause of bearing overload. Polishing occurs as friction surfaces make contact that does not result in a flow of metal (Harrington, 1992).

Erosion caused by electrostatic discharge, also known as spark erosion, is caused by electric potential generated by a rotating shaft as it discharges through a bearing (MAN Diesel, 2008). This type of erosion can be identified by fine pits with shiny bottoms, usually located in the area with the minimum film thickness (Harrington, 1992). The main cause of spark erosion is a faulty or non-existent shaftline earthing device (MAN Diesel, 2008).

### 2.6.7 Cylinder liner wear

The wear of cylinder liners is higher closer to the combustion space. There are various reasons why wear is exaggerated in this region. First of all, liner surfaces adjacent to the combustion space will be subject to high pressures and temperatures. Secondly, as the piston reverses at the top dead center, hydrodynamic lubrication cannot be maintained. Thus, lubrication will occur in the boundary or mixed region where wear is accelerated. Lastly, acids formed during the combustion will condense on the upper part of the liner, increasing the potential for corrosive wear (Morton et al., 2013). As previously discussed in section 2.6.2, abrasive wear is caused by hard particles. Abrasive wear of cylinder liners can be caused by such particles being present in the oil lubricating the cylinder liner. Particles may also be introduced from the combustion process itself, by the use of contaminated fuel or intake air. A common type of abrasive particle found in marine fuel originates from catalytic refining processes. These particles, commonly known as cat-fines are made up of aluminium-silicates and are extremely hard (Morton et al., 2013).

Another common type of wear of cylinder liners is corrosive wear. As explained in 2.6.5, corrosive wear is the combination of friction wear, i.e. abrasive or adhesive wear, in acidic environments. Surface material attacked by acidity will form corrosion products that are easily removed by abrasion or adhesion. This results in accelerated wear as the removal of corrosion products will expose new metal which can be attacked by the acidic environment. Corrosive wear in the combustion chamber is commonly referred to as cold corrosion (CIMAC, 2017). As described in section 2.5.1.2, during the combustion of marine fuel oils containing sulphur, the sulphur reacts with water and condenses as sulphuric acid on the cylinder liner walls. The alkalinity of the cylinder lubricant serves to neutralize these acids and thus prevent corrosive wear. There are various factors influencing the potential for cold corrosion. First of all, the content of sulphur in fuels determines the amount of sulphuric acids that potentially can condense on cylinder liner walls. Condensation of sulphuric acids will occur below its dew point, thus the rate of condensation is dependent on the cylinder liner wall temperature. To avoid condensation of sulphuric acid, the cylinder liner walls must be kept at temperatures above its dew point. Lastly, the alkalinity of the cylinder lubricant determines its ability to neutralize acids. If the lubricant BN is too low or if an insufficient supply of lubricant is provided, this might result in cold corrosion. By changing the operating parameters of an engine, it is likely that this will also have an influence on the corrosive level in the combustion space. This can be demonstrated by the practice of slow-steaming, i.e. operating vessels at reduced speed and engine loads, which has led to an increase of reported wear from cold corrosion. This is due to operation parameters changing as engine load is decreased. At reduced engine load, a reduction in cylinder liner wall temperatures will occur. This can result in an increase of condensed sulphuric acids on the cylinder liner walls. To prevent cold corrosion during such circumstances, it is important to supply the correct quantity and BN grade of cylinder lubricant (CIMAC, 2017).

When operating engines with too low BN lubricant, a phenomenon called "cloverleafing" can appear. Cloverleafing is identified by high corrosive wear between the cylinder oil injection ports. This is caused by the alkalinity being depleted before all acids have been neutralized. As a result, the lubricant becomes acidic and will contribute to corrosion. Severe cases of cloverleafing can cause blow-by of combustion gases and consequently lead to cylinder liner failure (Morton et al., 2013).

Adhesive wear of cylinder liners is often referred to as scuffing. It is caused by the direct contact between friction surface asperities, leading to localized welding and surface deformation. The principles of adhesive wear is further explained in section 2.6.1. The rate of scuffing is determined by the amount of asperity contact where rough surfaces are more likely to experience wear by scuffing. To achieve full separation between asperities, a film thickness three times greater than the mean asperity height is required. A low roughness of cylinder liners and piston rings is therefore important as this determines the film thickness required to avoid conditions where scuffing can take place. However, full separation of cylinder liner and piston ring is difficult to maintain close to the top dead center. This is due to high temperatures resulting in a low lubricant viscosity near the combustion space. The lack of full separation is dealt with by using various oil additives which improve lubricant film thickness or chemically react with the liner surface to provide a low friction layer. If conditions for adhesive wear exist, rapid wear will occur. This can result in damage to cylinder liners and piston rings and eventually to seizure (Woodyard, 2009).

Another type of wear that can be spotted on cylinder liners is micro-seizure. This type of wear can be identified by small marks along the axial direction of the cylinder liner and piston rings. They reassemble the appearance of abrasive wear but are caused by surface contact resulting from the breakdown of the lubricating oil film. The cause of film breakdown can be an insufficient supply of lubricating oil, low lubricating oil viscosity or high loads. This phenomenon may not be destructive and is common during the running-in of cylinder liners and piston rings. It will however become destructive if it is caused by insufficient lubrication during prolonged periods (Morton et al., 2013). Olander, Eskildsen, Fogh, Hollman, and Jacobson (2015) points out that micro-seizure can very well lead to more serious scuffing of cylinder liners.

## 2.7 Engine safety devices

To protect engines from sustaining damage, they come equipped with a variety of safety devices. These function by either slowing down or stopping the engine should the engine be operated outside its allowed operating parameters (Harrington, 1992). Harrington (1992) further describes what parameters that may cause safety devices to activate:

- Low lubricating oil pressure
- Overspeed
- Low cylinder oil flow
- Low cooling water pressure
- High cooling water temperature
- High charge air temperature
- High exhaust gas temperature
- Exhaust gas temperature deviations

An oil mist detector is another type of safety device commonly installed on marine diesel engines. If for instance a bearing would fail, this may result in a hot spot. This hot spot will evaporate oil into a fine mist. At a certain concentration, this mist will become explosive and may be ignited by the hot spot itself. Oil mist detectors will continuously monitor the air inside the crankcase and should there be any oil mist present, the oil mist detector will slow down or shut down the engine before the oil mist reaches concentrations where it risk being ignited (Morton et al., 2013).

## 2.8 Online oil condition monitoring

According to Lunt (2011), using the lubricating oil condition as a basis for planning and performing maintenance is a philosophy that is becoming more common. Traditionally, such a strategy is based on results provided by frequently recurring lubricating oil analyses. There are disadvantages to such analyses. For instance, there is a risk of errors that may not be detected unless multiple samples are sent for analysis, or if additional samples are sent for analysis when analysis errors is suspected. Another drawback is the delay from sending a sample for analysis until the results are returned. This allows for undetected wear and oil contamination to occur between analyses (Halme et al., 2010). To deal with issues of traditional analyses, the use of sensors for evaluating lubricating oil conditions in real-time is becoming more common. Currently, there exists a range of commercially available sensors which can be used to measure a range of oil parameters. Research is conducted by both academia and industry to develop new cost-effective sensors with improved accuracy and capability to measure additional oil parameters (Lunt, 2011). According to CIMAC (2011), the use of sensors for online oil condition monitoring is an extremely cost-effective method to monitor lubricant conditions. Although sensors will not be as accurate as oil analyses, they can give information on whether the lubricant is prematurely aging and indicate issues with the lubricant or engine in real-time. This gives operators the ability to detect issues before they become serious.

Compared to other industries, the adaption of online oil condition monitoring technology in the maritime industry is still at an early stage. When considering the high capital investment costs of merchant vessels, high requirements on technical availability, and potential consequences of failure of critical machinery, the need for real-time monitoring of oil conditions becomes even more apparent (Lunt, 2011). Commercially available sensors suitable for use in marine diesel engine applications will be discussed in the following sections.

### 2.8.1 Oil condition sensors

According to CIMAC (2011), oil condition sensors cannot be used to detect any specific oil variable. They work by measuring the lubricant capacitance or dielectric properties. Lunt (2011) describes how such properties are influenced by a number of factors. These include oil oxidation, soot, additive depletion, fuel, and water contamination. Oil condition sensors have been widely used within the automotive industry since the '90s, and it is currently the most established type of sensor for online oil condition monitoring applications. While the sensor is not capable of measuring any specific oil variable, it can provide an estimate of the remaining lubricant service life or the need for maintenance. CIMAC (2011) describes how these sensors can be used as the first line of defense since they will signal should any of the aforementioned parameters change.

### 2.8.2 Water content sensors

Water in oil can exist in three different forms. These include water dissolved in oil, water in emulsion, and free water. The ability of water to be dissolved in oil is determined by an oil's water saturation level. This describes the amount of water that can be dissolved and is usually expressed in wt%. The solubility of water in oil is generally low, where pure mineral oils are saturated with water concentrations as low as 0,001%. The water solubility will increase with the use of oil additives and can be as high as 5% depending on the oil formula. There are also other factors having an impact on the saturation level. These include the oil condition and temperature. The impact of aged oil on water solubility is significant, where the ability of aged oil to retain water can be increased 3-4 times compared to fresh oil. The saturation level will also increase exponentially with temperature. In practice, this means that oil in operating machinery can retain more dissolved water than a piece of machinery in standby, provided there is an increase of oil temperature as the machinery is in operation. Dissolved water is considered less harmful in comparison to water in emulsion or free water and precipitation of dissolved water should thus be avoided. Therefore, the water content should ideally never exceed the saturation level at the lowest anticipated oil temperature. When an oil is over-saturated, i.e. when the water content exceeds the saturation level, microscopic water droplets will emulsify within the oil. As water concentration further increases, the separation between the phase of oil and water can occur resulting in the formation of free water. This is caused by water droplet coalescence, i.e. merging of small droplets into larger ones (Myshkin & Markova, 2018).

There are a variety of different sensor technologies available for detecting water in oil. According to Myshkin and Markova (2018), the commercially available sensors for monitoring water in lubricating oil are capacitive type sensors. These sensors will only measure the relative saturation of water in the oil. This is the ratio between the mass concentration i.e. the concentration of water by weight and the saturation level of the oil. The relative saturation is expressed % or in relative units such as water activity. It is calculated using the measured dissolved water concentration and temperature and comparing these to a reference temperature curve, which describes how the saturation level changes with temperature. The drawback with these types of sensors is that they only function within the water saturation limits of any given oil. Thus, any water concentration above the saturation level will not be measured. Another factor is that as oil degrades, the water saturation level will part from the reference values, which results in decreased accuracy. Another type of sensor, not mentioned by Myshkin and Markova (2018) but described by Lunt (2011) utilizes infrared light to measure the total water content in oil. This sensor is capable of measuring total water concentration of up to 1% regardless of the water being dissolved, emulsified or being present as free water. According to Lunt (2011), this sensor was recently developed at the time of publishing and was still being tested. However, this technology is now commercially available from businesses directly targeting the marine industry (TRIBOMAR, n.d.). According to CIMAC (2011), some marine engine manufacturers recommend the use of online sensors for water detection.

### 2.8.3 Wear debris sensors

Sensors for detecting wear debris are capable of detecting ferrous and non-ferrous particles present in the oil. Developments in technology have increased the sensitivity of such sensors which has significantly improved the chance of detecting abnormal wear at an early stage. Typical applications where such sensors can be found are in turbines and gearboxes. The use of wear debris sensors has also been proven useful in marine applications, where it is commonly applied in two-stroke engines to optimize the dosing of cylinder lubricating oil (Lunt, 2011).

### 2.8.4 Viscosity monitoring

Sensors for measuring viscosity have traditionally been used in critical applications such as military vehicles, but are now finding more use in commercial applications. Despite being extensively used for control of heavy fuel oil in fuel oil systems in the maritime industry, the use in lubricating oil application is not very common (Lunt, 2011).

# 3
# Method

The method used in this thesis was a document analysis where documents related to lubrication failure claims were investigated. The process of selecting data, the type of documents reviewed as well as the procedure for implementing the method will be presented in this chapter.

## 3.1 Document analysis

The research conducted in this thesis was qualitative and the method used was a document analysis. This is a systematic method for reviewing documents and evaluating content. This is done through an iterative process involving skimming, reading, and interpretation of documents. This method combines elements of content and thematic analysis. Content analysis involves the organization of data into categories relevant to the research questions (Bowen, 2009). In this thesis, this included the initial selection of data. The research conducted involved the investigation of lubrication failure claims. Lubrication failure was already an existing category within The Swedish Club's database, which made the initial selection of data straight forward. Bowen (2009) further discuss thematic analysis, which forms the other major component of the method used within this thesis. In a thematic analysis, data is coded and categorized based on recognized patterns relevant to the investigated phenomenon, this coding form a basis for further analysis. The research conducted in this thesis aimed at investigating the cause of lubrication failures. Data were interpreted and thematically coded to form categories relevant for understanding the cause of failures. This included different root and immediate causes of failures and other factors identified to have had an impact on the materializing of failures. These categories are presented in detail in the results chapter of this thesis.

## 3.2 Data selection and limitation

The data used in this thesis was obtained from The Swedish Club's internal databases. These contain statistics as well as documents and information on claims from their members. When a claim has been investigated, it is attributed a "loss code", describing the immediate cause of damage. To make the initial selection of data, claims were filtered to only include claims with the loss code "lubrication failure". The selection was further narrowed down to only include claims with damages to main and auxiliary engines, excluding claims with damages concentrated to engine turbochargers. The selection was also limited to only include claims from casualties that occurred from 2009-01-01 until 2020-11-27, where the latter date is when the selection was made. Claims occurring before 2009 were not included, mainly because the electronic system used for archiving data was not widely implemented at that time and would consequently impact the accessibility of data. The accessibility of data is also impacted by The Swedish Club's role in a casualty. Often the risk is insured with multiple insurance providers, where one provider will be acting lead insurer and the others co-insurers. It is the lead insurer who handles and administrates a claim, and therefore the accessibility of data from claims where The Swedish Club is not the acting lead insurer is reduced. For this reason, only claims where The Swedish Club is acting lead insurer were included. Based on these selection criteria, 101 claims were included in the data sample.

## 3.3 Documents

The documents reviewed in this thesis were primarily damage survey reports. These documents are established by an independent surveyor after investigating the extent and cause of failure resulting in an insurance claim. They contain detailed descriptions of the event leading to the failure, the extent of damage, and often a consideration as to what caused the failure. In certain cases, damage survey reports were not available. Instead, information was obtained from service reports, e-mail correspondence, and statements by the crew or shipowner. The information available under certain claims was not enough to establish a cause of failure.

## 3.4 Ethics

The data includes insurance claims which are not finalized, and thus, may still have legal processes ongoing. To protect The Swedish Club and their members' interests, all data used in the thesis are anonymized. Thus, no data that can be directly connected to their members will be presented in the thesis.

## 3.5 Literature

The majority of literature was found using the Chalmers library search engine. This search engine indexes literature including scientific articles and textbooks from numerous scientific databases and electronic libraries. This includes, but is not limited to, databases such as Web of Science and Scopus, and electronic libraries such as Springer. Literature was also found searching the internet using search engines such as Google and Google Scholar. The literature reviewed in this thesis included textbooks, scientific reports, reports, and documents from companies and associations.

Certain information was also found on web pages and magazines dedicated to topics on lubrication. Keywords used in the first review included lubrication, lubricating oil, marine diesel engine lubrication and wear, etc. Additional search keywords were then used to address specific topics identified in the first literature search.

## 3.6 Procedure

When the initial data selection had been made, a first read-through of the data was performed. From the information gathered during the first read-through, short descriptions of the failures were created, including possible causes of failure. During this process, certain themes emerged which could explain the cause of the damage and enabled the creation of a first rough categorization of failures based on their causes. Upon completing the first examination of data, literature was reviewed to explain and understand the phenomenons identified within the set of data. Based on the literature findings, a second examination of the data was performed. This time, a more precise interpretation could be made, which resulted in more precise categorization and additional coding of the data. The final coding resulted in 5 main categories excluding non-applicable failures. Non-applicable failures are failures identified to not be caused by faulty lubrication. In total, 4 failures was regarded as non-applicable. Failures were further attributed to an immediate cause of damage, which describes the main contributing factor resulting in failure. In total 18 immediate causes of failure were identified. Additionally, information regarding lubricating oil management practices, lubricant analysis history, and crew negligence was recorded. During the entire process, data was structured in a spreadsheet. This enabled processing of data using filters with specified criteria and the presentation of codes based on their distribution.

# 4

# Results

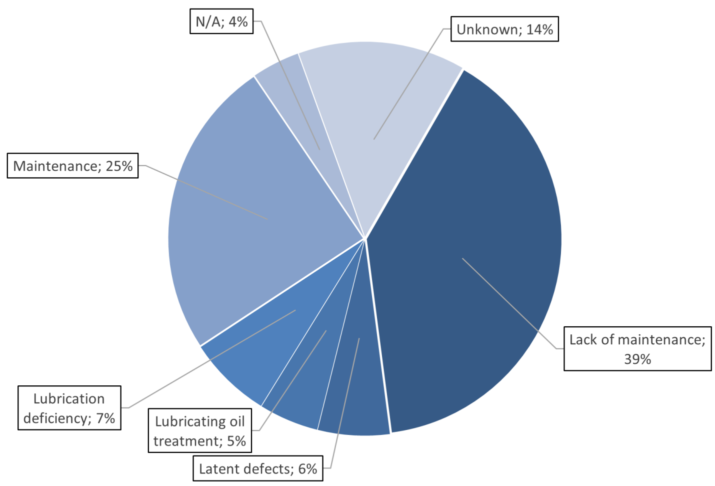
The typical engine damages found in the failures analyzed include damages to crankshafts, bearings, cylinder liners, pistons, and connecting rods. Often an engine failure is not isolated to one single engine component, but a number of components are damaged as a result of a chain of events. As components fail and excessive wear occurs, metal fragments and particles will be introduced to the lubricating oil. These can cause additional damage to other engine components as they are circulated within the engine through the lubricating oil. Additionally, fragments and particles can also get caught and block lubricating oil supply to other components. The majority of failures investigated included damages to engine bearings. In certain cases, the damage sustained to bearings was so severe that the wear condition leading to failure could not be identified. Failures would often also include substantial damages to engine crankshafts, which either had to be replaced or removed and refurbished. In either case, this is a costly operation. Although all investigated failures were unique in their own way, a common element is the high costs involved. On average, the costs associated with the investigated claims amounted to approximately US$ 550.000. Less severe and less costly failures are commonly not claimed by the insurance. This is because of the insurance policy deductible, which was found to commonly be in the US$ 100.000 range.

The data presented within this chapter is the result of the analysis performed on lubrication failures included in the sample. From the data analysis, different root causes and underlying immediate causes of failures could be identified. The identified root causes represent the state, action, or lack of action leading to a failure materializing. In addition to a root cause, an immediate cause of failure was attributed to each failure. This represents the main contributing factor resulting in the failure. To illustrate the difference between identified root and immediate causes, lets assume a failure is the result of a lack of maintenance. In such case, a lack of maintenance would be considered the root cause of failure. A lack of maintenance may additionally lead to damages in various ways. For instance, should a lack of maintenance lead to ingress of cooling water into the lubricating oil stream, water contamination will be considered to be the immediate cause of failure. Apart from causes of failures, data including oil analysis history, lubricating oil management, crew negligence, and engine safety systems were recorded. These will be presented in more detail in the following sections.

## 4.1 Root causes of failures

The root cause of most failures can to some extent be derived from crew negligence. This could for instance be negligence in performing timely maintenance, failure to act on the recommendations provided from an oil analysis report, etc. Since negligence is commonly occurring in the failures analyzed, this will not be treated as a root cause of failure. Instead, crew negligence will be presented separately in section 4.5. From a total sample of 101 failures, 4 failures were identified to not have been caused by lubrication failure and were therefore considered not to be relevant. These failures are categorized as N/A. In 14 failures, information was either missing or lacking in detail and a root cause could therefore not be established. These failures are categorized as having an unknown root cause of failure. In total, five root causes of failures could be identified. These are failure from lack of maintenance, maintenance, latent defects, lubrication deficiency, and lubricating oil treatment. The total percentage distribution of root causes of failures is visualized in figure 4.1, whereas the distribution of known root causes of failures is visualized in figure 4.2. The identified root causes, as well as the underlying immediate causes of failures, will be discussed in more detail in the following sections.

**Figure 4.1:** Root causes of failures

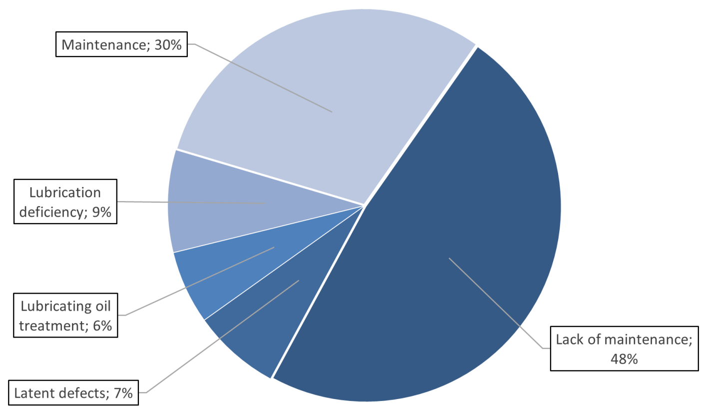



*Note.* Percentage distribution of root causes of failures including not applicable failures and failures with an unknown root cause.

### 4.1.1 Lack of maintenance

In total, 39 failures were identified as being the result of a lack of maintenance. This represents, as seen in figure 4.2, 48% of all failures where a root cause could be

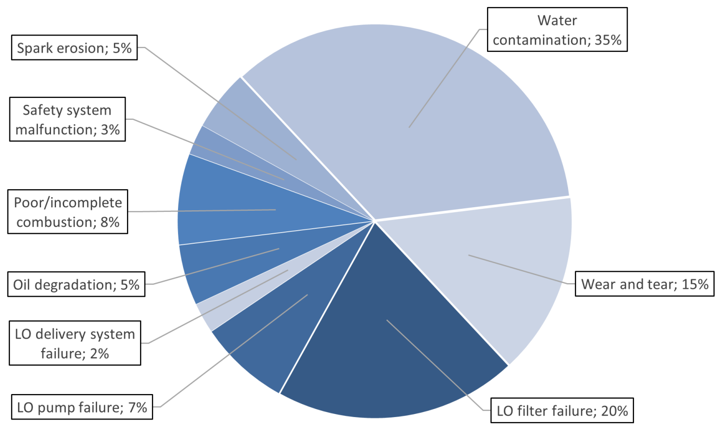
**Figure 4.2:** Known root causes of failures




*Note.* Percentage distribution of known root causes of failures.

identified. The immediate causes attributed to these failures and their distribution is visualized in figure 4.3

**Figure 4.3:** Immediate causes of failures from lack of maintenance




*Note.* Percentage distribution of immediate causes of failures from lack of maintenance.

#### 4.1.1.1 Water contamination

Water contamination is the most frequently occurring immediate cause of failure resulting from a lack of maintenance. A number of water contaminant sources were identified. These include water ingress from poorly maintained separators, clogged air cooler drains, internal engine cooling water leaks, internally leaking oil coolers, and clogged drains in common pipes used for crankcase ventilation. The most frequent occurring source of water contaminant was identified to be neglected maintenance of sump diaphragms. These diaphragms form a flexible connection between the crankcase and the sump tank on large crosshead engines and are situated below the engine crankcase. A damaged diaphragm will result in water ingress as the bilge level rises above the level of the diaphragm.

#### 4.1.1.2 LO filter failure

Poorly maintained filters allowed unfiltered lubricating oil to enter the engines.

#### 4.1.1.3 Wear and tear

Failures from wear and tear on various engine components, that could have been prevented by maintenance.

#### 4.1.1.4 LO pump failure

Neglected maintenance on lubricating oil pumps which caused these to fail, resulting in a loss of lubricating oil pressure.

#### 4.1.1.5 Poor/incomplete combustion

A lack of maintenance resulted in poor combustion, accelerating wear, and consequently leading to engine failure.

#### 4.1.1.6 Spark erosion

Lack of maintenance on shaftline earthing devices, resulting in spark erosion of engine bearings.

#### 4.1.1.7 Oil degradation

Oil degradation from excessive oil contamination, such as fuel and combustion products which could have been prevented by maintenance.

#### 4.1.1.8 LO delivery system failure

Failure of poor condition lubricating oil pipes.

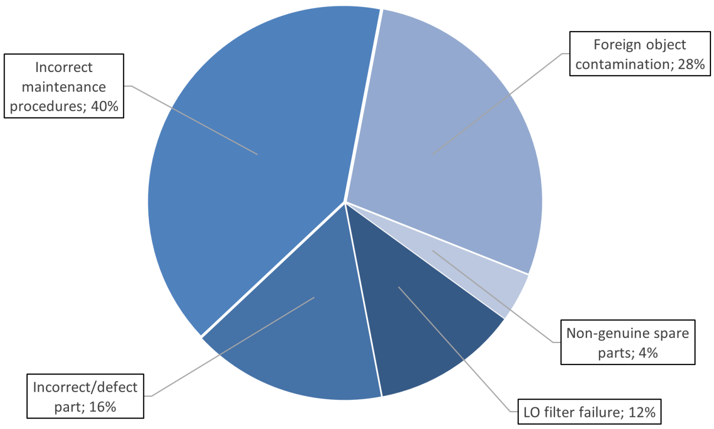
#### 4.1.1.9 Safety system malfunction

Malfunctioning engine safety shutdown failed to shut down the engine as lubricating oil pressure was lost due to a tripped lubricating oil pump. As a result, the engine was operated without lubrication.

### 4.1.2 Maintenance

In total, 25 failures were identified as being the result of performed maintenance. This represents, as seen in figure 4.2, 30% of all failures where a root cause could be identified. The immediate causes of failures from maintenance were identified to be incorrect maintenance procedures, foreign object contamination, lubricating oil filter failure, incorrect or defective parts as well as non-genuine spare parts. The distribution of these is visualized in figure 4.4

**Figure 4.4:** Immediate causes of failures from maintenance




*Note.* Percentage distribution of immediate causes of failures as a consequence of maintenance.

#### 4.1.2.1 Incorrect maintenance procedures

Failure from incorrect maintenance procedures. For instance, incorrect tightening of bolts or incorrect mounting of parts.

#### 4.1.2.2 Foreign object contamination

Failure from contamination by foreign objects or particles introduced when performing maintenance on engines and filters. Larger objects such as rags or pieces of gaskets were found to be able to block engine oil passages and lubricating oil coolers. This resulted in the starvation of lubricating oil and reduced lubricating oil cooling capacity. Contamination commonly occurred during filter maintenance.

#### 4.1.2.3 Incorrect/defect part

During maintenance, incorrect or defective parts were installed which eventually resulted in failure.

#### 4.1.2.4 LO filter failure

Failure due to faulty lubricating oil filter caused by maintenance. This was the result of either incorrect maintenance procedures or incorrect/defective/missing parts. For instance, in two failures, incorrect o-ring seals were installed which allowed unfiltered oil to pass through the filters.

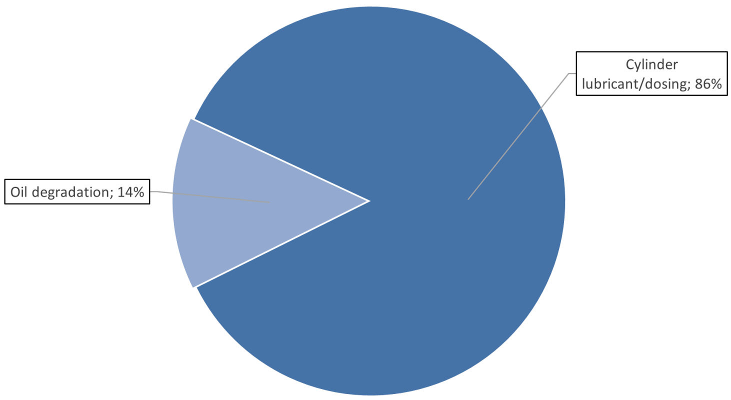
#### 4.1.2.5 Non-genuine spare parts

The use of non-genuine spare parts was on one occasion concluded to be the immediate cause of failure.

### 4.1.3 Lubrication deficiency

Failures with a root cause of lubrication deficiency are identified to be caused by deficiencies in engine lubrication. Thus, they are not the direct result of maintenance or the lack thereof and are also not a direct result of poor lubricating oil treatment. These failures are the result of incorrect lubricants, incorrect dosing of lubricants, or the use of degraded lubricating oil unsuitable for further use. In total, 7 failures were identified to have been caused by lubrication deficiency.

**Figure 4.5:** Immediate causes of failures from lubrication deficiency




*Note.* Percentage distribution of immediate causes of failures from lubrication deficiency.

#### 4.1.3.1 Cylinder lubricant/dosing

Failures caused by the incorrect dosing of cylinder lubricant alternatively the use of a too high/low BN cylinder lubricant.

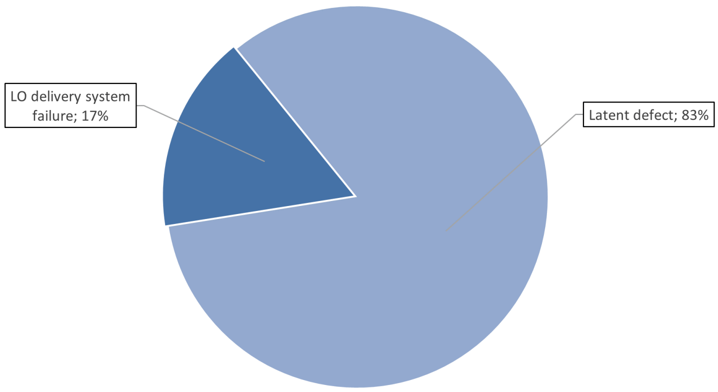
#### 4.1.3.2 Oil degradation

On one occasion, the failure was concluded to be the result of severely degraded lubricating oil.

### 4.1.4 Latent defects

These failures occurred on well-maintained engines with proper lubricating oil treatment and were not the result of previous maintenance. The only reasonable cause of these failures was concluded to originate from latent defects present in various engine components. In total 6 failures were identified to have been caused by latent defects.

**Figure 4.6:** Immediate causes of failures from latent defects




*Note.* Percentage distribution of immediate causes of failures from latent defects.

#### 4.1.4.1 Latent defect

Latent defect present in various engine components.

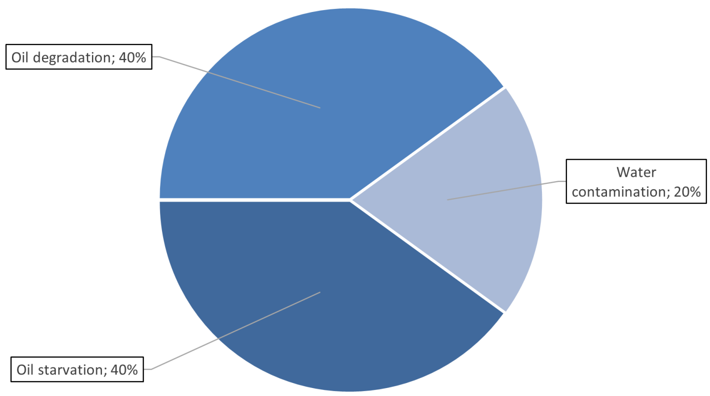
#### 4.1.4.2 LO delivery system

One failure was due to a latent defect in a compensator element installed on the lubricating oil delivery system. This resulted in the starvation of lubricating oil.

### 4.1.5 Lubricating oil treatment

This category includes failures caused by incorrect/faulty operation or the lack of operation of separators. The immediate causes identified from failures caused by poor lubricating oil treatment are oil degradation, oil starvation, and water contamination as seen in figure 4.7. In total, 5 failures were identified to have been caused by poor lubricating oil treatment.

**Figure 4.7:** Immediate causes of failures from lubricating oil treatment




*Note.* Percentage distribution of immediate causes of failures from lubricating oil treatment.

#### 4.1.5.1 Oil starvation

Incorrect/faulty operation of separators resulted in exhausted lubricant levels in engine sump tanks. The failures occurred as engines were started without lubricating oil.

#### 4.1.5.2 Oil degradation

Poor treatment of lubricating oil due to separators not working as intended and separators taken out of operation. As a result, lubricant condition was not maintained which eventually caused engine failure.

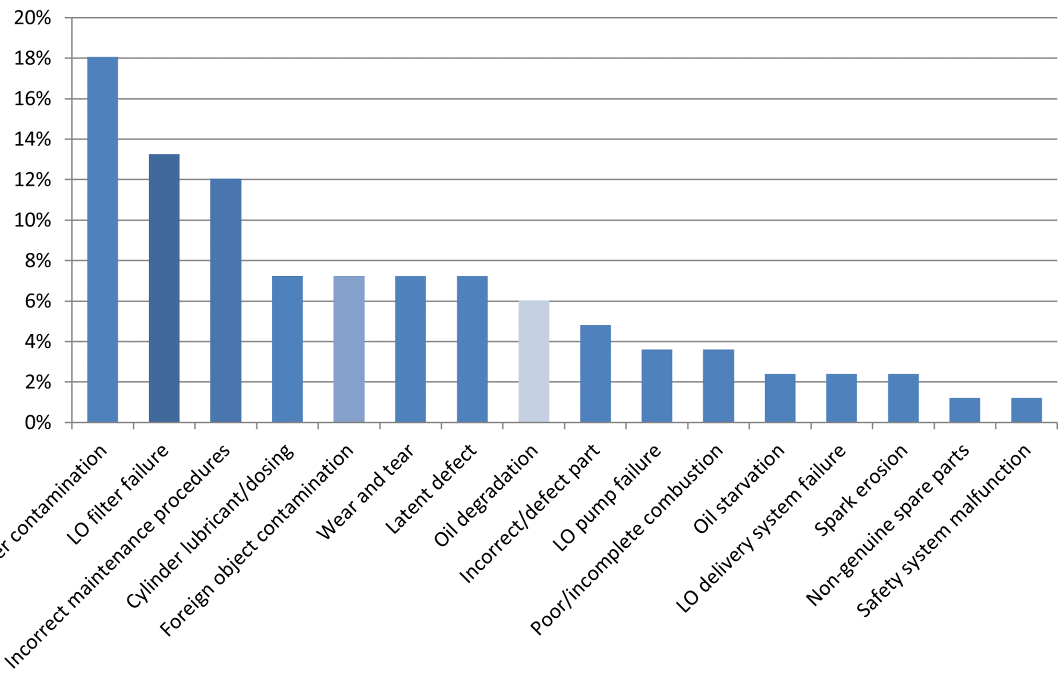
#### 4.1.5.3 Water contamination

Water ingress from the faulty operation of separators.

## 4.2 Immediate causes of failures

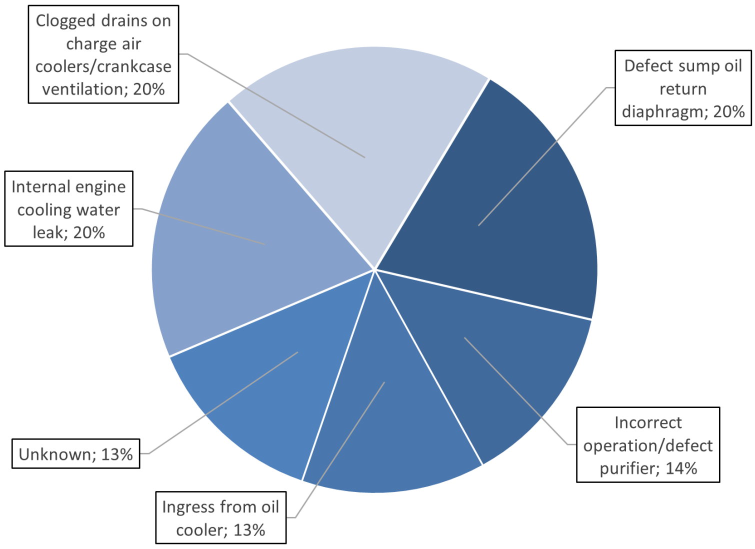
Immediate causes of failures were attributed to each failure, these were discussed in more detail in the previous sections. The immediate cause of failure represents the main contributing factor resulting in failure. These were constructed to provide a better understanding of the prevailing conditions leading to a failure and enable the quantification of such conditions. Figure 4.8 visualizes immediate causes of failures where such could be identified, which was possible in 83 failures. The most prominent immediate cause of failure is water contamination which constitutes 18,1% of all known immediate causes of failures. The sources of water contamination is presented in figure 4.9. The second most frequent immediate cause of failure is lubricating oil filter failure, accounting for 13,3%. Incorrect maintenance procedures account for 12%, wear and tear, cylinder lubricant/dosing, foreign object contamination, and latent defects all account for 7,2% of the known immediate causes of failures.

**Figure 4.8:** Known immediate causes of failures




*Note.* Percentage distribution of known immediate causes of failures.

**Figure 4.9:** Sources of water contamination

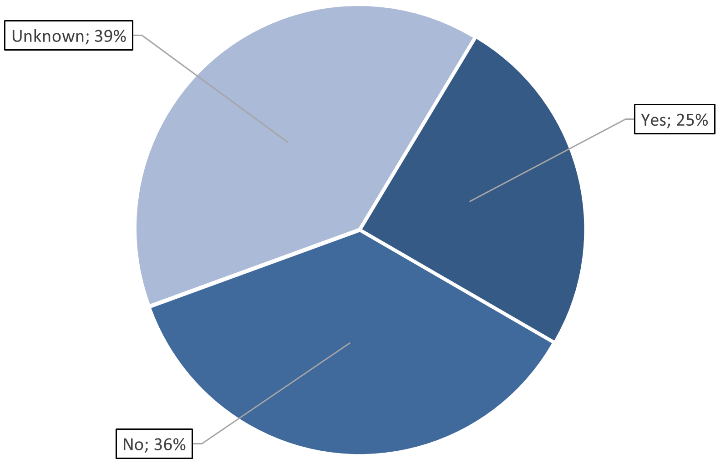



*Note.* Percentage distribution of sources of water contamination.

## 4.3 Lubricant analyses

Damage survey reports and lubricant analyses were reviewed to identify deviations and trends in engine lubricants. If such deviations or trends were considered to be negative, i.e. having an impact on lubricant performance or indicating potential engine issues, these were recorded. The data was based on recommendations provided by lubricant analyses and analyses carried out on board by the crew. More specifically contamination by water, fuel, and combustion products, presence of wear elements, and signs of oil degradation were investigated. The latter includes deteriorating lubricant properties such as viscosity and BN. Excluding not applicable failures, lubricant analyses were not available in 39% of all investigated failures. Negative trends could be identified in 25% of all investigated failures whereas, in 36%, no negative trends could be identified. This is visualized in figure 4.10. Excluding failures where lubricant analyses were not available, negative trends were present in 41%, whereas no negative trends were present in 59% of the failures.

**Figure 4.10:** Distribution of negative trends/deviations in lubricant analyses

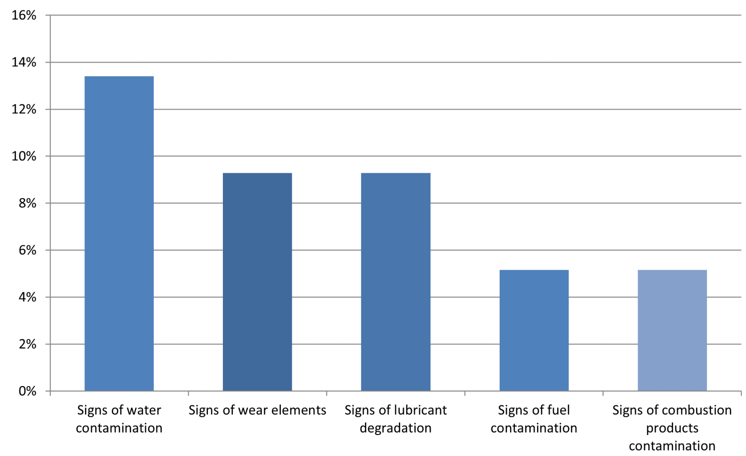



*Note.* Percentage distribution of negative trends/deviations in engine lubricant prior to failure. Yes indicates that negative trends/deviations could be identified, no indicates occurrence of such trends/deviations.

### 4.3.1 Distribution of negative trends/deviations

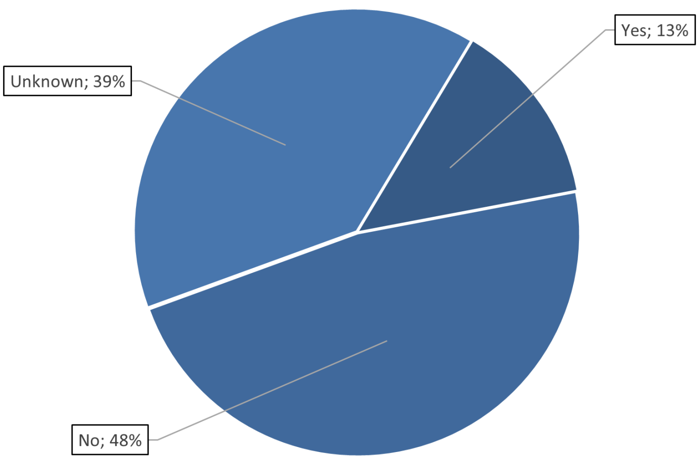
The type of negative trend/deviations identified was recorded and will be presented in this section. Certain failures were attributed to more than one type of negative trend/deviation, for instance, if signs of excessive wear and water content were identified, a failure was attributed to both types. The distribution of such trends/deviations is presented in figure 4.11. Following this will be a breakdown of each type of trend/deviation.

**Figure 4.11:** Distribution of negative trends/deviations in lubricants by type



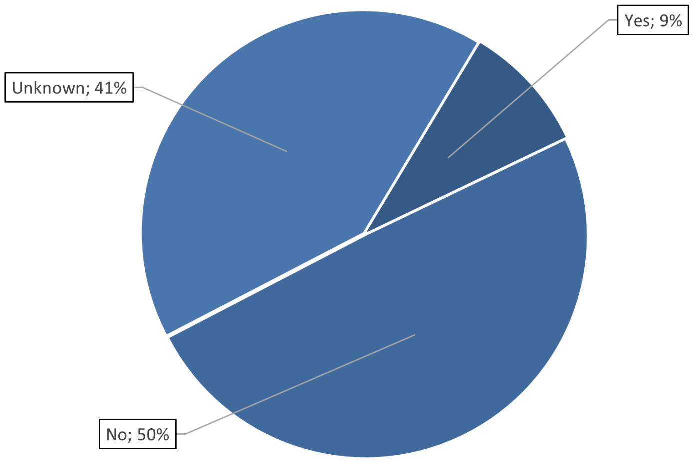

*Note.* Percentage distribution of identified negative trends/deviations in engine lubricants prior failure.

**Figure 4.12:** Distribution of signs of water contamination in lubricant analyses



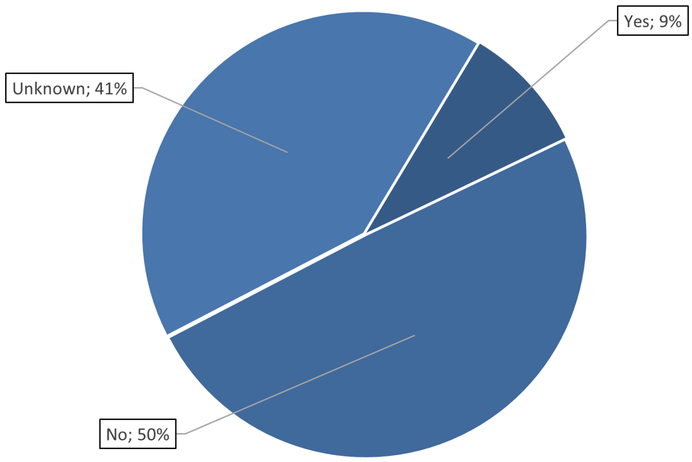

*Note.* Percentage distribution of failures where signs of water contamination could be detected in lubricant analyses or on-board water-in-oil analyses prior to failure. Yes indicates signs of water contamination.

**Figure 4.13:** Distribution of signs of wear elements in lubricant analyses



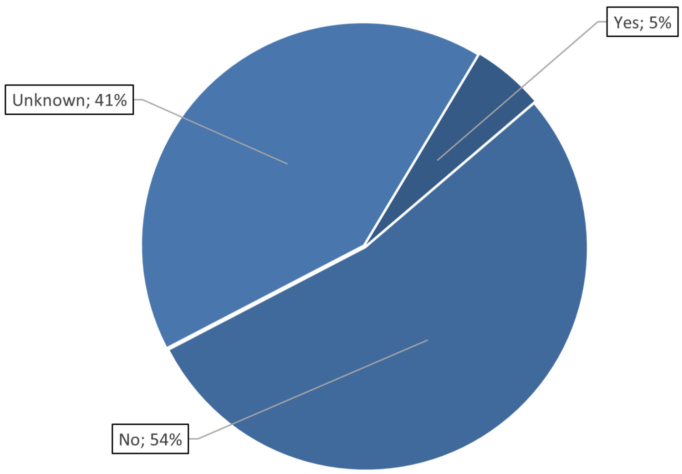

*Note.* Percentage distribution of failures where signs of wear elements could be detected in lubricant analyses prior to failure. Yes indicates signs of wear elements.

**Figure 4.14:** Distribution of signs of oil degradation in lubricant analyses



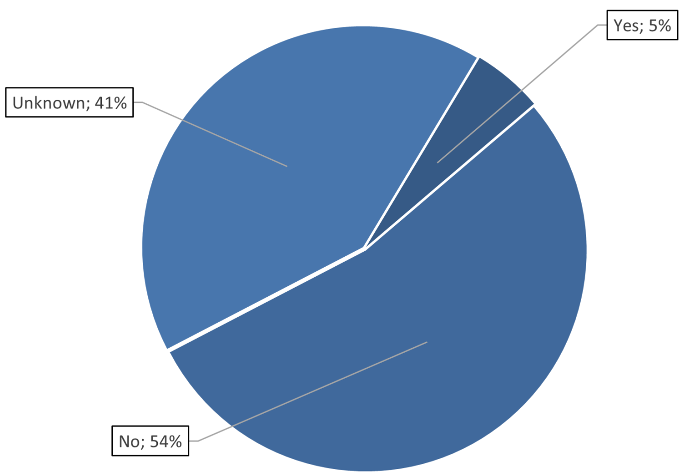

*Note.* Percentage distribution of failures where signs of oil degradation could be detected in lubricant analyses prior to failure. Yes indicates signs of oil degradation.

**Figure 4.15:** Distribution of signs of fuel contamination in lubricant analyses




*Note.* Percentage distribution of failures where signs of fuel contamination could be detected in lubricant analyses prior to failure. Yes indicates signs of oil degradation.

**Figure 4.16:** Distribution of signs of combustion products contamination in lubricant analyses

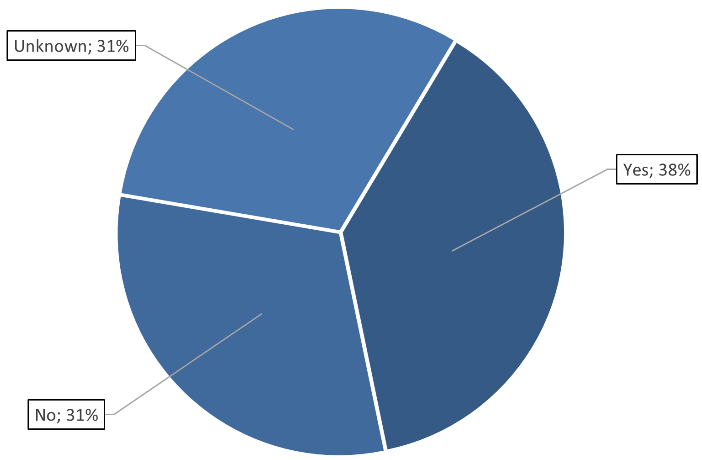



*Note.* Percentage distribution of failures where signs of combustion products could be detected in lubricant analyses prior to failure. Yes indicates signs of combustion products.

## 4.4 Lubricating oil management

Data regarding lubricating oil management were recorded and will be presented in this section. Lubricating oil management summarizes the practices involved in maintaining and managing lubricants on board. This includes elements such as lubricating oil treatment and lubricant condition monitoring with lubricant analyses. For instance, in situations where separators were not in operation alternatively, these were operating at greatly reduced temperatures, the management of lubricating oil was considered to be poor. This was also the case in situations where lubricant analyses were not performed, alternatively, the crew did not act on recommendations provided by the lubricant analysis. Excluding not applicable failures, poor lubricating oil management could be identified in 38% of all failures, whereas in 31% of the failures, no deficiencies in terms of lubricating oil management could be identified. In 31% of the failures, the information provided was not sufficient to assess the state of lubricating oil management. This is visualized in figure 4.17.

**Figure 4.17:** Poor lubricating oil management

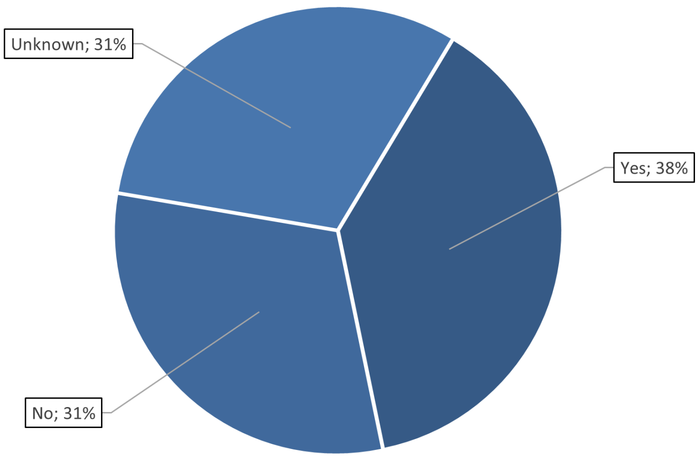



*Note.* Percentage distribution of failures where poor lubricating oil management could be identified. Yes indicates failures where poor lubricating oil management could be identified. No indicates failures where no deficiencies in lubricating oil management could be detected.

## 4.5 Crew negligence

Crew negligence can to some extent be attributed to almost every failure. Because of this, crew negligence was not treated as a root cause of failure. To determine whether crew negligence was an element leading to the failure, the circumstances revolving around the failure were analyzed. This included how maintenance was performed, engine operation, lubricating oil treatment, lubricating oil management, and other factors which could be related to a failure. A mild deficiency in for example maintenance alone was considered not to be enough to attribute crew negligence to a failure. Instead, crew negligence was attributed to failures where deficiencies in multiple areas could be identified or in situations where for example engine maintenance was grossly neglected. For instance, if a failure was caused by the lack of maintenance of a single component but the engine was otherwise well-maintained with proper lubricating oil management practices in place, the failure was not attributed to crew negligence. On the other hand, a failure caused by the lack of maintenance on a poorly maintained engine with lacking lubricating oil management practices was attributed to crew negligence. Excluding not applicable failures, crew negligence could be identified in 38% of all failures. This is visualized in figure 4.18

**Figure 4.18:** Crew negligence

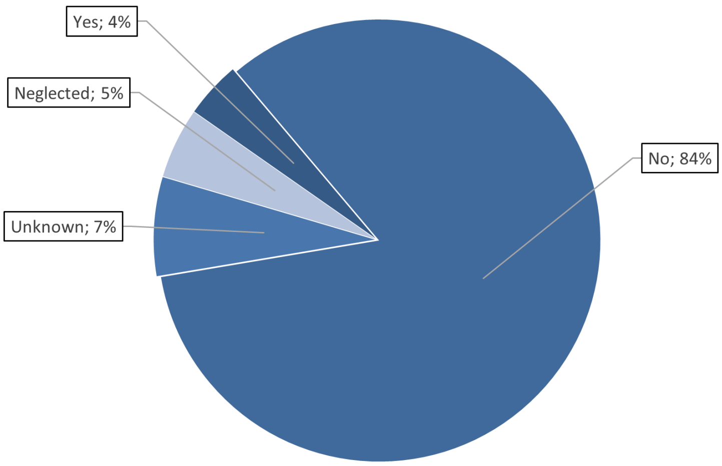



*Note.* Percentage distribution of failures where crew negligence could be identified. Yes indicates failures where crew negligence could be identified.

## 4.6 Engine safety systems

Engine safety systems serve the purpose of protecting the engine under abnormal operating conditions. Data regarding the functionality of these systems were recorded and will be presented in this section. Excluding not applicable failures, no engine safety system deficiencies were reported in 84% of all failures. In 4% of the failures, a faulty engine safety system was identified. In 5% of the failures, safety systems were functional but neglected by the crew. This was for instance in situations where engines were restarted repeatably after an oil mist shut down without any cause investigation. In other cases, engine safety systems were bypassed to not interfere with engine operation. 7% of the failures are unknown since not enough information regarding the failure was provided. This is visualized in figure 4.19

**Figure 4.19:** Faulty engine safety system




*Note.* Percentage distribution of faulty or neglected engine safety systems.

# 5

# Discussion

A more detailed discussion about wear, lubrication and common types of failures, and potential preventive measures will be presented below.

## 5.1 Wear

The mechanics of lubrication and wear discussed in the theory chapter of this thesis were an important element in understanding and interpreting the information provided on the investigated engine failures. The type of wear could in many cases provide useful insight as to what might have caused the failure. For instance, scuffed cylinder liners were a recurring type of damage. According to Hutchings and Shipway (2017), scuffing, which is a type of adhesive wear, occurs in the absence of adequate lubrication between sliding surfaces. There are various reasons why situations with inadequate cylinder lubrication could occur. The most obvious is when the supply of lubricating oil is too low, which was identified to be the case in multiple failures. There are also other reasons why inadequate lubrication of cylinder liners can occur. Woodyard (2009) describes the roughness of surfaces as an important element in maintaining adequate lubrication. As the surface roughness increases, the oil film thickness required to separate the surfaces will also increase. There are many reasons why the surfaces might be roughened. Brice and Bown (2019) describes that the use of a cylinder lubricant with a too high BN in relation to the fuel sulphur content can cause an accumulation of deposits of excess alkaline detergents on piston crown lands. These deposits are hard and will contribute to abrasive wear which will roughen cylinder liner surfaces. This was a phenomenon that could also be identified in the investigated failures. Likewise, Morton et al. (2013) describes other possible contaminants which may lead to abrasive wear of cylinder liners, these include cat-fines present in the fuel and particles entering the combustion space via the intake air. Since four-stroke engines utilize no separate cylinder lubricant, particles present in the engine oil will also have the potential of causing abrasive wear on cylinder liners. This scenario is could be seen in multiple cases. Scuffing can also occur if the oil film thickness on the cylinder liner is decreased. According to Stachowiak (2005), the oil film thickness is dependant on oil viscosity, where a higher viscosity will result in a thicker oil film. The viscosity of a lubricant is in turn dependant on the temperature, where a higher temperature results in a decreased viscosity. It is, therefore, possible that conditions where scuffing can occur, could arise in situations when the cylinder liner wall temperature is increased. There was also scuffing damages that could be identified to have been caused by water contaminated intake air. The water contained in the intake air resulted in the lubricant film being washed away, partly eliminating cylinder lubrication.

**Figure 5.1:** Cylinder liner with scuffing marks

*Note.* Cylinder liner with scuffing marks. In this particular failure, the oil film was washed away by moisture in the scavenging air. Published with permission from The Swedish Club.

As mentioned in the results chapter of this thesis, the majority of failures included damages to engine bearings. Sometimes, the damages was so severe that the wear condition leading to failure could not be identified. In other cases, bearing failure modes described by Harrington (1992) could be used to identify a specific type of wear and a probable cause. Harrington (1992) describes normal wear as wear caused by particles originating from adhesion between surface asperities, whereas abnormal wear is caused by foreign particles or byproducts from corrosion. Normal bearing failures are defined as the bearing clearance exceeding the maximum allowable limit. In other words, the bearing is considered to have failed once this limit is reached, but it does not imply that the bearing is no longer functioning. Once a bearing has exceeded its maximum allowable clearance, it is however likely that the rate of wear will significantly increase. When talking about journal bearings, this could be explained by how hydrodynamic lubrication works. Hutchings and Shipway (2017) describes that in order to maintain hydrodynamic lubrication, the lubricated surfaces must be conformal. As the clearance increases, the conformality of the surfaces is reduced. This will eventually result in a loss of hydrodynamic pressure and the lubricated bearing will enter the mixed and finally the boundary lubrication regime. According to Totten (2017), in the mixed lubrication regime, the load is shared between the hydrodynamic lubricant film and surface asperities and in the boundary regime, the entire load is carried by the contact between the surfaces (Hutchings & Shipway, 2017). Under such conditions the rate of wear is significantly increased and this can explain why bearings, or bearing lubrication, will fail from a lack of maintenance.

There are many potential reasons why hydrodynamic pressure could be lost. As discussed above, bearing wear has the potential of initiating conditions for boundary lubrication to exist. This wear can in turn be the result of a variety of wear processes. Patil et al. (2019) describes the ability to maintain hydrodynamic pressure is dependent on bearing load and lubricant viscosity. Thus, operating engines at high loads or not providing sufficient lubricating oil cooling can lead to a loss of hydrodynamic lubrication. Water contamination is another factor that can impact hydrodynamic lubrication. Water emulsified in oil will reduce the load-carrying capacity of the oil film (CIMAC, 2011). As a result, bearing lubrication might transit from the hydrodynamic into the mixed or boundary lubrication regimes. For reference, Lunt (2011) describes how a lubricant water content of 0,1% can reduce bearing lifetime by up to 75%. This is substantial and conforms with the results of this thesis, where water contamination is the most common immediate cause of damage.

Another common type of bearing failure was overheated and seized bearings. This would happen under extreme conditions of wear, and as a result, bearing shells would shift or rotate inside the bearing housing. This would often result in a blocking of oil supply to other engine components and the extent of damage would dramatically increase. In those cases, determining the initial wear condition that lead to bearing failure was difficult. Other bearing failure modes described by Harrington (1992) could however be identified in the investigated failures. These included failures from corrosion, spark erosion and overload and misalignment.

## 5.2 Maintenance

As presented in the results chapter of this thesis, the most common root cause of failure was a lack of maintenance. This involves cases where maintenance was grossly neglected as well as cases where maintenance was performed as planned, but for some reason, certain components were forgotten and therefore not maintained. If the maintenance is done according to a planned maintenance system, and certain maintenance procedures are not included, it is easy to see how such procedures can be forgotten. In severe cases of neglected maintenance, it is difficult to identify any specific reasons why maintenance is not performed. It is easy to draw the conclusion that a lack of maintenance is directly the consequence of an incompetent, negligent or lazy crew. Crew negligence will be discussed in more detail in section 5.11. It is worth mentioning that this phenomenon might have more complexity to it, and may very well stretch to ship management. There could for instance be economic incentives to not supply vessels with needed spare parts or to postpone certain maintenance. While the availability of spare parts was not reported in the investigated documents, this is a prerequisite for the crew to be able to perform maintenance in the first place. The crew and the technical management should be aware that maintenance is a necessary element in operating a vessel. Maintenance schedules are set up based on the equipment maker's recommendations and in cases where maintenance was grossly neglected, it is unlikely that the crew nor the technical management was not aware of this. It is therefore hard to see how any preventive measures including recommendations on the execution of maintenance would make any difference. Instead of looking at the act of performing maintenance, it is likely that measures focusing on the symptoms of neglected maintenance could be more helpful in preventing failures. For instance, the oil condition can provide information on engine issues and sources of contamination before a severe failure occurs. This will be discussed in more detail in sections 5.6 and 5.7. To fully understand the underlying factors to why maintenance is neglected, further research will be required.

The second most common root cause of damage was identified to be maintenance, i.e. failures materializing as a direct consequence of performed maintenance. The predominating cause of failure from maintenance was incorrectly performed maintenance procedures. A common cause of damage was an incorrect tightening of bolts securing exhaust and intake valve assemblies and connecting rod/piston assemblies. The crew should have access to documentation on how to perform these procedures including specified tightening torques where applicable. Whether such documentation was missing, not adhered to, or if tools used were defective or not calibrated remains unknown. To prevent such failures from happening, it is of great importance that correct tightening torques are used and that tightening tools used are accurate. While the information on how to perform maintenance procedures should be available in the engine maintenance manuals, it is possible that the crew occasionally will attempt to perform procedures without consulting the manual. Even if crew members have performed certain procedures previously and may believe that they know the procedure, mistakes obviously do happen. It is also possible that a lack of, or deficiencies in communication can result in incorrectly performed procedures. For instance, when a new crew member, unaware of certain procedures is tasked to join an experienced crew member who relies on his experience instead of the maintenance manual, it is possible that the procedures will be communicated incorrectly. This could also be the case even if the manual was consulted, but not by all crew members participating in the maintenance. When considering the noisy engine room environment and mixed nationality crews with different native languages, it is easy to see how communication could be affected. It is also possible that the available documentation on maintenance procedures is lacking in detail or structured in a way which make them hard to comprehend. One way of increasing the availability of information on maintenance procedures would be to make sure that instructions are available on the work descriptions provided by the vessel's planned maintenance system. Instead of reaching for manuals, work descriptions can be printed directly from the system as the crew plans their daily work.

Next to incorrect maintenance procedures, contamination by foreign objects or particles was the most common cause of failure from maintenance. The contaminants in these failures did not necessarily have to be foreign by origin, but instead foreign as in being present in the lubricating oil system where they should not have been present. The most common source of contamination occurred during the maintenance of filters, but contamination frequently occurred during other engine maintenance as well. There are various likely scenarios that can describe how the oil is contaminated during filter maintenance. When filters are maintained, particles and debris retained within the used filter elements may be released into the filter housing as they are dismantled. Likewise, as filters are dismantled, contamination can also occur from particles or objects with a foreign origin. Depending on the filter construction, such contaminants could potentially enter the engine. Therefore, filter housings should always be drained and properly cleaned before putting filters back into operation. Another likely scenario of contamination is that previously cleaned replacement filter elements are not sufficiently protected and could have collect particles from storage. The process of cleaning filters could also introduce particles, which is why this should be done in a way where the likelihood of contamination is low. For instance, cleaning and disassembling/assembling a filter in a location with the presence of abrasive particles such as dust in a metal workshop would not be advised. Filters should always be cleaned according to the instructions provided by the maker.

Another type of frequently occurring failure was due to particle contamination from a previous, less severe failure. The crew performed repairs but shortly after, engines sustained more severe damages. This was due to particles and debris originating from the first failure that was left behind in engine crankcases and lubricating oil systems. It is unclear whether efforts were made to remove all particulate contaminants in these failures. However, if such contaminants would have been removed, it is likely that these failures would not have happened. Therefore, after sustaining engine damage, extra caution should be made to ensure that all debris and particulate contaminants are removed from the engine and lubricating oil system. This may require additional parts to be dismantled, pipes to be flushed or quantities of oil to be replaced. Other sources of contamination were identified to be left behind tools and rags in engine crankcases after performed maintenance.

According to Harrington (1992), engine safety devices protect engines by slowing down or shutting down the engine in the event of an abnormal operating condition. This can for instance be; low lubricating oil pressure, over-speed, or oil mist alarms. It was found that a lack of maintenance on such devices can result in severe failure. For instance, one failure was the result of a malfunctioning lubricating oil pump. As this pump failed and lubricating oil pressure was lost, the safety system failed to shut down the engine. This resulted in the engine being operated for several minutes without any lubrication. This highlights the importance of keeping engine safety devices well-maintained.

## 5.3 Filter failure

The next most common cause of failure was identified to be faulty lubricating oil filters. According to CIMAC (2005) filters are installed to protect engines from harmful particles which may otherwise cause damage. Wright (2008) further describes how particles are the most destructive oil contaminant. This statement can be considered accurate considering the high frequency of failures from poor oil filtration. The level of protection from filters is determined by the filter mesh size. Particles larger in size than the mesh size will be retained within the filter. Should a filter sustain damage leading to a formation of holes larger than its mesh size, particles that would normally be retained within the filter will be able to pass through (CIMAC, 2005). A visual reference of filter elements which are not able to retain particles is presented in figure 5.2. Likewise, if filter parts are not installed or sealed properly within the filter housing, internal leakages can occur. This will enable unfiltered oil to by-pass the filter. This phenomenon was identified to be a common cause of failure, where internal leakages was caused by incorrect assembly during maintenance, internal seals missing or being of the wrong dimensions. As particles are allowed to enter an engine, they will accelerate wear. Hutchings and Shipway (2017) describes the kind of wear caused by particles as abrasive wear. One of the factors influencing abrasive wear is particle size, which can increase in size should they not be retained in a filter. Severely damaged filter elements will allow for even larger particles and debris to enter an engine. Such was found to be able to block internal oil passages and cause oil starvation to blocked off components. The root causes for lubricating oil filter failures was identified to be a combination of lack of maintenance and a consequence of maintenance. In failures caused by the use of poor condition filter elements, which would fall under the lack of maintenance category, it is possible that a lack of maintenance instead could be a lack of spare parts. If no spare parts are made available to the crew, it is very likely that poor condition parts will be put back into operation after maintenance. Additionally, the process of cleaning filter elements was identified to be able to cause damages to filter elements. The use of ultrasonic cleaning units has the potential of causing damage to the filter elements if not used correctly. If filter elements are not spaced correctly inside such unit, they will oscillate against each other which can cause material fatigue. This can in turn result in pieces or strands of filter mesh wire making its way into the engine where it can cause severe damage. Since malfunctioning filters have the potential of directly exposing an engine to situations where increased wear can occur, it is vital that maintenance is performed according to the manufacturers' recommendations and that filter functionality is ensured. Poor condition filter parts should under no circumstances be reassembled. Therefore, the availability of filter spare parts on-board must always be ensured.

**Figure 5.2:** Missing mesh on automatic filter candles

*Note.* Severely damaged filter candles. The missing mesh allowed unfiltered oil to pass through the filter. Published with permission from The Swedish Club.

## 5.4 Separator failure

Several failures were identified to be the direct result of incorrect operation of separators. For instance, two failures occurred due to engines being started with empty lubricating oil sump tanks. This was in turn the result of the crew, prior to the failures, changing the engine to be separated by a common separator. This setup, where one separator is used to separate the lubricating oil of multiple engines in the sequence is common. It is unclear exactly what caused the sump tanks to be emptied, but it is likely that valves were not maneuvered into their correct position when separation was shifted from one engine to another. Thus, the separators were likely set to draw oil from the engines which sustained damage while discharging it to other engines. This highlights the need for regularly checking the engine sump oil levels, especially after shifting the separation sequence. Should such checks have been made before starting the engines, the engines would likely not have been started in the first place and the failures could have been prevented. Another measure with the potential of preventing such failures would be to install equipment to monitor the level of the sump tanks. A low-level alarm, alternatively a level sensor connected to the engine alarm system, would in real-time alert the crew should the sump oil level decrease.

In another failure, incorrect operation of a purifier resulted in water contamination. In this case, the crew had been trying to optimize the separator operation in an attempt to reduce an already elevated content of water in the lubricating oil. Instead of reducing the water content, the oil was further contaminated. Likewise, a faulty purifier also resulted in water ingress in another failure. Since purifiers utilize water in their process which evidently can cause water ingress, the need for maintaining and making sure that purifiers are operating as intended is emphasized by CIMAC

(2005). In other failures, the incorrect operation or lack of operation of separators was likely a contributing cause leading to failure. The efficiency of separators is largely impacted by the temperature at which they operate, and the oil is therefore preheated before entering the separator, typically to 95°C (CIMAC, 2005). In certain failures, separators were not in operation or operating temperature was significantly reduced to temperatures as low as 55°C. This will according to CIMAC (2005) results in a significantly reduced separation efficiency, which was identified to be accurate after reviewing oil analysis records.

## 5.5 Cylinder lubrication failure

In total 6 failures were identified to be caused by insufficient or incorrect lubrication of cylinder liners. These were the result of insufficient dosing or using cylinder lubricants with either a too high or too low BN. The importance of matching BN to the level of acidity present in the fuel is emphasized by CIMAC (2011). The BN describes the amount of alkaline detergents present in a lubricant, which determines its ability to neutralize acids and thus protect against corrosive attack. Acids in the combustion space originate from the combustion of fuel, and the level of acidity is directly connected to the sulphur content of the fuel. Using a low BN oil in combination with a high sulphur fuel can exhaust the supply of alkaline detergents in the cylinder lubricating oil. If the amount of additives available to neutralize acids is not sufficient, this will result in corrosive attack on cylinder liners. In turn, this will lead to corrosive wear which is an especially harmful process of wear. According to Totten (2017), corrosive wear is the combination of friction wear and an acidic environment. As acids attack the surface of metals, the surface will be weakened and subject to an increased rate of wear by friction. As the surface layer of attacked metal is worn off, new metal will be exposed to the acidic environment and the process will start again. In failures where corrosive wear of cylinder liners could be identified, it is very likely that this was caused by a low BN oil with poor acid neutralization capabilities. This could easily have been avoided by simply increasing the dosing of cylinder lubricant alternatively changing to an oil with a higher BN. On the opposite side, two failures were identified to be caused by a too high BN. According to Brice and Bown (2019), the use of a high BN oil paired with a low sulphur fuel can cause a build-up of deposits of excess base additives. These are abrasive and can promote scuffing or polishing of cylinder liners, which conforms with the type of damages that could be identified. There are other factors than fuel sulphur content which can initiate conditions for corrosive wear. CIMAC (2017) describes how a decreased combustion temperature can lead to increased precipitation of acids on cylinder liner walls. Operating engines at a reduced load i.e. slow-steaming could therefore increase the potential of corrosive wear. No evidence of this could however be identified in the investigated failures.

These type of failures are likely an effect of vessels utilizing fuel of different grades concerning sulphur content. Regulations prohibiting the use of fuels with a sulphur content above 3,5% by mass were enforced in 2012. This limit was further decreased to 0,5% in 2020 (Fanø, 2019). While these regulations limit the use of certain fuels on a global level, more restrictive local regulations have simultaneously been enforced in certain areas of the world. These areas are commonly referred to as SECAs, and the use of fuels with a sulphur content above 0,1% has been prohibited in these since 2015 (Mallidis et al., 2020). Since low sulphur fuel comes at a higher cost, ship operators trading in and out of SECAs, will likely change to a high sulphur fuel outside SECAs (Jao & Verhelst, 2013). A high and a low sulphur fuel will have very different requirements in terms of lubrication. Because of this, vessels utilizing different grades of fuels must also carry lubricants on-board suitable for operating on the different grades of fuel. With the recently enforced global sulphur limit of 0,5%, the range of available fuels in terms of sulphur content has dramatically decreased. With this in mind, the range of different lubricants which must be carried on-board will also decrease. This reduces the risk of mistakes and simplifies ship operations in areas with different regulations. It is possible that this alone has the potential of reducing the frequency of damages from cylinder lubrication failures. However, it is worth mentioning that this will only apply for vessels that do not utilize an exhaust gas cleaning system. Higher sulphur fuels will still be available for use on vessels equipped with such systems.

## 5.6 Water contamination

Water contamination was identified to be the predominating cause of failure, accounting for 18% of all failures where an immediate cause of failure could be established. After examining lubricant analysis history, indications of water contamination could be detected in 13 out of 97 failures which represent in total 13,4% of the investigated failures. Considering that no lubricant analysis history regarding water contamination was available in 38 (39,2%) failures, it is probable that water contamination, in reality, was more frequently occurring. A variety of sources of water contamination could be identified. These included ingress from purifiers, internal cooling water leakages, leakages in lubricating oil coolers, and clogged drains in scavenge/charge air coolers, and crankcase ventilation as well as ingress through defect sump oil return diaphragms. Since none of the identified sources of contamination were over-represented, this discussion will focus on water contamination in general and how the frequency of failures resulting from water contamination can be reduced. According to Wright (2008), water is the second most harmful lubricating oil contaminant next to particles. As oil is contaminated with water, the lubricating oil film is weakened which renders engine components more susceptible to wear by friction processes. This was confirmed by looking at the type of wear present in failures caused by water contamination, where the vast majority did involve excessive wear by abrasion or adhesion. CIMAC (2011) describes another potentially harmful impact of water contamination being an increased potential for corrosion damages to bearings. Such damages could be detected in certain cases, but always together with excessive frictional wear. It is therefore unclear exactly what caused those engine failures, but it is likely that deteriorated lubricant properties from water contamination had a more destructive impact than the corrosion damages. While the occurrence of failures from water contamination was high, the occurrence of corrosion was not as common. There are various possible explanations for this. First of all, water contamination would likely need to persist for an extended period of time before such damages appear, which was not always the case. Secondly, corrosion inhibiting additives used in oil to protect against corrosion (Carter & Green, 2010) are likely effective.

Water also has the potential of dramatically accelerating the rate of oil oxidation, especially in the presence of wear elements commonly found in marine diesel engines (SIGNUM, n.d.; Wright, 2008). As oxidation occurs, sludge formation can take place and may also lead to thickening and darkening of the oil. Oxidation may additionally lead to formation of highly corrosive organic acids, which can cause corrosion damages on engine parts (ATC, 2016). The occurrence of darkened oil and corrosion damages could be identified in multiple failures. This could be the result of acids forming from oxidized oil. However, these symptoms may also be the result of microbial growth in the engine lubricant. According to Wright (2008), water contamination increases the potential of microbial growth, and such growth will further increase the rate of oil oxidation and formation of organic acids. There was no reports of microbial growth in any of the investigated failures. However, to establish presence of microbial growth in a lubricant, additional lubricant analyses have to be made. It is unclear whether such analyses was ever made since no evidence of such could be found within the set of data. Since no reports confirming the presence of microbial growth could be found, no conclusion regarding the impact of microbial growth in relation to the investigated engine failures could be made.

Another consequence of water contamination is additive depletion. According to CIMAC (2011), many oil additives are sensitive to water and may form sludge deposits that can be removed from the oil in a separator. More research would have to be done to identify which additives that are sensitive to water, as well as their occurrence in marine engine lubricants. Provided that modern marine engine lubricants contain additives that are sensitive to water, it is likely that additive depletion could have contributed to failures caused by water contamination, since depletion of additives would further deteriorate the lubricant performance. This is more likely to have been the case in failures where elevated water content could be detected for an extended period of time.

As described by Myshkin and Markova (2018), water in oil can exist in three different forms, dissolved, emulsified, and free water. The amount of water that can be dissolved in oil is described with its saturation level. The oil saturation level is dependant on the oil formulation, level of degradation, and temperature. As long as the water remains in its dissolved form, the more destructive emulsions and free water forms will be avoided. Lunt (2011) suggests that water content of 0,1% can reduce bearing lifetime by as much as 75%. This is somewhat contradictory since CIMAC (2011) means that it is commonly agreed that water concentration should be kept below 0,2% in marine engine applications. In the end, the acceptable limit will vary between different oil formulations and the level of oil degradation. While searching for information, no specifics on common ranges of saturation levels in marine lubricants could be found, and therefore the water content limit presented by CIMAC (2011) could not be confirmed to be acceptable.

According to the literature, there is no doubt that water is a destructive contaminant in engine lubricants. To reduce the occurrence of failures from water contamination, any water contamination must be detected and the source of contamination rectified in a timely manner. The methods used for detecting water contamination in the investigated failures included lubricant analyses, which were usually carried out every three months, and in addition to this, supplementary water-in-oil analyses carried out on board. The practice of carrying out on-board analyses was not widely implemented, but on vessels where such analyses were performed, this was done on a weekly, bi-weekly, or monthly basis.

Lubricant analyses, discussed in more detail in section 5.7, is a useful method to detect and provide information on engine issues and lubricant condition (CIMAC, 2011). In terms of water contamination detection, this method does come with a few drawbacks. First of all, analyses are not carried out frequently enough. In the investigated failures, it was found that a common interval for lubricant analysis was every three months. In certain cases, analyses were carried out even less frequently. Another factor to consider is the lag from sending a sample for analysis until the results are returned (Halme et al., 2010). For instance, in one case the crew did send an oil sample for analysis, probably as they did suspect a potential contamination. The results did not return until days after the failure was realized. Considering that the time from contamination to failure can be short, performing lubricant analyses a few times a year cannot be considered a reliable or even reasonable method for preventing failures from water contamination. Even if the level of contamination is low, it could potentially persist undetected for months until the next sample is sent for analysis. While the source of contamination most likely will be rectified as analysis results are returned, engine components might already have sustained damage from increased wear. For this very reason, it is probable that failures that were not identified to have been caused by water, were in fact caused by previous but unreported or undetected water contamination.

To reduce the risk of prolonged undetected water contamination, routines for frequent on-board analysis of water-in-oil concentration should be implemented. Preferably these should be carried out on a weekly basis. This will reduce the window of potential undetected water contamination from months to days. Another factor that is highly important in preventing these type of failures is to identify and rectify the source of contamination. This was in some situations, not the case. This was highlighted by the presence of water in the engine lubricating oil in concecutive analyses carried out months apart.

Another measure with the potential to have a significant impact on the frequency of water contamination failures is equipment for online condition monitoring. More specifically, sensors capable of detecting and monitoring the water-in-oil content in real-time. Such sensors will, if connected to the engine alarm system, alert the crew as soon as the water-in-oil content exceeds a preset limit. The adaption of online condition monitoring technology within the shipping industry lags behind other industries (Lunt, 2011). This could be considered accurate since the use of such technology was not once reported in any of the investigated failures. Myshkin and Markova (2018) describes the commercially available sensors for water-in-oil monitoring of lubricating oil. These are according to Myshkin and Markova (2018) exclusively of capacitative type. This type of sensor will only measure dissolved water content and could be considered limited in that respect. However, this might in fact be an advantage. Since the crew will be alerted before the oil is saturated with water, the risk of emulsions and free water formation will be reduced. The disadvantage with these types of sensors is that they must be calibrated specifically to the oil in use. As the oil degrades, the accuracy of the sensor decreases (Myshkin & Markova, 2018). Perhaps this is the reason why this type of sensor is not more widely used. Another type of sensor, also commercially available, utilizes infrared light to measure water contents up to 1% regardless of the form of water (Lunt, 2011; TRIBOMAR, n.d.). Another advantage to consider when using online sensors connected to the engine alarm system is that the crew would constantly be reminded of potential contamination as long as the alarm condition persists. This would likely have a higher chance of leading to a cause investigation of the contaminant source. In comparison, the results of an ordinary oil analysis would in the best case exist on paper. Even then, the risk of crew members missing out on vital information regarding their engine oil condition is high.

According to CIMAC (2011), certain engine manufacturers recommend the use of sensors for online monitoring of water-in-oil content. A valid question to ask is why such sensors are not more commonly installed by default on new engines. It might be worth considering what impact such sensors could have, not only on the rate of failures but also on engine maintenance requirements. Enabling operators to continuously monitor the water content by default would give them the ability to instantly detect and rectify any sources of water contamination. Thus, unknowingly operating the engines under conditions where increased wear can take place can be avoided. Provided the water content is monitored and kept at an acceptable level, the time between failure on engine bearings etc. would likely increase which could justify an increased interval between maintenance. The question is how this would impact engine manufacturers' revenue stream from maintenance services and spare parts sold, and if a small premium for installing such sensors by default could justify a potential decrease in revenue from aftermarket services.

## 5.7 Lubricating oil analysis

Lubricating oil analysis can according to CIMAC (2011) help in detecting issues with an engine and provide an overview of the lubricant condition. This was determined to be accurate after reviewing the oil analysis history of the investigated failures. In 39% of the failures, no oil analysis history was available. In 36% the oil analysis history showed no indication of engine or lubricant issues, whereas, in 25%, negative trends which did indicate engine or lubricant issues could be detected in analyses performed before the failures were reported. Excluding the failures where no data was available, failures, where negative trends could be detected, representing in total 41%. It is likely that this distribution of negative trends would be similar in failures where no data was available. This is a significant amount, considering that failures in many cases likely could have been prevented should the crew has acted on the results from their oil analysis.

While lubricant analyses in theory is an effective way of monitoring engine health and detecting potential issues, the act of performing oil analyses does not necessarily reduce the frequency of failures. There are several drawbacks with ordinary oil analyses, which in accordance with the results of this thesis, will have the potential of resulting in failure even when issues are detected in lubricant analyses. Lubricant analyses were commonly found to be carried out every three months, in certain cases, this was done even less frequently. This leaves a lot of room for undetected engine and lubricant issues. For instance, contamination that severely impacts the oil's lubricating properties might not be detected for months and in the meantime, situations with excessive wear could occur. Even if such issues are rectified after receiving the results from the next scheduled analysis, damages could already have been inflicted which may in time result in failure.

In order for lubricant analyses to reduce the frequency of failures, the warnings and recommendations provided must be acknowledged by the crew and acted upon. This was commonly found to not be the case. In many cases, situations where negative trends indicating potential issues could be identified in multiple analyses in sequence. In such cases, a negligent crew is likely to blame. However, another potential explanation for why recommendations are not acted upon and why issues are not immediately rectified once detected could be a lack in how analysis results are communicated on-board. From experience, oil analysis results are returned electronically, either via e-mail or by a web interface provided by the lab. This limits the availability of information to crew members with access to computers, and further to crew members on the lab e-mail recipient list or with access to their web interface. In reality, lubricant analysis results might only be accessible to one single crew member. While this is an important document that needs to be communicated on-board, there are likely other important matters going on simultaneously, and it is easy to see how communicating the results could mistakenly be omitted. In the best-case scenario, the results will exist on paper. Even then, vital information might be missed. For this very reason, measures to ensure that crew members have access to, and that they have taken part of the information, could potentially reduce the risk of engine or lubricant issues not being investigated. The risk of information being omitted is further increased during crew changes. This could be prevented by implementing routines for hand-overs that explicitly require lubricant analysis results to be communicated.

As discussed earlier, there is a lag from sending a sample for analysis until the results are returned (Halme et al., 2010). After identifying and rectifying a potential issue, the crew will likely want confirmation that the oil parameters have improved. Hence, a new sample will be sent for analysis. Likewise, the crew can send samples for analysis if they suspect oil contamination. Depending on the circumstances, engines could be put into operation in the meantime. Should there be any lubricant issues remaining, this might result in engines sustaining damage or even severe failure before the results are returned. This was as mentioned earlier the case in one severe failure. In certain cases, the crew had no routines for performing regular lubricant analyses. This was motivated by the oil being replaced frequently, and that this made oil analyses redundant. However, it is likely that engine issues could have been detected in these cases should oil analyses have been performed.

The adaption of emerging and existing technologies for online condition monitoring of lubricating oils could potentially reduce the frequency of lubrication failures. As discussed in section 5.6, viable options for real-time detection of water contamination exist and is commercially available. Besides water-in-oil, sensors for detection of oil condition, wear elements and viscosity is also available (Lunt, 2011). While sensors used for online oil condition monitoring will not be as accurate as an analysis performed in a lab, they will indicate any issues the moment they arise. Considering that a lack of maintenance was identified as the root cause in 39% of the failures, it is highly likely that many failures were preceded by a period of excessive wear. If equipment for wear debris detection would have been installed, it is possible that the crew would have been alerted of any abnormal wear situation. While the reason for neglecting maintenance remains unknown, it is probable that the reason could be attributed to crew negligence in many cases. It is hard to see how even a negligent crew would ignore an alarm that tells you that an engine is about to fail. As discussed earlier, one advantage of online monitoring equipment, provided that this is connected to the engine alarm system, is that the crew would instantly be alerted should any abnormal conditions arise. With ordinary lubricant analyses, such conditions may otherwise remain undetected for months. This enables the crew to swiftly perform cause investigations and implement measures to rectify any potential issues. Another advantage, with reference to communicating oil condition information discussed above, is that any alarms would remain as long as the alarm condition persists. In the future, online oil condition monitoring might be able to replace ordinary oil analysis. But in the meantime, they provide an excellent supplement to such analyses, with the potential to reduce the frequency of lubrication failures.

## 5.8 Oil degradation

In total 7 failures were determined to have been caused by lubrication deficiency. These include the failures discussed in section 5.5 and one additional failure which was determined to be caused by severely degraded oil. Within the entire lubricating system, sludge particles could be found. An example of these can be seen in figure 5.3. Apart from sludge, lacquers were present on engine component surfaces. These would flake off and get stuck in oil passages and filters. According to Stachowiak (2005), oil oxidation could cause the symptoms described above. In this particular case, the reason for oil oxidation could however not be established. According to Wright (2008), water contamination can accelerate oil oxidation and can enable microbial growth within the oil, which also causes the oil to oxidize. Previous oil analysis records did indicate previous contamination by seawater, which can explain why the oil was oxidized. However, elevated levels of vanadium could also be detected, which could indicate potential fuel contamination (SIGNUM, n.d.). Fuel contamination can according to CIMAC (2011) also cause lubricating oil to oxidize. Fuel contamination could in this case also explain the formation of sludge. If asphaltenes are present in the fuel, these may coagulate in contact with the lubricating oil to form sticky sludge deposits (Jao & Verhelst, 2013).

**Figure 5.3:** Sludge residue likely caused by oxidation or fuel contamination

*Note.* Sludge residues in the under-piston space. This type of residue was found throughout the entire engine and lubricating oil system. Published with permission from The Swedish Club.

There are plenty of examples in the investigated failures where the oil was either degraded or contaminated and thus, the lubricant ability to perform its functions reduced. Water contamination could be detected in 13% of the failures, fuel contamination in 5%, oil degradation 9% (including oxidation and changes in oil viscosity and BN), combustion products in 5%, and wear elements in 9%. The effects of water contamination is already discussed in section 5.6.

The importance of maintaining the engine lubricant condition cannot be emphasized enough. By monitoring the lubricant condition by oil analysis, any indications of oil degradation can be detected and actions to rectify issues resulting in degradation can be made. According to the findings of this thesis, keeping engines well-maintained will reduce the risk of oil contamination/degradation.

## 5.9 Latent defects

In total 6 failures, representing 7% of all failures with a known cause of failure was identified to have been caused by latent defects. Since no other cause could be identified, the only reasonable explanation in those failures were latent defects present in various engine components. Such defects could originate from the manufacturing process or the materials used for manufacturing. However, as previously mentioned in this discussion, it is possible that failures from latent defects were in fact caused by something different. This could for instance be previous water contamination that was fixed by the crew. If damages were sustained but did not immediately result in failure, it is easy to see how such detail could be missed during a damage survey and why a failure is determined to have been caused by a latent defect. It is also possible that damage sustained by mechanical means could cause a component to fail. For instance, one failure was determined to have been caused by a latent defect in a rubber compensating element that ruptured and resulted in a loss of lubricating oil pressure. The reason why the element ruptured may have been a latent defect, but could as well be the result of damage sustained for instance during assembly of said element.

## 5.10 Lubricating oil management

Data gathered from investigated failures show that in 38% of failures, poor lubricating oil management could be identified. In cases where poor lubricating oil management was identified, practices involving lubricating oil treatment, oil condition monitoring, and management of lubricants on-board were lacking. The latter is easily described with how contaminated oil was handled in a certain failure. After an ingress of bilge water into the engine sump, contaminated water was transferred to a storage tank where the crew attempted to drain most of the water from the oil. After instructions from their technical management ashore, the oil was returned to the engine and soon thereafter engine failure was a reality. Deciding to reuse contaminated oil, especially considering that it had already been removed from the engine, shows poor practices regarding how lubrication is managed on-board. In many failures, lubricant analyses had been showing poor values in consecutive analyses. This indicates that the crew did not act on the warnings and recommendations they were provided, which also indicates poor lubricating oil management practices.

Considering how frequent poor lubricating oil practices were, this could help explain why lubrication failures do occur. Where lubricating oil is well maintained and management practices are not lacking, failures likely do not occur as frequently. This theory is however difficult to test with the data that was available in this thesis. Such investigation would require additional data from vessels that did not suffer from engine failures claimed by their insurance policy. How well practices of managing lubricating oil could potentially be used as an indicator to determine the risk of future lubrication failures. By reviewing previous oil analysis results, it is easy to get an overview of how well the lubricants are maintained on-board a specific vessel. Should there be any issues with for instance engines or insufficient separation, this will become apparent when reviewing lubricant analysis results. From an insurer's perspective, it is possible that simply asking for such documentation on a regular basis could impact the lubricating oil management on-board insured vessels. Further, using this information when negotiating renewal premiums would likely have an even more significant impact.

## 5.11 Crew negligence

The majority of the failures investigated could to some extent be traced to have been caused by crew negligence. Whenever maintenance is not performed as it should, the crew can be blamed to have neglected their duties in performing maintenance.

The same applies in cases where oil analysis results indicated engine issues and the crew did not perform any action to investigate or rectify those issues. For the data collected about crew negligence to provide any value, certain requirements were defined to distinguish failures caused by "mild" negligence from failures where gross negligence could be identified. In failures where mild negligence could be identified, it was determined that symptoms of such negligence could as well be the result of a mistake or accident. In other words, there was no systematic negligence in performing maintenance or maintaining engine lubricating oil conditions. Therefore, those failures were not attributed to crew negligence in the results of this thesis. 38% of the failures investigated were however attributed to crew negligence. In those failures, systematic negligence could be identified.

In terms of maintenance, it is possible that the data recorded regarding crew negligence does not reflect reality. For instance, maintenance could be reported in the vessel's planned maintenance system without actually being performed. The act of forging evidence of maintenance being performed can definitely be regarded as crew negligence. The information regarding maintenance history was often retrieved directly from the vessel's planned maintenance system. Because of this, in certain cases where maintenance was reportedly done, it could in fact have been neglected. No detailed analysis could be done to identify the occurrence of this phenomenon with the data that was available.

Below are some examples of situations where crew negligence could be identified. In two failures, main engines were suffering from high exhaust gas temperatures. This was due to neglected maintenance which resulted in poor combustion. Despite prominent indications that the engines were in need of maintenance, the crew of both vessels decided to disregard this and continued to operate the engines. In case of elevated combustion temperatures, there is usually an engine safety system that slows down the engine (Harrington, 1992) to reduce load and consequently the combustion temperature. On one vessel, the engine was operated at reduced speed to deal with the elevated combustion temperatures, and in the other, alarm parameters were tampered with to allow for higher combustion temperatures without causing the engine to slow down. Common for both failures was that the engines were operated like this for a prolonged period of time. By continuing to operate the engines in this condition, the solutions enforced by the crew cannot in any way be considered to be temporary. With a temporary solution, maintenance should have been performed at the earliest possible opportunity. In these cases, there is no doubt that the crew had been negligent. Another example of negligence would be when engines are restarted multiple times after oil mist detector shutdowns, without performing any cause investigation.

Something else that might be worth considering in terms of crew negligence, is that there could be a lack of understanding for commercial and economic consequences from technical unavailability. Should the crew have a better understanding of the economic values that they are managing on-board, not only in terms of property values in engines and machinery but also in terms of commercial values i.e. the cost of downtime, it is possible that critical maintenance would not be neglected to the same extent. It is possible that by educating and informing crews on the commercial

values involved, certain risk behavior on-board could change.
This method was appropriate

## 5.12 Method discussion

The selection of method was a document analysis as described by Bowen (2009). Considering the number of failures investigated and the availability of existing documents that could be analyzed, this method was considered appropriate. Since the data about failures would be difficult to obtain in any other way, qualitative methods such as interviews and questionnaires was considered not to be suitable.

The documents analyzed were somewhat unbalanced, in certain cases, documents would contain a lot of use-able information whereas in other cases they would lack in detail or be non-existent. The variance in detail of damage survey reports can possibly be explained by the individual surveyors' level of particularity and experience. Other reasons may be discrepancies in insurance policy terms. Certain insurance terms cover a wider range of casualties, hence require less investigation to determine whether a claim is covered by insurance or not, whereas in other cases, detailed surveys are required to establish whether the casualty is covered or not. While the documents reviewed in many cases did provide a lot of insight, they may not necessarily have provided an accurate or complete picture of the event leading to a failure. For instance, the crew could for various reasons have withheld information that was key in understanding a certain sequence of events leading to failure. This could result in the investigator on site not being able to fully establish the cause of damage. In such cases, the content of the reports often had to be interpreted to provide meaning. How the content of documents is interpreted will directly impact the outcome. It is likely that the content could be interpreted differently if analyzed by someone with a different background. The author of this thesis is marine engineer by trade with several years of experience working on-board ships. This experience likely influenced the outcome, but was also helpful in understanding and interpreting the reviewed content. If this research would be reproduced by someone with a similar background, most probable the outcome would also be similar. This is important as it directly reflects the reliability of this research. In cases where the data undoubtedly points towards a certain cause of failure, with specific conditions present to confirm this, the failure could in fact have been caused by something entirely different, with the identified conditions only being a contributing factor. This would impact the validity of the data. Given the nature of the data and engine failures analyzed, reproducing the exact conditions to validate the causes of failures would be difficult, if not impossible. Likewise, finding additional information with the potential of changing the outcome of any given failure could be challenging, especially when considering that some failures occurred over ten years ago.

The use of a different technique for coding and categorizing data as well as the use of a different method would likely also have had an impact on the outcome. Other methods which could be used are for instance interviews and fault tree analysis. The issue with these methods is that they are time-consuming. While it is possible that such methods could result in a more detailed understanding of certain failures, restrictions in terms of time would require the data sample to be significantly reduced. Another problem would be the availability of data. It is unlikely that ship owners etc. would share or even possess more information than what was available in the documents related to each failure. Since the failures investigated occurred during an 11-year time period, the probability of vessels having changed owners, change of crew, etc. would further complicate the collection of data. Another aspect to consider is the sensitive nature of insurance claims, which would likely reduce the willingness of sharing information. By performing a document analysis the data sample could be increased. Considering that more failures could be included, a more accurate presentation of the causes of lubrication failure could be achieved.

# 6
# Conclusion

The majority of lubrication failures occur due to a lack of maintenance or as a consequence of previously performed maintenance. The most common causes of damage include contamination by water, faulty lubricating oil filters, and incorrectly performed maintenance procedures. The predominating cause of damage is contamination by water, representing 18% of the failures where a cause could be identified. In reality, this number could be higher as failures attributed to other causes could instead be the result of a previous, but unreported water contamination. There are two major factors which can describe why these type of failures are commonly occurring. First of all, water in lubricating oil is extremely destructive and can significantly accelerate the rate of wear in lubricated systems. Secondly, the methods used for detecting water-in-oil were identified to not be very well developed, and could in many cases allow for contamination to exist for prolonged periods without being detected. By implementing routines for weekly on-board analysis of water-in-oil content, the potential of undetected water contamination can be reduced from months to days.

The second most common cause of damage was identified to be faulty lubricating oil filters, representing in total 10,9% of all failures where a cause could be identified. This was the result of filters being incorrectly assembled, missing parts, or incorrect parts being installed during maintenance. Neglected maintenance or the use of poor condition filter parts were also major contributors resulting in failure from faulty lubricating oil filters. By ensuring the availability of filter spare parts on-board, the risk of poor condition or incorrect parts being reinstalled during maintenance can be reduced.

The third most common cause of damage was identified to be incorrectly performed maintenance procedures, representing in total 9,9% of all failures where a cause could be identified. By ensuring the availability of information on maintenance procedures, the frequency of this type of failure could potentially be reduced.

Ordinary oil analysis should always be carried out as these will provide information on potential engine or lubricant issues. If warnings and recommendations provided by the lubricant analysis results are acknowledged and acted upon, the risk of failure can be reduced. By implementing measures to ensure that analysis results are properly communicated on-board, the risk of any potential issues being left unattended will likely also be reduced. Installing online oil condition monitoring equipment can further help the crew to quickly detect potential engine or lubricant issues.

Poor lubricating oil management practices will in many cases become apparent when reviewing oil analysis history. This could be used as an indicator for detecting an increased risk of future lubrication failures.

The findings regarding preventive measures with the potential to reduce the frequency of lubricating oil failures is summarized below.

- Perform weekly water-in-oil analyses on-board.
- Perform ordinary lubricant analyses on a regular basis.
- Frequent oil renewal is not a substitute for lubricant analysis.
- Acknowledge warnings and act on recommendations provided from lubricant analysis results. Investigate potential sources of contamination and ensure these are rectified.
- Implement measures to ensure that lubricant analysis results are communicated to all relevant crew members.
- Consider installing online condition monitoring equipment, in particular equipment measuring water-in-oil content.
- Ensure availability and easy access to information on maintenance procedures.
- Implement measures to reduce the likelihood of contamination by particles/-foreign objects.
- Ensure availability of filter spare parts on-board.
- Perform regular checks of sump lubricating oil levels, especially after changing engine to be separated.
- Consider installing low-level alarms or level sensors on engine sump tanks.
- Ensure sufficient preheating of oil in separators.
- Perform maintenance according to the engine or equipment manufacturers' recommendations.

While a frequent replacement of engine lubricating oil may reduce the requirement of lubricating oil treatment, it cannot be considered a substitute for regularly performing lubricant analyses.

# 7
# Suggestions for future research

In this thesis, it became apparent that failures often occur due to a lack of maintenance. What still remains unknown, is why maintenance is neglected. An interesting topic for future research would be to investigate the underlying factors of why maintenance is neglected. Another area identified within this thesis in terms of maintenance that could be interesting for future research, is why maintenance procedures are so commonly incorrectly executed, and what can be done to increase the chances of successful maintenance.

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