The Environmental Effect on Condition Based Monitoring of Cylinder Liners by Machine Learning & Oil Analysis

Ph.D. Dissertation

Graduate School of Environment and Information Sciences

Yokohama National University

By

FAMAKINWA OTITONIYI AYO

17TF903

Supervisor
Professor TADAHIRO SHIBUTANI

2022

Acknowledgment

I would like to use this platform to express my appreciation to my supervisor Associate Professor Shibutani Tadahiro for his tireless effort in supervising this project. His outstanding prows on building discussion on progress and contributing his knowledge approach for research.

To my colleagues at Shibutani lab who are there to listen and ask questions on this despite project despite lack of knowledge about my work, I appreciate all their efforts and support. Most importantly my gratitude to Mr. RYOMA AIHARA for accepting the invitation to work together on this project. He worked with XRF equipment, results from compilation, and algorithms for machine learning on data results. Thank you so much for your patience and good attitude despite our difficult circumstances in handling this project. Please keep up your good work and precious attitude you will surely reap the rewards in your career. May the creator Jehovah bless your effort and steps.

To my workmates at SIGMA SHOJI CO. LTD, your supports and encouragement are undeniable during the period on this project. During my absence from work, you extend hands to fill the void the keep the work functioning despite my absence at work. My manager Mr. Takashi Kawahara thanks so much for your understanding giving me chance to take a day off for this project and permission to use work-related customer service information. Without your affection, attitude and support this project will not begin and be accomplished to write this dissertation for the benefit of marine engine maintenance management. Those whose names were not mentioned please accept my

sincere gratitude for your support. Let us keep working as a family that will benefit society in general.

My family without them I'm lifeless and brainless to accomplish my project. To begin wife Opeyemi Omolere, parents, elder brothers, elder sisters, relatives, and friends ESE PUPO-PUPO for asking about the progress of my project every day. Please continue to remember us in your prayers and we share the same success.

Finally, the creator of everything JEHOVAH, the source of wisdom, knowledge, and prowess that give mankind to keep building the society for better living. Thanks for giving me life to this peak of my career and I acknowledge your greatest loving kindness in my life from the infant. I will continue to hold on to this scripture "*Taste and see that Jehovah is good; Happy is the man who takes refuge in him*" Psalm 34:8.

Table Contents

Abstract

Risk management of cylinder liner mechanical failure of the slow speed of 2-stroke marine needs regular maintenance procedures to maintain the engine in service for a longer duration. Traditional maintenance procedures for this type of engine are the time-based or total engine running hour methods. A new maintenance procedure is needed because the number of engine failures continues to climb within the marine industry for only reported incidents and there are unreported cases. Introduction of Condition Based Maintenance will alleviate maintenance decisions because of in-situ monitoring of equipment. It leads to early detection and diagnosis of equipment reducing unexpected downtime of the engine.

This dissertation will improve the application of Condition Based Maintenance considering the environmental effect on monitoring of marine slow speed 2-stroke engine. The environmental effect is used in my dissertation refer to monitor ships sailing at different Oceans and studying how it affects the durability of cylinder liners and piston rings of the main engine. The route selected is the Northern Pacific Ocean and Southern Pacific Ocean and a total of 4 ships was monitored for my project. We have 2 ships for the Northern Pacific Ocean and another 2 ships for the Southern Pacific Ocean. All ships

started sailing from Japanese ports to US ports and Oceania ports. We investigated how different sailing environments affect the wear pattern of cylinder liners and piston rings. The result shows that ships sailing to Oceania ports generate more metallic debris than ships voyaging to the US.

Gaussian Graphical model was used on wear elements in the drain oil sample, by an algorithm of machine learning the pattern of wear was closely monitored and this makes it possible to anomaly rate engines reliability. In this paper, we extend the Gaussian Graphical model to include rating that makes maintenance decisions shorter to flagged abnormal engine conditions.

The application of the proposed model is based on the cylinder liner and piston rings dataset from drain cylinder lubricating oil analysis. The data from the drain cylinder oil sample correlate wear elements by using a machine learning algorithm and rate all ships cylinder liners anomaly for the operational assessment.

The physical measurement of cylinder liner wear rate was calculated and based on XRF results we were able to estimate the wear rate using iron particles found in the drain oil samples. Our methodology contributed to improving condition-based monitoring of cylinder liners using these tools for equipment maintenance management.

Chapter 1

Introduction

All moving or rotating equipment do experience failure mode during operation. Equipment manufacturers give an outline of maintenance procedures and troubleshooting methods to keep the machinery alive for its purpose. To date, marine engine maintenance practice is calendar base or total engine running hours. Time-based maintenance is mostly associated with moving equipment in machinery, involving metal-to-metal contact that generates wear materials over some hours of operation. Periodic-based maintenance involves months of active operation regardless of the total time in active operation and conditions of the equipment.

As the machinery accumulates running hours, time-based maintenance will be idea maintenance best practices on ships. However, the disadvantage of this practice is a steady increase of mechanical failure, and recovery duration may last longer. When this scenario occurred, it results in economic loss from operational downtime. The marine engine of a 2-stroke large bore cylinder is complex in design involving several components that are manufactured by different companies.

The research reported in this thesis considers the benefits of condition monitoring of slow-speed 2-stroke engines. Condition monitoring offers improvements that include Ocean environment on cylinder liner over traditional time and cycle-based maintenance methods. Strategy maintenance can significantly reduce maintenance costs and prolong the life of machinery. Condition monitoring aims to take maintenance to extra steps by allowing fault detection early before deterioration stages. In this study drain, oil samples were utilized because it is contaminated with metallic elements due to wear elements.

Global commerce largely depends on slow speed 2-stroke Diesel engines whether they powerboats, trains, bulk items can be transported via Ocean due to engine capabilities and cheapest logistics method. The necessary technology and mindset of modern business require that the business can operate equipment suitably and be protected against blackout. When called upon, a ship must keep sailing and ready to take load because businesses and lives depend on it.

Under economic pressure, maintenance expenditure is likely to be leaned because of the maintenance budget during a financial crisis. The effect will increase the risk of engine failure and an unplanned long period of downtime. With condition-based monitoring of engine maintenance, it is more beneficial when a specific component is monitored. The merits are not limited to costs reduction alone engine downtime and improve safety on equipment operation. Condition monitoring in this thesis aims to consider the side effect of sailing surrounding as the environmental effect on internal combustion components that are piston rings and cylinder liners.

1.1 Research Background and Motivation

Condition monitoring of internal combustion for a 2-stroke slow-speed diesel engine requires regular or periodic inspection and overhauling of cylinder liners, piston rings, sealing materials, and lubrication valves. The current maintenance methods do have their shortcoming on equipment monitoring, for merchant ships using a 2-stroke engine face challenges in maintaining the engine when operated in a high-risk environment. To maintain engine cylinder liners manpower is involved to solve faults with the cylinder liner. When a human error occurs it can be costly, deadly, and it can take a long period to restore the equipment. I have read and seen reports of catastrophic events unfold like a chain reaction from malfunctioning equipment, either at industrial sites or diesel engines malfunctioning. Though running condition monitoring may be seen as time-consuming, and less useful for maintenance costs cut to attain budget target levels. But in a financial turbulent for the company, it is likely the maintenance expenditures will be constrained by tight budgets. As a result, the cost and time on equipment inspections will decline to reflect on a lean budget. However, maintenance carried out correctly on time and properly will afford optimization and safe running of the engine. A minor failure can reduce the remaining useful life of machinery there by escalating to secondary or more serious faults that have the potential to cause serious financial loss due to unplanned downtime, or worse, injury or death. Given the large investments on ships from parties involved the best interest is to avoid unplanned losses of these machines. The early detection and diagnosis of wear are essential, as the maintenance engineer can schedule the maintenance and potential downtime. Machinery failure has been responsible for the loss of life and an impact upon the environment both on minor and large scales and could have been prevented by better monitoring practice.

In the advancement of condition-based monitoring applications, technical know-how and scope on condition monitoring will alleviate machine learning on equipment capabilities, durability, and productiveness. The experience acquires through the study of environmental effects on equipment internal combustion cannot be disregarded. This research is beneficial to the marine engine only but beam light to the core of equipment monitoring that operates in different ambient environment.

More also, the marine industry has been stepping up on their environmental conscience for the planet. As for Carbon, Nitrogen, and Sulfur emission from the combustion of fuel oil from ships, by strict regulations and port authority's laws, the marine ship is cutting down their Green House Gas (GHG) emission. The new regulations are not favorable to existing ships making use of an old design that has a high risk of engine failure and it is a huge economic lost impact when the main engine failure occurs.

Condition-based monitoring of cylinder liner and piston rings are more important than ever as new regulations and laws are established, while old engine on ship faces enormous challenges to sail afloat amid laws and regulations to protect the environment.

1.2. Condition Based Monitoring

Condition-based monitoring is the platform of maintenance engineering, by extracting information concerning the target system from a healthy standpoint, and based on this information they need for maintenance can be decided. The purpose is to detect anomalies at onset and follow up on patterns of faults in anticipation of failures or possible breakdowns. Maintenance can be scheduled just in time to prevent the economic loss, and in doing so operation can be optimized. Condition-based monitoring methodology seems pretty advancing compared to the other concepts of maintenance. It is an extension of service engineering on the engine, acquiring more information about the engine condition using their data to improve maintenance decisions. Human judgment can remain, but advanced condition-based monitoring tools will accurately implement maintenance on the engine.

Not all failures can be detected before occurrence by monitoring alone nor prevented because the human error does affect the utilization of condition-based monitoring. There is signal or anomaly data from equipment before failures occur without any warning to the systems. It is a type of failure when noticeable necessary procedures can ensue to prevent major mechanical failures. Condition-based monitoring applications can mitigate such incidents and ultimately prevent major mechanical failure. Detection of faults by condition-based monitoring can be done in two different ways, trend monitoring and condition checking (Yan Liu et. 2000). Trend monitoring is when close observation of data by their trend or characters from equipment before failure while condition checking can be done if the failure of the system is quite predictable and sufficient data has already been achieved from the equipment. The most important aspect in applying condition-based monitoring is in retrospect to the predictable maintenance concept for the engine. When faults or symptoms are identified, a proper condition-based monitoring model can be utilized to identify the origin of faulty. A model consists of several condition measurement techniques which all must be applied in the right manner to be able to identify known possible symptoms.

The other major advantage of condition monitoring knows the exact condition of cylinder liner and piston rings. For example, a manufacturer may recommend replacing a part every 1000 running hours. Condition monitoring gives maintenance decisions on knowledge of the current situation whether replacement is urgent and access failure risk of the cylinder liner. There have been rapid advances in condition monitoring techniques to improve the maintenance of 2-stroke diesel engines. Engines such as this type of progress through their lifetime and follow regular manufacturer prescribed maintenance schedules. A traditionally run slow speed 2-stroke diesel engine and its components also tend to follow the `*Bathtub Curve*', a general example of the failure rate of components throughout their lifetime.

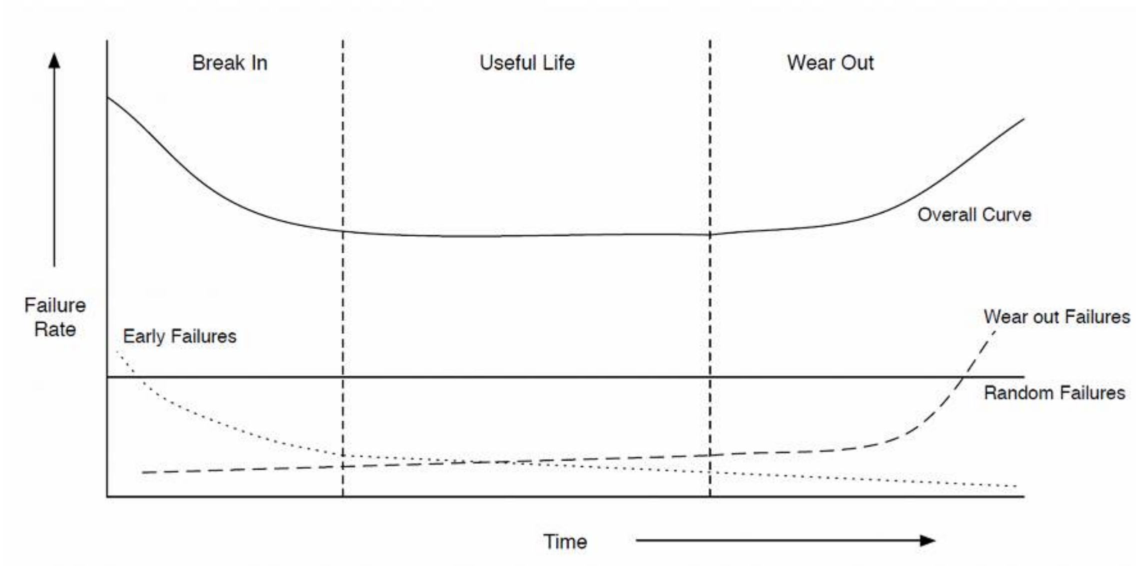


Figure 1 Equipment life cycle represented by Bathtub Curve

In bathtub Curves the early portion of the curve demonstrates the `early mortality' of equipment, it failed sooner than it was designed, the middle section shows the useful life of the component where the failure rate within this section is essentially random but at a constant rate. While the third section shows the wear-out of the component and the failure rate is increased within this portion (Andrew et al. 2006). The figure of Bathtub Curves depicts the life cycle of the equipment. This research focuses on a slow-speed 2-stroke diesel engine that is only powering large merchant ships. Condition monitoring is important for this engine, as they do not follow the manufacturer-recommended time-based schedule for maintenance.

The current level of monitoring technology is still in its relative infancy as the prediction of faults from the relatively low-level signals produced from a very early underlying incipient fault is still relatively hard (G. O. Chandroth et al.).

Regarding these techniques, the rest of the chapters that follow will be about the different types, their applications, and case study. The subject ships will be discussed universally because is the focus and our techniques discussed are seldomly applied in the field of condition-based monitoring engineering. After a general explanation at the beginning of each chapter, the subsections explain the specific subject relating to the main title and discussed it in detail.

However, cylinder oil samples collected from subject ships for the condition-based monitoring have a time lag at time sampling and oil analysis. It is not real-time sampling to analyze for cylinder liner condition-based monitoring. Another challenge is that no GPS data available, ocean conditions, and weather conditions were not included in the data shared for this case study cylinder liner monitoring.

1.3. Condition Based Monitoring Oil Analysis

Condition-based monitoring using oil from the equipment, and a brief overview of steps of condition monitoring techniques. Some of these techniques are used in industry to monitor machinery health and the result is used for maintenance decisions.

A sample of oil is taken from the used oil tank or drain pipe for oil analysis provides a hint of wear occurring within metal-to-metal parts via the type of debris contained within it. The test ranges from simple to a comprehensive analysis of oil where a standard oil analysis will be compared with the used oil sample result. Examples of tests on used oil amount of wear metals, additives level, viscosity, base number, and density (N. k. Myshkin et. al. 2003). For wear metals like Iron which is the majority composition of cylinder liner materials and Chromium would be associated with the piston rings. Also elevated Copper in oil samples is usually a sign of bearing and bushing wear. Thus, spectral analysis by X-ray fluorescence can very accurately indicate the metals or minerals contained within oil, as this will not give a 100% indication of where the issue lies only a good idea of where to look (Sherman J 1955, 1959).

Viscosity will determine oil grade and whether its chemical structure has been altered during the combustion reaction. It is measured when a reference temperature of 40°C in the unit is mm^2/s. because it is a measurement of how long it takes the oil to flow through a standard. The viscosity test is not going to tell you exactly what is wrong with the engine, it will indicate potential issues. For example, a decrease in viscosity would potentially indicate solvents ingress by fuel while an increase in viscosity would indicate water, soot, or antifreeze contamination (Yan Liu et al 2000).

Insoluble is among analysis on oil sample is the amount of insoluble material present in the oil. By centrifugal test, the oil sample is mixed with a heated agent and spun in a centrifuge. The insoluble materials gather at the bottom of the test tube and can then be identified and quantified. The insoluble test is a good indication of how quickly the oil is oxidizing, contaminants, and how well the engine's filtration system is working. It can provide some indications that something may be wrong with the engine. A bad test result is not an ample indicator of an issue, but several in a row would be a cause for concern.

Flash Point is the lowest temperature at which the oil will flash, at vapor state to ignite when exposed to a naked flame. A change in the flashpoint compared to the fresh oil flash point shows the presence of contaminants. Flashpoint testing is an indication as to whether there is any fuel or solvent contamination. Used oil sample flash point can indicate combustion reaction situation of fuel during combustion phase.

Total Base Number (TBN) for oil sample ranges from 15-100mgKOH/g and is analyzed by Potentiometric Determination (Test method: ASTM D4739). This method makes use of solvent and weaker titrant than the fresh oil version. The sample is dissolved in a solvent mixture and then titrated with standardized HCl acid. A voltmeter/potentiometer detects a change in the potential of an electrode which will display milligrams of potassium hydroxide per gram (mgKOH/g). More test on oil sample in comprehensive is as follow in the below table 1

Table 1 Comprehensive Analysis of Oil Sample

Test	Basic Relevance
Appearance	Presence of contamination
Color	Potential oxidation
Total Acid Number	Acidity of oil, oxidation
Total Base Number	Alkalinity of oil, depletion of additives
Viscosity	Breakdown of oil protective capability
Wear Metals	Wearing of machinery
Additive elements	Depletion of additives
Water content	Ingress of fresh or saltwater, production of emulsions
Particle Count	Ingress contaminant
Particle Quantifier Index (PQI)	Presence of ferrous magnetic particles
Flashpoint	Presence of fuel
Insolubles	Presence of contamination, filter issue
Soot and Dispersancy	Combustion by-products
Oxidation	Oxidation of oil, high temperature, increased acidity
Nitration	Nitration of oil, increased acidity
Wear Debris analysis	Presence and type of particles

Oil analysis can be classified as dynamic methods for condition-based monitoring of the internal combustion of an engine. When samples are drawn for testing while the equipment is either running or not operational. Drain oil sampling is characterized by constant changes in state or conditions for the engine. In embedded analysis use of the online and in-line sampling method is advancing lubricating oil sampling. The drain oil is analyzed when passing between the lubricant pump from scavenging space to analyzing points (Eid S Mohamed et al 2018). In an off-line analysis of the common practice on monitoring of an engine, the drain oil sample is drawn out from the machine and analyzed in the laboratory. For best practice on maintenance decisions, the integrity of the lubricant sample, which is a legitimate representative, must be guaranteed.

The suitability of different sampling types may be adopted depending on different conditions of the cylinder liner. Proper methods and frequency of drain oil sampling are essential for the integrity and representation of condition-based monitoring of cylinder liners. The drain oil sampling and monitoring using online monitoring, common sensor detection methods are challenging due to the environment of operation. Wear characteristics such as debris concentration could be detected using X-ray, while debris size could not be estimated by X-ray. There are other physical features to be considered on drain oil samples such as physiochemical properties, water contamination, and soot contamination, and in addition machine learning on used oil samples, data will improve the dynamic of condition-based monitoring using oil analysis data for maintenance decisions.

1.4 2-Stroke Slow Speed Marine Diesel Engines

The Diesel engine is the most widely used engine due to its durability and ruggedness. The engine is vastly in a different form of mobility such as in commercial vehicles, vans, trucks, power plant machinery, and ships from small size to large size. Large Diesel engines are also used to powerboats and container ships both for propulsion and for electrical power. Diesel engine system mode is a compress-ignition method as they do not require spark ignition like their petrol counterparts. Diesel engines run by controlling the air dynamic in and out of the engine and by regulating the fuel injection. When the parameters sequences are working correctly by compression the ignition will occur. There are other merits of diesel engines for example at higher compression ratios the initial compression timing is only air mixtures. Diesel engines are very complex and intricate engines, with many systems and subsystems coming together to produce power. The engine theory is based mainly upon thermodynamic cycles known as the *otto cycle*, it continues to be a fundamental design for diesel engines till date (Oihane C et al 2015). However, the cycle is ideal and does represent the actual cycles that occur in the engine itself. The research and development on this engine continue to upgrade the engine system information on what is going on inside during the combustion of fuel. To understand the health of a diesel engine it is important to take a deep look at the cycles of operation.

For every internal combustion engine make use of a crankshaft. This crankshaft transmits the power or energy of piston movement in the cylinder of an engine. As the crankshaft rotates the components attach to its ends move the gear train and then to the ship stern, which propels the ship to sail. As the piston moves from top to bottom, the air valve opens and closes simultaneously which makes it possible to supply atomized fuel for combustion. In essence, all engine operations are related to the crank angle of movable components. This thesis focus on slow speed 2-stroke diesel engine that is commonly mounted large ship transporting goods in bulk quantity.

A 2-stroke engine is used in large ship engines because of economic benefit on maintenance and cost-effectiveness for transportation of bulk goods. In complete combustion when the crankshaft completes a revolution 360° . However, the weakness of the 2-stroke is that it is not as efficient as the four-stroke in comparison because of the exhaust mechanism, air induction process, and poor scavenging. In four-stroke cycle does not use scavenge due to its dedicated inlet and outlet mechanism. The following is a 2-stroke engine operation sequence are power stroke, blowdown, scavenge, and compression (Doug Woodyard 2004).

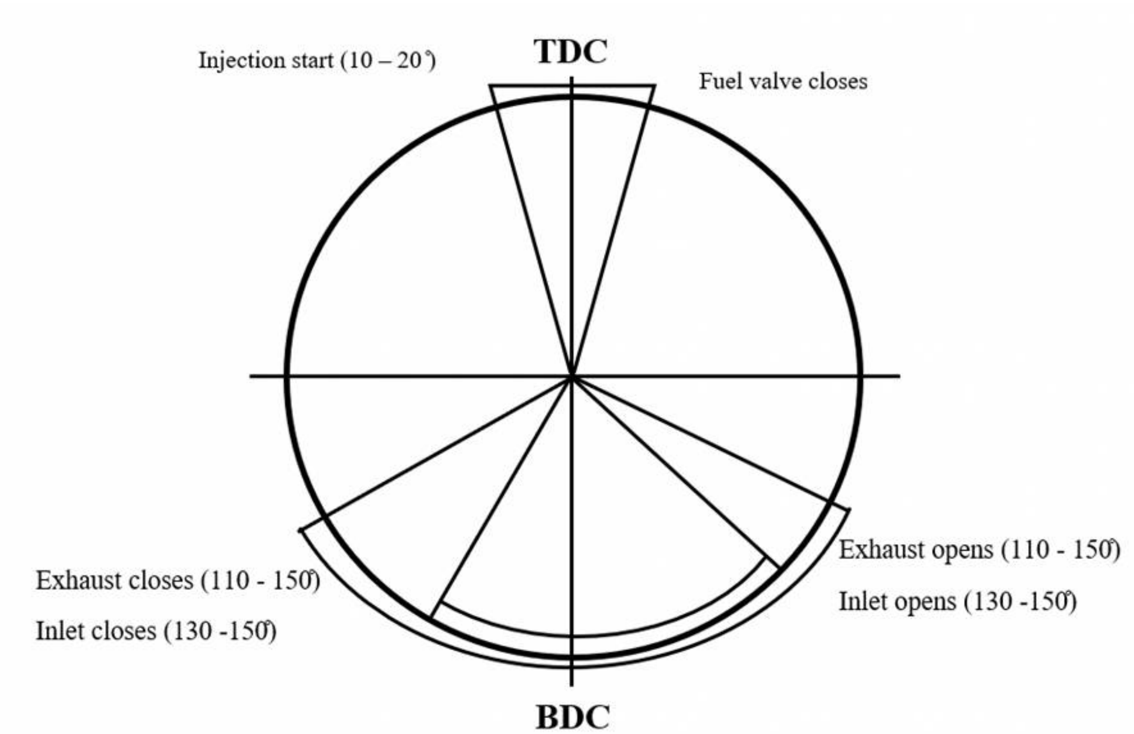


Figure 1 A complete cycle for 2-Stroke engine

Figure 1 represents the sequence of events in a two-stroke cycle for an engine, the Top Dead Center (TDC) combustion commence and the exhaust open at 110° ～120° At Top Dead Center (ATDC) to elevate rapid blow-down before the gas inlet open 130° ～ 150° ATDC. The exhaust gases move at the speed of sound to allow the incoming air to flow quickly through the cylinder with a small mixture. The exhaust valve will close to allow air compression stroke to maximize the air charge into the cylinder for the next stroke of combustion. The engine is designed to be in the opposing position of each piston when a piston is at the ATDC the other will be Bottom Top Dead Center (BTDC) repeating all the phases of ATDC.

The diesel engine type for this project is a long-stroke design and large bore size ranging from 500mm above and this improves stroke-bore that effective power ratings that correspond to mean effective pressure. Figure 2 shows the cross-sectional drawing of a slow-speed 2-stroke diesel engine (Pevzner 1998).

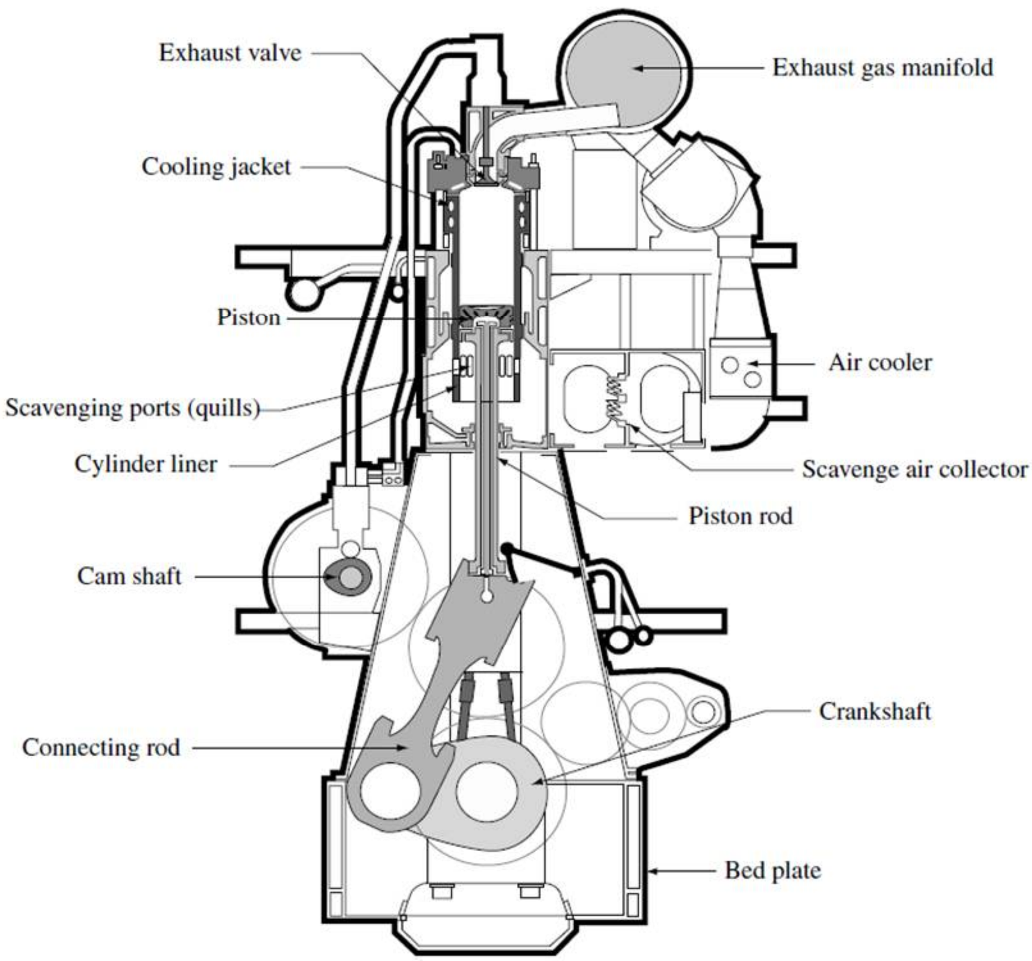


Figure 2 Cross-section drawing of low-speed 2-stroke crosshead marine engine (Lubr. Eng., 54, 16-21 Pevzner 1998a)

A diesel engine system is designed with occurring events that are heavily predetermined at every motion. This motion is related to crank angle and data can be taken from a running engine for condition monitoring and engine prognostic. Since the engine is enormous the crank angle understanding is important in prognostic and maintenance. For example, in a situation where earlier or late injection of fuel will affect the rise of pressure within the cylinder and the crank angle at combustion event will intensify the combustion. A poorly seated valve and a variation in the crank angle at which they open and close will also have an impact on the combustion. The knowledge about crank angles has advanced in aligning the crank angle (Eid S Mohamed 2018). However, knowing the crank angle of a healthy data set will hinder condition-based monitoring of engine combustion which is the primary noise generation mechanism within an engine.

1.5 Research Ship Description

The ships used for this thesis are Pure Car & Truck Carriers (PCTC) and all ships are built at Nagasaki Shipbuilding designed by Mitsubishi Heavy Industries. Table 2 represents the external particular of the ships for this project as follows.

Table 2 Particular design of Ships

	AV1, 2	OV5, 6
Ship classification	Nippon kaiji (NK)	Nippon kaiji (NK)
Overall length (m)	199.99	199.99
Breadth (m)	32.26	32.26
Depth (m)	22.03	22.03
Full load draft (m)	7.3	9.02
Car capacity	6,000	6,000
Dead-weight capacity (t)	13,336	14,906
Gross tonnage	52,863	60,414
Ship speed (kt)	20.0	20.5

1.6 Limitations of this study

This study seeks to evaluate the effect of the environment on the marine slow-speed engine. A ship that departs from a port to another faces different kinds of weather conditions that may circumnavigation or maneuver to avoid harsh weather. Condition-based monitoring of cylinder liner steps also requires actions to protect and elongate the remaining useful life of the equipment. Our intention is a new approach for condition-based monitoring that will include the environmental effect on maintenance decisions for marine slow-speed engines on a ship.

However, the study has limitations on environmental data such as weather conditions, ocean conditions, and in-let air molecules. The environment effect used for the title is based on the sailing route of the ship. In the study, North Pacific Ocean ships sail only between Japan ports and American ports, while South Pacific Ocean ships sail only between Japan ports and Australia, New Zealand ports. Considering the geographical locations of destination ports environmental effects were used for the thesis title.

More also, data accumulated is limited to 4 ships, and the period of sampling is insufficient to build a dataset for machine learning. This does not invalidate the work done with limited ships and cylinder lubricating oil sampling. And for machine learning, there is no limit to a large dataset, though the study data is limited the method is valid and verified.

The intent is to apply proposed condition-based monitoring on the marine slow-speed diesel engine of the subject ships. This was challenging because non-agreement with the managing company and our input on maintenance decisions are not accepted. Our proposed condition-based monitoring when adopted could prevent mechanical failure and extend the remaining useful life of the cylinder liner during operation.

These should be addressed in the next future work on this project for the benefit of marine slow-speed diesel engines.

2. Lubricating Oil and Equipment
    - 2.1 Cylinder Oil and Characteristics
    - 2.2 System Oil
    - 2.3 Composition and Properties of lubricating oil
        - 2.3.1 Oil Additives
    - 2.4 Lubricant Oils Analysis
        - 2.4.1 Cylinder Drain Oil Analysis
    - 2.5 Cylinder Liner
        - 2.5.1 Cylinder Liner Materials
        - 2.5.2 Cylinder Liner Insulation
    - 2.6. Piston Rings
        - 2.6.1 Piston Ring Materials
        - 2.6.2 Rings Coating
    - 2.7. Wear

Chapter 2

Lubricating Oil

Low-speed 2-stroke crosshead design diesel engines are large and energy-efficient in operation. The engine output speed ranges from 90 to 250 rpm. This engine makes use of a diaphragm and stuffing box to separate the cylinder and crankcase, it allows each component to be lubricated separately. The bore sizes range from 300mm to 600mm, and the strokes are over 3 m. The piston speed is top 7 to 8 m/s, and the power output for the largest engines is over 65,000 kW. This engine is mostly used in a ship for logistics of bulks item and passenger liners for vacation.

The engine cylinder liner was designed to separate from the crankcase. This makes it possible for the engine to use different lubricants for cylinder liners and another type for the crankshaft system separately. The benefit is that this special environment makes it possible to maintain each cylinder without adversely affecting other components. This design's main reason is that marine fuels contain easily dissociate acidic atoms after combustion, removing the products from an engine is the best approach to prevent corrosion and corrosion-assisted fatigue and wear.

For continuous operation of the engine that produces enormous power and is complex in design as briefly explained above, this whole section will focus on cylinder liners lubricant and its monitoring advantages.

2.1 Cylinder Lubricating Oil

Cylinder lubricating oil will be effective for cylinder liner when oil can create a tenacious and constant film on the cylinder walls to protect it from wear and make a seal prevent gases from leaking between the piston rings. The cylinder oil needs to be thick enough and at a high temperature must be thin enough to spread evenly over the whole cylinder liner surface. The viscosity must be within the right range to achieve this function. The deficiency of this function will waste cylinder oil, high power losses due to friction, excessive wear between the rings and the cylinder liner, and engine leakage. The grade ranges from SAE 50 to 60, and the alkalinity Base Number is 70 for neutralization of acidic products. These are the basic roles of cylinder oil for low-speed 2-stroke diesel engines.

Cooling system: There are refrigerating systems that can reduce the temperature of fuel oil after heating and other equipment that need temperature control. But engine temperature cannot be cooled by the refrigerating system. Engine components that are directly or indirectly involved in heat energy such as piston heads, cylinders, valves, and other inner parts of the engine like the bearings, the crankshaft, connecting rods, gears, etc. are cooled by the circulating cylinder oil and system oil for the crankshaft.

Cleaning: Cylinder lubricating oil has a role in cleansing carbon particles, soot, and other combustion residues. These residues blend with oil and are removed by scrap down every time the oil is supplied. There is a situation when more residues are accumulated than fresh oil, which could cause potential engine failure. Cylinder lubricating oil must be able to clean the cylinder wall as the piston moves from top dead center to bottom dead center and if it remained clean it would mean that is doing its role right. It contains additives like detergents and dispersants which are responsible for keeping clean the engine cylinder wall by uplifting contaminants and residues in suspension and preventing its sedimentation in vital parts of the engine. Combustion residue always exists in an internal combustion engine despite cleansing, detergents, and dispersants functions a cylinder lubricating oil may have and without the engine wear and tear of the engine, components will be rampant.

Sealing: For piston rings, surfaces and cylinder liner walls cannot completely seal when in close contact due to their polished surface. When pressure is reduced during the compression phase of combustion, this will lower the engine output and be less efficient in operation. The cylinder lube oil will seal the gaps at the peaks and valleys of the ring-cylinder wall. On the other hand, the cylinder oil would never be able to prevent a high amount of wear between rings and liners wall in too close contact as the film is not that thick especially new or overhauled engine. It is recommended to initially operate an engine on *running in* that is increase the cylinder lubricating oil feed rate till engine manufacturer recommended operating hours of operation.

Corrosion Prevention: Cylinder lubricating oil must have a chemical film that can settle on the surfaces of the cylinder liner that protect it from corrosion. Also, oil additives protect the surfaces from acidic corrosion that is created by the combustion of fuel oil. Contamination by saltwater can galvanize corrosion of the tin, forming a black oxide layer. This layer will cause interference between the bearing and the journal, and can also flake off, resulting in a wear scenario. Preventing metals from seawater contamination is only possible by a protective film of cylinder lubricating oil.

Wear prevention: The sliding friction between the rings and the liner must be at the minimum, supporting minimal metal-to-metal contact and frictional wear. According to the American Society Testing Materials (ASTM), definition wear is damage to a solid surface that involves progressive loss of material and is due to relative motion between the surface and a contacting surface or substances. It must contain dispersants, detergents, and other additives, which are used to suspend oil-insoluble resin oxides products and particularly contaminants from heavy fuel oil. It must minimize sludges formation, particulate-related to abrasive wear, increase viscosity, and oxidation related to deposit formation. It must keep sufficient viscosity at high temperature and still be able to sufficiently spread over the entire surface of cylinder liner and form oil film to adsorb particles. The inclusion of additives like polymethacrylates and ethylene-propylene are co-polymers helps to maintain the prerequisite oil film thickness. It must create an effective seal in between the cylinder liner wall and the piston rings, preventing gas blowing by and burning of oil film when lacking compression. It must combust cleanly leaving as little or soft deposit as possible and building up of deposit in ring's housing. It must be able to neutralize the effect of corrosive sulfuric acid formed during the combustion of heavy fuel oil (Y. Iwai et al 2010).

These are cylinder lubricant oil must have qualities for 2-stroke slow-speed marine diesel engine as follows:

- Reduction of sliding friction between the rings and the cylinder liner to the minimum. It will minimize metal-to-metal contact that caused frictional wear. Wear damaged the solid surface of the liner and generally involves loss of materials. Dispersants, detergents, and additives are added to cylinder oil. The additives are used to suspend oil-insoluble resinous oxidation products and particulate contaminants from fuel oil. It also minimizes sludge formation, abrasive wear, increase viscosity, and oxidation-related deposit formation.

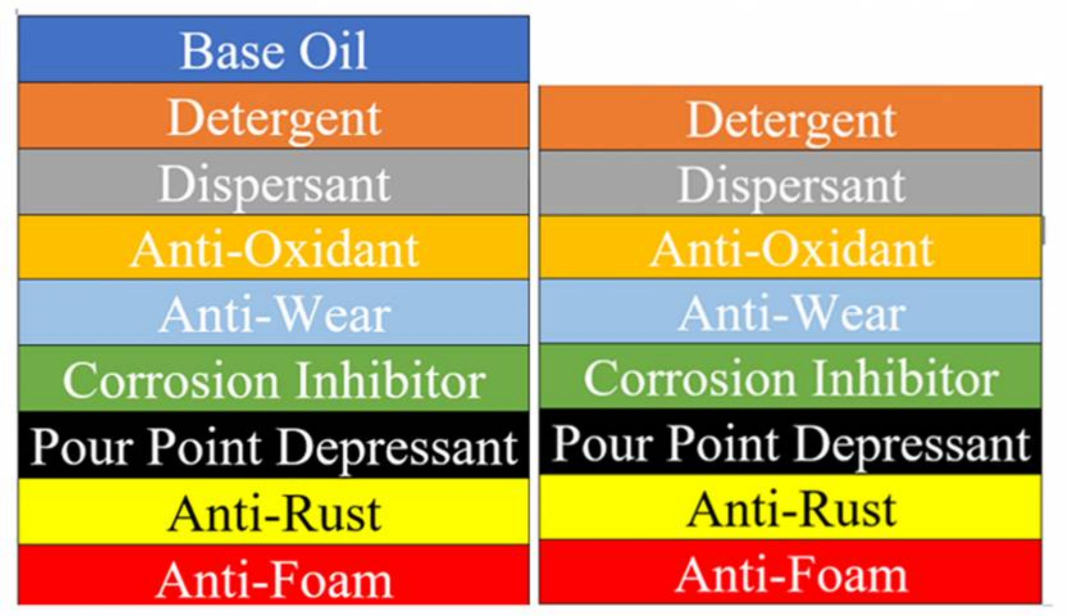
- Cylinder oil must have adequate viscosity at high operating temperature, and it must be sufficiently fluid to spread over the entire working surface of the cylinder liner by forming adsorbed oil films. Multi-level lubricating systems increase lubricating oil film thickness. The additives such as polymethacrylates and ethylene-propylene co-polymers help in maintaining oil film thickness due to the molecular bonding with porous cylinder liner.
- The oil must form an effective seal between piston rings and cylinder liner. It will prevent gas "blowing-by", burning away of the oil film, and lack of compression. It must burn cleanly without a deposit and clear soot produced. Also, effective in preventing the building up of deposits in the piston rings and exhaust gas ports.
- Neutralization of corrosive acid formed during combustion of the fuel oil. This effect can be minimized by alkali in cylinder oil with enough base number (BN) that ranges from 20-100 BN. And it must ensure that the cylinder liner temperature doesn’t go below the dew point temperature of Sulphuric acid at the top dead centre or bottom dead centre.

2.2 System Lubrication Oil

The system oil lubricates the bearing journals and crankshafts in other engines including the turbocharger. The disadvantage with low-speed diesel engines is the isolation of crankcase and cylinder oils, which make it possible for migration of cylinder oil through the piston rod diaphragm to the crankcase, which is inevitable. As the implication is the introduction of cylinder liners wear debris and acid combustion products mixing with systems lubricating oil. Penetration of seawater causes corrosion and rusting of journal bearings and white metals.

2.3 Compositions and Properties of lubricating oil

This subsection discusses the composition of lubricating oil and its properties. There are 2 types of lubricating oil, which are minerals and synthetic oil. Minerals Oil comprises base oil and additives, the base oil is a by-product of crude oil refinement. This is composed of iso-paraffin and naphthenic with the portion of aromatics which make soluble with additives and stable oxidation. On the other hand, Synthetic oil does not contain base oil but chemical compounds produced from organic chemicals. It is classified into Olefin oligomers, Organic esters, Polyglycols, Phosphate esters, and Polyalphaolefins. It is formulated with special properties for machinery operation such as low viscosity that make it usable in the cold environment and biodegradable formulation for environmental protections. Among the advantages of synthetic oil are consistent molecule, high purity, varies viscosity index, low congelation points, and high-temperature oxidation resistance. However, the disadvantages are the high cost of production, non-compatibility, and limited availability. Figure 1 listed components of lubricant crude oil-based (a) and synthetic-based oil (b).



(a) (b)

Figure 1 lubricating oil composition for (a)mineral oil and (b)synthetic oil

It is known to prevent hardware usage longevity these properties are very important for lubricating oil as shown in figure 1. Many of the properties are achieved with aid of oil additives that give it additional features suitable for the equipment mechanical operation. In some special applications, *extra* additives are needed to suppress the temperature because of viscosity suitability and other extreme requirements. The following are oil properties that are briefly explained and apply cylinder lubricating oil (Sergey Victorovich et al 2016)

1. *Viscosity*: This is the basic property that determines the fluidity of oil at high and cold temperatures and is refined to the specification requirements for equipment mechanics. It also creates resistance to internal friction when flowing among itself. Oil viscosity is not constant because of the influence of pressure and temperature.

2. *Oxidation and thermal stability*: During combustion, the piston temperatures increased to a high level, at higher temperatures lubricants are required to prevent a loss of viscosity or breakdown.

3. *Demulsibility*: It is important for seawater contamination quickly controlled and separated from the oil. Additives features will be able to limit the volume fraction of water by water shedding which is dispersed or emulsified in the oil.

4. *Rust and corrosion prevention*: it is alkaline additives that quickly suppress acidic by-products of combustion or from saltwater. This additive also inhibits corrosive interactions with cylinder liners surfaces.

5. *Antifoaming Additive*: It enables proper wetting of surfaces and pumped operation efficiency.

6. *Detergency*: There will be carbon deposit or ash-based soot, these need to be reduced at every complete cycle so that fouling and engine inefficient will be avoided.

7. *Extreme pressure performance*: when metal-metal contact occurs, it is likely loaded, and with high temperature and pressure all chemical properties must be maintained to reduce friction.

2.3.1 Oil Additives

Oil additives are like a vehicle for oil properties to improve lubricant performance. All lube oils contain these additives to some certain amount in the formation whether mineral oil or synthetics oil. Oil additives can modify oil viscosity and density properties to suit the environment of mechanical operation.

For viscosity as stated above the role is a fluidity of oil at various temperatures, so external force makes it non-constant value. The measurement system is determined at a temperature between 0°C and 100°C and guidelines of measurement are in ASTM D2270 as a standardized metric. Also, viscosity can be used as classification, this was done by the Society of Automotive Engineers (SAE). The SAE grade has been set as the standard for internal combustion lubricating oil to suit the environment of engine operation. As the temperature deepens the grading varies, therefore it is necessary to know the minimum temperature of the environment.

2.4 Lubricant Oils Analysis

lubricant is to protect and separate metal-to-metal gliding each other in the engine. For example, journal, bearings, compressors, cylinder with piston and all moveable parts in machinery, lubricating oil make it to function effectively by reducing friction. To know the condition of operating machinery oil analysis is an important method before maintenance or re-engineering of machinery for it to be able to run as smoothly and efficiently. It will not only improve the machinery efficiency but also reduce the downtime from mechanical failures.

Oil test is for condition monitoring of equipment and physical properties of oil in use. These are the test on lube oil samples, viscosity, water, and soot content, acid and base numbers, particles quantity index, wear elements, and quantity. Chemical Properties analysis is a type of analysis that analyzed the current physical and chemical state. It is possible to tell if the oil inside the engine is satisfied or within range of oil specifications and additives that are being used depletion conditions. Wear debris analysis categorically determines the presence and identify wear particles produced because of mechanical wear, corrosion, or other machine surface degradation. It is possible to determine if exists abnormal wear of the machine, and wear debris is produced from which internal component is more likely to be known in the wear analysis. Periodic tests vary based on the component and the environmental conditions, but analysis conducted will include viscosity tests, wear analysis in particle counts, base, and acid number.

Oil analysis is a non-intrusive way to evaluate the wear of an engine component, and identification of wear debris fragments can clue which components are damaged and the nature of the problem by wear quantity. And enhance microscopic images of wear particles debris can show the severity of fatigue wear. Viscosity and temperature relationship is a very important characteristic of lubricant oil. Monitoring of oil's viscosity is a critical metric because any changes in values at a certain temperature can lead to problems with thermal stress. When the value readings of viscosity are too low or too high it may be due to the presence of an incorrect lubricant, mechanical shearing of the oil, oxidation, or effect of fuel. Some changes may be acceptable within a marginal limit of approximately 10% higher or lower than the original viscosity.

Kinematic viscosity is determined in the laboratory by a capillary tube viscometer. The oil sample is placed into a glass capillary in a U-tube shape. It is drawn through the tube using suction until it reaches the start position indicated on the tube's side. The suction is then released, allowing the sample to flow back through the tube under gravity, using a calibration constant supplied for each tube. More viscous grades of oil take longer to flow than thinner grades of oil. This procedure is described in the American Society for Testing and Materials (ASTM) D445 and International Standard Organization (ISO) 3104.

Acid and base number in the oil sample is analyzed to avoid metallic corrosion. The acid number is the concentration of acid in the oil, while the base number is the reserve of alkalinity in the used oil. The alkalinity volume unit is milligrams in potassium hydroxide per grams (mg KOH/g) that is required to neutralize the acid in the oil. Acid number testing is not performed on crankcase oils, while base number testing is mainly for combustion machinery. An acid number that is too high or low may cause oil oxidation, because of the presence of an incorrect lubricating property or additive depletion. While base number that is too low can indicate high engine blow-by conditions (fuel, soot, etc.), the presence of an incorrect lubricating property, leakage contamination, or oil oxidation.

2.4.1 Cylinder Drain Oil Analysis

Used cylinder oil from the scavenge space that is the bottom drain can be used for cylinder condition monitoring. Drain oil analysis is a strong method for judging the engine wear condition. Drain oil samples taken in active Adaptive Cruise Control operation the oil sample taken and analyzed will be able to judge if the cylinder oil feed rate can be optimized while keeping the remaining BN of cylinder oil within optimized range and iron (Fe) wear particles content below 200 Particles Per Millions (PPM) in the drain oil (Susan Alaswad et al 2017).

It is crucial to note that elevated iron values may be the result of the piston ring running-in period or the coating gradually wearing off. Cylinder oil degradation can spike corrosion levels. The level of depletion is varying among oil brands and engines type. The cylinder oil drain analysis report gave information to support monitoring of engine performance and for engine maintenance, the decision is based on data acquired. The merit of cylinder Lubricant drain monitoring is detecting a problem at an early stage, like rings and cylinder liner wear, water contamination, and diaphragm leakages. Also, the physical inspection of piston rings and cylinder liner condition through the scavenge ports help precise maintenance decisions can be made.

The procedures for cylinder drain oil sampling is as follows:

1. Step one is closing the cock of sludge line link with the main drain line and re-open the sampling cock to blow out any oil or sludge remaining in the cock and the line.

2. Then collect about 500-1000 ml of cylinder drain oil. The container must be clean from dirt, water, and metallic debris.

3. Afterward sampled oil is poured into a 100 ml sample bottle. The sample labeling details include cylinder number and engine conditions at the time of sampling.

4. Sampling interval is 300 to 360 hours of main engine operation or change of conditions such as new fuel oil and sea conditions.

5. Oil sample in 100 ml bottle is used for XRF analysis and BN analysis.

2.5 Cylinder Liner

Cylinder liner is an asymmetrical design for separate lubricating oil consumption. The cylinder liner bores have a cool jacket on the larger engine models, and it is available in two different configurations with or without a cooling water insulator to meet the required cooling intensity. The lower joint between the cylinder liner and the cover design makes heat exposure from the combustion chamber to be contained within the steel cylinder cover better than in the cast iron cylinder liner. The cylinder liner adequately controls the temperature of the liner surfaces to safeguard against cold corrosion caused by the condensation of Sulfuric acid formed during the combustion of Sulphur content from heavy fuel. and, at the same time, ensures stable lubrication conditions by preventing excessive temperatures.

Cylinder liners design includes a material composition that has strength, ductility, heat transfer, and wear-resistant properties. Cylinder liners are bore-cooled made of grey cast iron for engines cast-in cooling pipes. Various parallel designs were developed based on the use of stronger materials, and improvements to the original design. A modification of cast-in pipes and combine with a tightening-up of the production and quality specifications, result in considerably improved reliability from cylinder liner.

The inner surface temperature of the cylinder liner greatly affects cylinder liner operating conditions. The cooling system design has been laid out to withstand the maximum continuous rating load however, there is a demerit in controlling the liners' wall temperature in relating to the thermal load. For instance, engine design has tried different solutions for maximum continuous rating load on cylinder liner cooling. One approach is adjusting the cooling water flow through the cooling ducts in the liner but the results do not reach the target aim. In another modified design it features different sets of cooling ducts in the bore cooled liner. The results, at a certain power and high loads the inner ducts cool cylinder liner wall and yield the highest cooling intensity. However, the intermediate load range cooling function shifted to another set of ducts that are located further away from the internal surface. This means that the cooling intensity is reduced because of heat conduction and the liner wall temperature needs to be kept at the optimum level. When at very low loads rows of cooling ducts are circumvented to limit cooling intensity. Tests reported that the optimum liner temperature could be maintained for a very wide load range, but the engine design becomes complex over the service advantages. For cylinder liners and piston rings, the operating conditions are a functionality of the temperature, as the top dead center part is particularly important and a multi-fuel valve configuration aims to reduce the thermal load. The piston rings and high top-land ensure that an appropriate pressure is dropped across the ring pack. Also controlling the system temperature for the individual piston rings. The rise in cylinder liner wall temperature purpose is counterbalancing the tendency of cold corrosion at the top dead center of the liner. Cylinder liner design with cooling ducts and modified types to meet thermal load on cylinder liner as shown in figure 1,

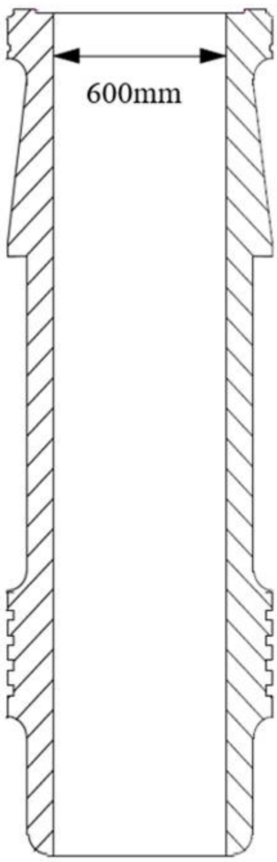


Figure 1 Cylinder Liner sketch drawing

2.5.1 Cylinder liner materials

The cylinders liner is made from cast iron containing phosphorus, manganese, chromium, molybdenum, vanadium, and titanium as alloying elements, or steel or aluminium. Most large marine engine cylinder liner is made with cast iron and the material specifications for cast-iron cylinder liners are listed in table 1.

Table 1 typical material composition for cast iron cylinder liners (Affenzeller, 1996)

	Composition (%)							
	C	Si	Mn	P	Cr	S	Mo	Ni
Standard 45	2.8 – 3.2	1.7 – 2.4	0.5 - 0.8	0.4 - 0.45	0.25 – 0.4	< 0.03	-	-
Standard p	2.8 – 3.2	1.7 – 2.4	0.5 – 0.8	0.6 – 0.8	0.25 - 0.4	< 0.3	-	-
ASTM 247	3.1 - 3.4	1.85 - 2.3	-	< 0.12	< 0.35	< 0.18	0.25	0.50

Modular cast-iron cylinders with cermet surfaces are used in low-speed two-stroke diesel engines. The liner surface is coated with a chromium layer to improve the wear resistance of the cylinder liners. Cast iron is beneficial because graphite layers material support oil reservation and forming oil films to prevent starvation conditions.

2.5.2. Cylinder Liner Insulation

The insulation of cylinder liner with and without tribological insulation has been studied. Understandably, the cylinder liner operating temperature overlaps with the dew point temperature of the water. This results in low-temperature corrosion that is present on the entire length of the stroke. For instance, Wartsila RTA83T engine cylinder liner with tribological insulation at the top dead center (TDC) area and in the middle of the stroke, the operating temperature of the cylinder liner deviates significantly from the dew point temperature. This leads to cold liner walls causing cold corrosion and cold corrosion increased friction, scuffing, and high wear rate. Using fuel oil containing sulfur when combusting produced sulfuric acid and ultimately causes so low-temperature corrosion. Although cylinder lube oil does neutralize sulfuric acid cylinder liner design is more important to mitigate low-temperature corrosion. Below equations 1 to 4 are chemical reactions for sulfuric acid formulation.

$$S_{(s)} + O_{2(g)} \rightarrow SO_{(g)} \quad (1)$$

$$2SO_{2(g)} + O_{2(g)} \rightarrow 2SO_{3(g)} \quad (2)$$

$$SO_{2(g)} + H_2O_{(l)} \rightleftharpoons H_2SO_{3(aq)} \quad (3)$$

$$SO_{3(g)} + H_2O_{(l)} \rightarrow H_2SO_{4(aq)} \quad (4)$$

Most slow speed 2-stroke engine design is long stroke and its longer distance time add to corrosive combustion residues on the liner surface. A 2-stroke engine with a long-stroke needs more accurate temperature control. It will be possible to predict accurately cylinder liner wall temperature, and the critical temperature line limit that leads to corrosion taking place in different engine environments.

2.6 PISTON RINGS

A unit of the cylinder has a piston head with a *ring pack*. This includes the top ring or Controlled Pressure Relief (CPR), second ring, third ring, and fourth ring attached to the piston head. The CPR ring has a double lap joint and is the optimum pressure drop across from the top piston to others. With the thermal load on the cylinder liner, CPR is responsible for reducing it and ensuring no gas escapes the double lap joint. The second ring ensures an even distribution of the thermal load from the combustion gases over the circumference of the cylinder liner, resulting in a reduced load on the liner as well as on the third piston ring.

Rings are aluminum-bronze alloy coated to ensure safe running-in when newly fitted to the piston head, also it is effective in protecting rings and cylinder liner surfaces during the running-in period. The operating lifetime of rings ranges from 1000–2000 hours, depending on such factors as the cylinder oil feed rate and cylinder liner surface roughness.

The piston ring groove extends the interval before reconditioning the piston ring. The grooves are chromium plated thereby adding about 0.5 mm thickness and it reduced the risk of bristle cracking and fostering a longer service life. At the top of the cylinder liner, there is a slightly smaller diameter hole in the liner that supports piston ring cleaning from carbon deposits building up on the piston top-land. Without such a piston ring cleaning, it will prevent cylinder lubricating oil optimization whereby the oil is prevented from circulating between the top-land and the cylinder liner wall. In some cases, leads to deposition formation on the top-land causing bore polishing the liner wall and contributing to the deterioration of the cylinder condition. Piston rings groove coatings prevent penetration of hard solid particles in the space between the ring and the piston groves that can cause perforation of the horizontal working surface of the piston ring groove. If perforation occurs it will lead to scuffing of a piston ring in its groves, and unable to seal. When coated it prevent the perforation of piston rings and contributed to extending the time between overhauling of the cylinder unit. Figure 2 illustrates piston rings packed on a piston head for the main engine.

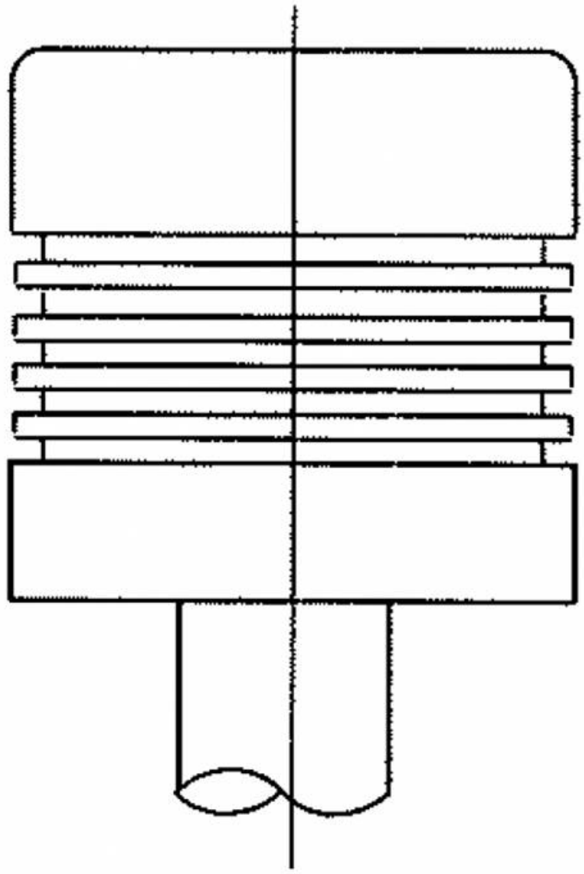


Figure 2 Piston head with ring grooves

The use of coatings on piston rings is essential to optimize time between overhauling piston rings of marine engines. There is a demand for increasing the power output of all engines and higher power output leads to increased thermal heat load. The higher mechanical load on piston rings and cylinder liners caused the re-development of new piston ring coatings materials that give excellent wear properties under increasingly load running conditions. There are two main types of piston rings coating that are currently available these are running-in coatings and wear-resistant coatings.

2.6.1 Piston Ring Materials

A piston ring material is chosen to meet the demands set by the running conditions. This material should be resistant to damage even in severe conditions. The mechanical property such as elasticity and corrosion resistance of the ring material is required for the ring to be used. The ring coating needs to be compatible with both the ring and the liner materials, as well as with the lubricant. As one task of the rings is to conduct heat to the liner wall, good thermal conductivity is required. From a tribological point of view, "the grey cast iron is beneficial, as a dry lubrication effect of the graphite phase of the material can occur under conditions of oil starvation. Furthermore, the graphite phase can act as an oil reservoir that supplies oil at dry starts or similar conditions of oil starvation" (Glaeser, 1992).

Coatings rings are widely used such as Chromium, molybdenum, metal composites, metal-ceramic composites, or ceramic composites, such as molybdenum-nickel-chromium alloys, chromium oxide (Cr_2O_3) with metallic chromium, alumina-titania (Al_2O_3-TiO_2), tungsten carbide (WC) with metallic cobalt binder, MoSi2, CrC-NiCr.

"Hard chromium layers can be improved by plasma spraying chromium ceramic on the ring face, thus increasing the thermal load capacity. Thin, hard coatings produced by PVD, or CVD include coating compositions like titanium nitride (TiN), chromium nitride (CrN); however, coatings of this type are currently used exclusively for small series production for competition engines and selected production engines" (Broszeit et al., 1999)

2.6.2 Rings Coating

The running-in coating is applied to the ring's running surface to properly seal rings with liner surface within the first few hours of operation after cylinder liner unit overhauling. Also, the running-in coating is to gently polish the surface of the cylinder liner during the first few hundred hours after installation of a new liner. While the running-in coating is applied directly to the base material or as an addition to a wear-resistant coating during manufacturing.

Cermets is a composite material composed of ceramic and metallic materials representing an important family of thermally sprayed wear-resistant coatings. Cermets is applied to the running surface of the ring for highly loaded applications and the coatings prolong the lifetime of the ring packs. Cermets is applied by plasma-spraying equipment, and this is illustrated in figure 3.

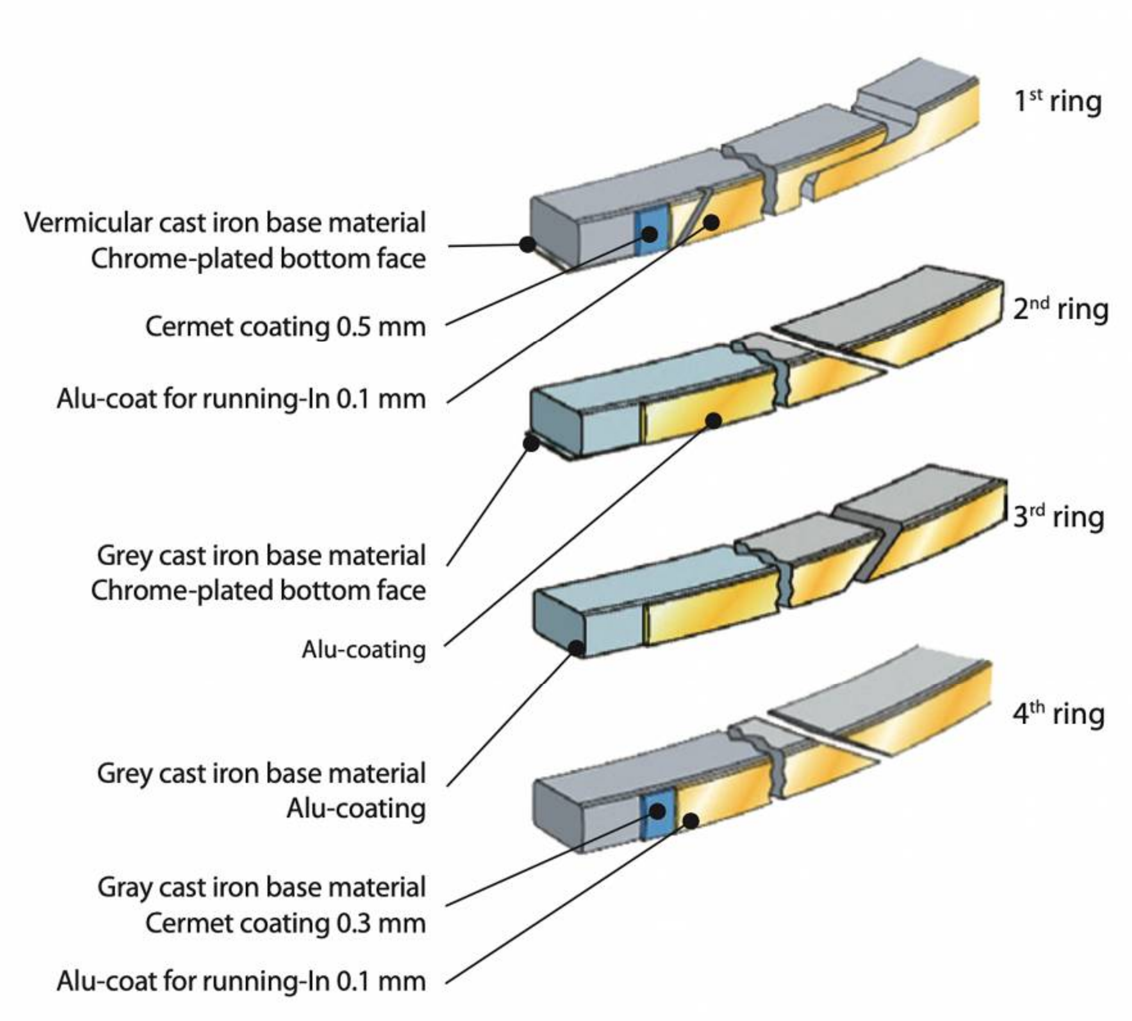


Figure 3 Physical looks of rings surface coated (MAN B&W)

2.7 Wear

Wear is the removal of material from two surfaces by the mechanical movement that rubs together. The definition does include subsurface deformation, surface damage, or chemical corrosion. Therefore, in an expandable definition of wear, the study of surface degradation and material loss. In contexts, wear is a complex phenomenon because of the broadness of the very natural wear process. It is transient and depends upon the historical timeline of the process. Wear is a cumulative process that happens at one time in a stroke and by repetition of its function. The damaged surfaces wear as the final amount of material loss may be much higher than the previous function. Wear behavior can depend on material inhomogeneity, misalignment, and contamination that contribute to the damage.

Equipment surface evaluation aims to improve material performance and the methodology contributing to the effort to explore the material's wear characteristics concerning increasing thermal stress (Baurko O.C et al 2015). In severe operating conditions give insights into the dominant material's wear mechanisms. On other hand, lubricants containing additives to prevent wear is evaluated on how wear is reduced during a simulation cycle. For lubricants, the development focus on the interfacial layer between metallic surface but not on to mechanical stress of materials.

Wear Mechanism

Wear behaves according to the different applications. In the case of cylinder liner and pistons, a combination of different wear mechanisms occurs in many large marine engines such as;

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

Abrasive Wear

Abrasive wear is caused by hard asperities in the components rubbing against the surface of each other or by solid particles from contaminants fuel oil such as catalyst fines or cat fines. The particles embed themselves into the piston ring and cylinder liner surface by breaching the cylinder oil film, resulting in abrading the surfaces and wearing them down during sliding. Abrasive wear is also displacement or stripping of material when there are hard protrusions or hard particles that are forced against moving solid surface. For protrusion or asperity, the wear is two-body abrasion or *three-body abrasion* in the case of external hard particles such as cat fines in fuel oil.

Figure 4 showed the model of abrasive wear progression of equipment in comparison with normal wear for the cylinder liner.

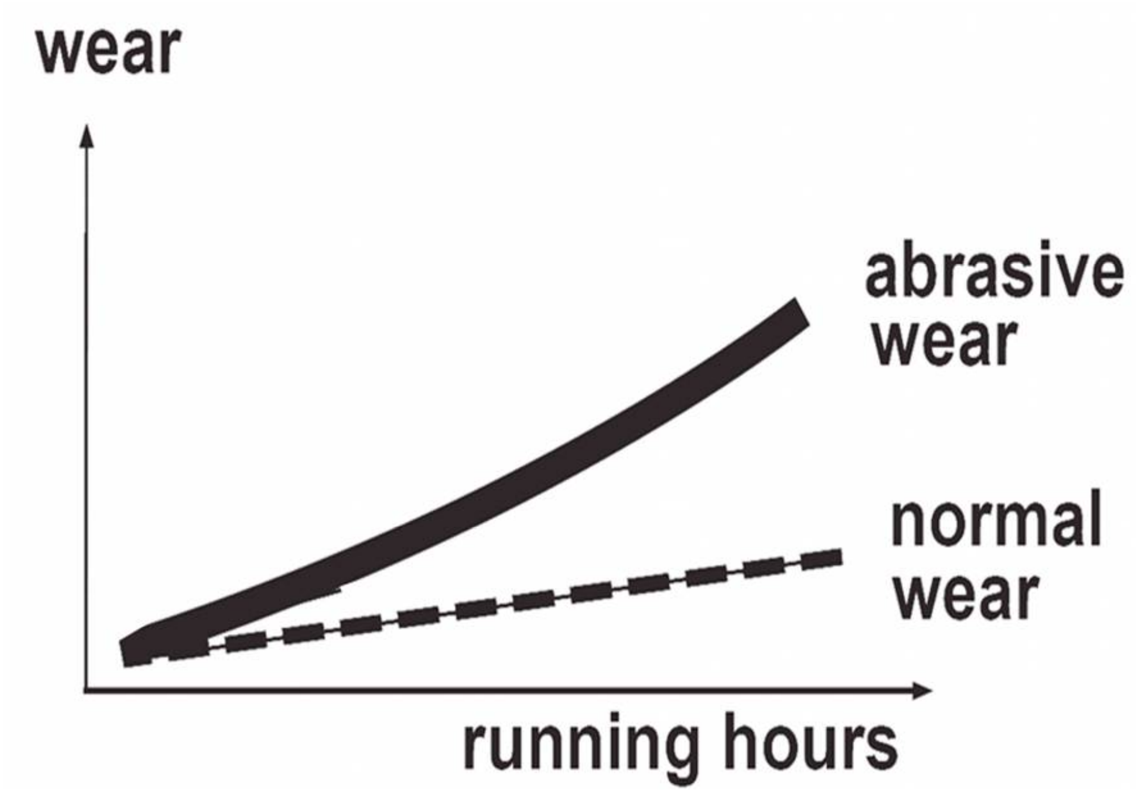


Figure 4 The graphical model for abrasive against running hours

The amount of wear primarily depends on the hardness of both metallic materials in contact. In the situation whereby a surface hardness is more than half of the abrasive particle or protrusion, there is sufficient wear resistance for the metal. When the machinery moving part is lubricated abrasive wear will only occur when the lube oil is lacking to separate the two metals touching each other. This leads to polishing, scratching, and grinding of the surface. Abrasive wear is a rampant type of wear in large marine engines.

Cat fines are found mainly in fuel oil when it is combusted in the combustion chamber of 2-stroke engine cylinder liner and piston rings glide cat fines that caused abrasive wear.

Cat fines are hard particles that are trapped between sliding surfaces of piston ring and liner, or ring groove. In this situation, the wear process is 3-body abrasive wear. Cat fine can accumulate to bigger particles peeling of the metallic surface of the metals. Rings and liners are made of cast iron that different phases and have different inherent properties such as hardness, brittleness, and ductility.

Adhesive Wear

Adhesive wear of metal takes place because of oil film loss between cylinder liner and piston rings. It is metal-to-metal contact and produced friction at high temperatures. When a severe situation occurs, it leads to metal sticking together by micro-welding of the metallic surface resulting in cylinder liner scuffing.

In a high mechanical load of machinery, the sliding surface metal increases the temperature during contact because adhesive wear causes plastic deformation of metallic structure leading to tearing of the material. The factors causing high adhesive wear are load force, hardness, material oxidation, crystal structure and lack or retainment of cylinder lubricating oil films contribute to hyper adhesive wear of cylinder liners and piston rings. Typically, adhesive wear begins from the top of asperity and quickly spread to the microstructure of the cylinder liner in high load operation. This phenomenon is called galling or scuffing of the cylinder liner. When adhesive wear occurred in cylinder liner the progression of adhesive wear is illustrated in figure 5.

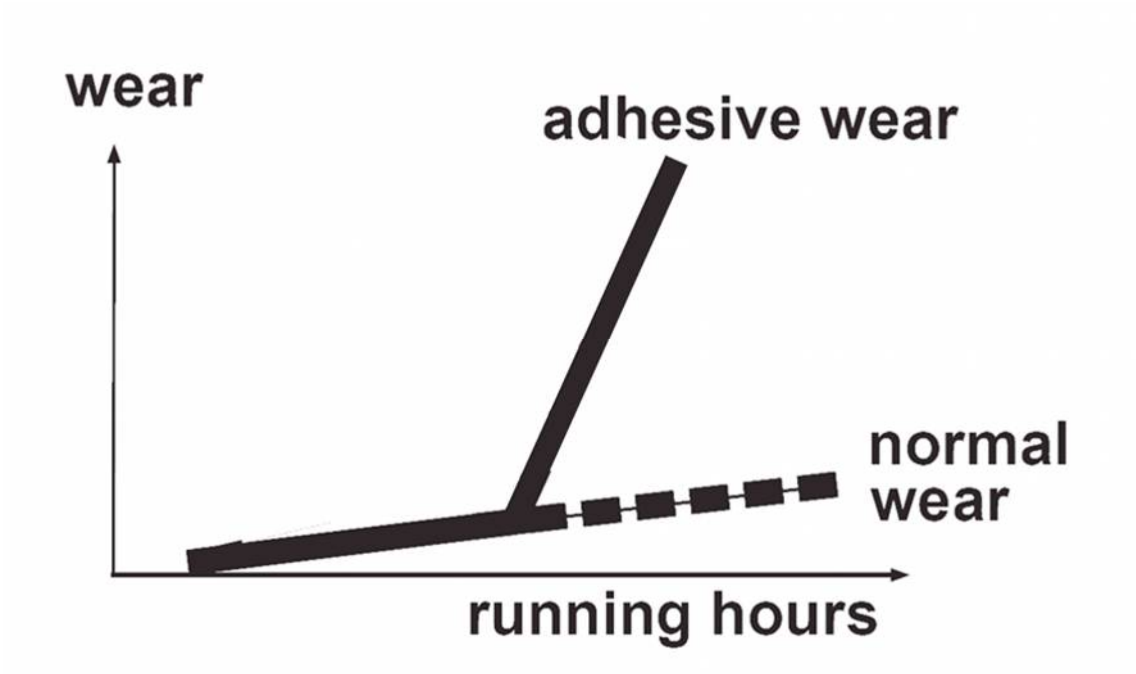


Figure 5 The graphical model of Adhesive wear metallic surface

Corrosive Wear (Cold Corrosion)

Corrosive wear is the combination of abrasive and adhesive wear caused by a corrosive environment. The amount of material wear loss can be very high because of the combination of wears phenomenon in the cylinder liner, piston rings, and piston groove. It is because of loose corrosion products that are easily removed by continual wear even fresh metal surface beneath corrode quickly.

Cold corrosion is chemical corrosion that resulted from by-products and a friendly environment on the metallic surface. Cold corrosion can only take place when the acid molecules are deposited on the cylinder liner wall without being neutralized by the cylinder lubricating oil. Cylinder lubricating oil will normally protect the surface against corrosion, but titration may limit the protection given way to both abrasive wear and adhesive wear. The cylinder liner surface will be unprotected and chemical corrosion can continue to extensive wear. Corrosive wear cannot be completely prevented if either the corrosion factors or the wear factors are included in the design. The corrosive wear graphical model of progression is represented in figure 6 deflecting from normal wear of metallic material surface.

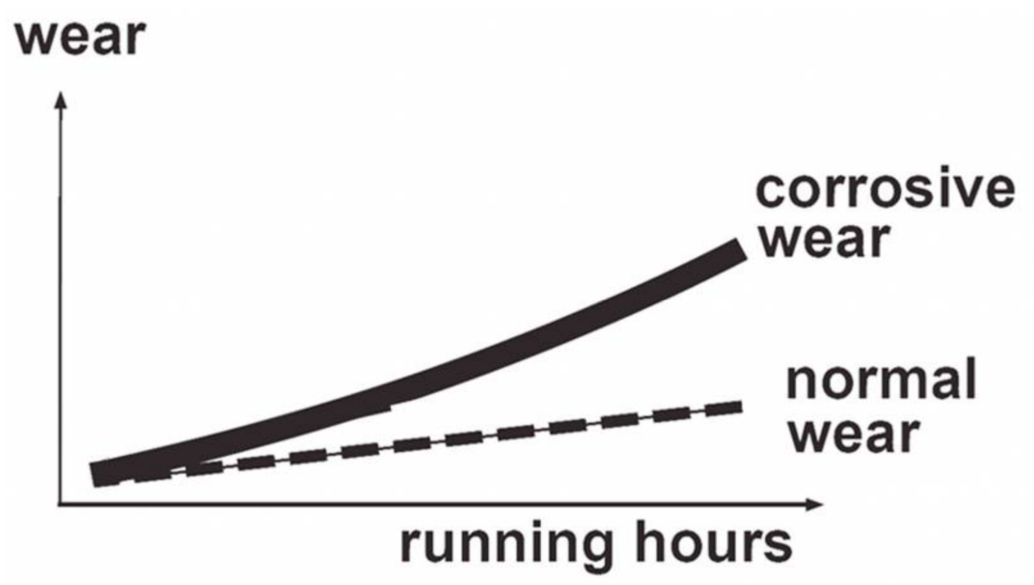


Figure 6 The graphical model of corrosive wear progression on a metallic surface

Combustion of heavy fuel oil produced a by-product of unstable oxide films that would normally amplify corrosion and instantly wear the surface protective films away. Corrosive wear is attributed to the combustion chamber, and after combustion end products are acidic compounds that condense to liquid or mist in appearance and the reason for commonly referred to as "cold corrosion". Cold corrosion has been very much in focus with the large marine engine with large bore size design and longer piston stroke in recent years, but 2 main influences are:

I. Slow steaming of the engine due to economic advantages on fuel oil economy that will lower operating expenditure on running large marine engine in a single voyage.

II. The International Maritime Organization (IMO) demands better fuel efficiency that leads to redesigning of marine engines and tunings.

Heavy fuel contains sulfur and the end by-products include oxidized to sulfur dioxide (SO_2). This reaction is chemically unstable and easily reversible to sulfur dioxide (SO_2) compounds formed. A little amount of SO_2 can further be oxidized to sulfur trioxide (SO_3). Sulfur trioxide (SO_3) is formed by the dynamic equilibrium between sulfur dioxide (SO_2) and oxygen (O_2). According to Le Chatelier's principle the equilibrium dynamic depends on the concentration of the chemical elements, vessel pressure, and the temperature, when the environment for the equilibrium is right it continues to reproduce and for the marine engine combusting heavy fuel oil that contains sulfur will continue to produce sulfur trioxide (SO_3). The design, engine tuning, and operating conditions such as load, fuel sulfur percentage, ambient conditions, etc. for a large-bore marine engine corrode by up to 10% of SO_2 oxidation to SO_3 acidic oxides during combustion. These reactions are highlighted in the above sub-section 2.1. cylinder liner insulation.

The percentage mass of sulfur in fuel oil leads to roughly calculating the concentration of SO_2 in the cylinder liners can be estimated by the knowledge of fuel oil consumption and the airflow through the engine. The unstable acidic oxide SO_3 concentration is more difficult to determine as the reaction is in the equilibrium state when the external factors already highlighted the concentration increase proportionally. The by-product is the gas mixture formed at the combustion results in an equilibrium system of SO_3, H_2SO_4, and H_2O, at below dew point temperature the vapor state in equilibrium reacts with the liquid which in turn produces the aqueous sulphuric acid. In definition, the dew point is the temperature at which a vapor state condenses to a liquid state. When the temperature is below the dew point, the vapor state condenses to either aerosols or film onto the surface. The dew point temperature for H_2O, SO_3, H_2SO_4 vapor to a liquid state is influenced by the pressure of the components resulting in the aqueous sulphuric acid concentration.

The lower cylinder liner temperature is associated with slow steaming and modified engine design. Also, ambient temperature allows condensation of aqueous sulfur trioxide during the scavenging phase but higher pressures and temperature are associated with engine efficiency. Sadly, both factors can increase the likelihood of cold corrosion.

Cylinder liner cold corrosion

Alkaline or base in lubricant oil is used to neutralize sulphuric acid to avoid cold corrosion of piston rings and cylinder liner surfaces. The additives are included such as calcium carbonate ($CaCO_3$) is mostly cylinder lubricating oil. The chemical reaction of alkyl and the sulfuric acid compound is as follows.

$$H_2SO_4(aq) + CaCO_3(s) \rightarrow CaSO_4(s) + H_2O(l) + CO_2(g) \quad (5)$$

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

$$Fe(s) + H_2SO_4(aq) \rightarrow FeSO_4(s) + H_2(g) \quad (6)$$

The likely hypothesis for the acid formation process is highlighted below as follow.

I. Sulphur trioxide (SO_3) formed in the combustion gas

II. At the dew point condensation of water or aqueous sulphuric acid make oil film absolute on the cylinder liner surface

III. Deficiency of alkaline in-cylinder lubricant to neutralize acid

IV. Because of the chemical equilibrium phase increased amount of acidic concentration can cause severe cold corrosion of cylinder liner.

3. Monitoring of Ships Sailing in North & South Pacific Ocean

- 3.1. Heavy Fuel Oil
  - 3.1.1. Cylinder Lubricating Oil
- 3.2. Drain Cylinder Lubricating Oil Sample Information
  - 3.2.1. Sampling Intervals
  - 3.2.2. Sampling Procedures
- 3.3 American Ships and Oceania Ships Used Oil Samples
- 3.4 Total Base Number Monitoring of Both Sailing Routes
- 3.5 Wear Elements Comparison and Explanation
- 3.6 Summary on Monitor Results
- 3.7 Wear Discussion
  - 3.7.1 Cold Corrosion
  - 3.7.2 Incomplete Combustion Conditions
  - 3.7.3 Piston Rings Abrasion

Chapter 3

Marine Engine on ships

The 2-stroke slow-speed crosshead marine diesel engine has been the preferable prime mover for large seagoing merchant ships. This chapter focuses on the thesis engine and drain oil sample test. The result is utilized to discuss means of monitoring of cylinder liner and piston rings through cylinder oil samples from engines in operation. This project makes use of a total of 4 ships and split the total into 2 fixed routes of sailing. That is 2 ships voyage between Japan ports to Oceania ports and other 2 ships voyage from Japan port to North American ports. All the routes are fixed without any changes to the call ports or deviation from the routes. See table 1 brief specification of mounted ship engines for both routes

Table 1, Ships engine specifications

	American Vessels (AV)	Oceania Vessels (OV)
Model	6UEC60LSA	7UEC60LSII
Max Power (kW)	11,180	14,315
Number of Cylinders	6	7
RPM	110	105
Bore size (mm)	600	600

There are reasons for mounting a 2-stroke slow-speed crosshead marine diesel engine in the marine ship for transporting bulk cargoes internationally and locally. It is as follow,

- From engine speed and torque no intermediate gear to meet exactly propeller speed demand.
- Less hustle on maintenance of components in ratio comparison with high-speed engines
- It is graded as the most efficient fuel consumption in comparison with Dead Weight Tonnage
- Engine burn on the bottom product of refined crude oil which is economically wise the fine product.

3.1 Heavy Fuel Oil

Although heavy fuel oil (HFO) may be categorized as diesel fuels, there are lighter diesel fuels that have a relatively low viscosity in comparison with heavy fuel oil of high viscosity. HFO contains substances or components that can be harmful to both the marine engine and the environment if the maximum amount allows contents exceeded, or if not treated properly onboard the ship.

However, HFO international standards are set or stipulated by International Maritime Organization (IMO) in collaboration with members states on the MARPOL agreement. Also, a marine engine is designed and manufactured with Original Manufacturer Equipment (OME) recommendations as to which types of fuels can be burned in a particular engine, how in-take fuels must be treated, and physical conditions before entering the engine.

There are challenges in using HFO due to air pollution and environmental laws in different countries of fuel oil origin. As a result, marine diesel engines must be flexible on fuels usage and have a whole range of diesel fuels to meet the local laws at the calling port. Another problem is the physical properties of HFO which can range from, a high amount of aluminium Silica, waxing, bacteria, sludge, high amount of cappuccino, high amount of water in fuel, and other chemical contamination. To navigate through problems onboard numerous types of machinery will refine the fuel oil to the degree of an acceptable standard that is recommended by the OME. Onboard HFO refinement is 3 steps which are separation phase, heating phase, and setting Phase. This creates numerous challenges for the crew and the engines.

When HFO catalytic particles other known as catalytic fines or simply cat fines concentration is high the refinement process can be extraordinarily tedious and labouring to limit the amount to an acceptable value. This cat fine consists mainly of aluminium and silicon oxides ranging from 10 to 20 μm in size. When it becomes consolidated is very hard and caused abrasive wear of cylinder liners and piston rings. Also, the fuel injector can clog by the catalytic fines. The onboard centrifuges and filters can reduce the amount before entering the engine.

At the time of monitoring ships engine for this project, the allowed maximum of sulfur is according to table 2, and other properties max amount and the engine entry.

Table 2, Heavy Fuel Oil ISO 8217 Typical Specification

Parameters	Unit	ISO 8217 RMG 380 (max)	Test Method (ISO)	Engine Inlet Limit (max)
Density @ 15℃	kg/m^3	0.991	3675/12185	0.990
Viscosity @ 50℃	mm^2/s	380	3104	13 – 17
Micro Carbon Residue	m/m (%)	16 – 18	10370	22
Sulphur	m/m (%)	3.50	8754/14596	3.50
Ash	m/m (%)	0.10	6245	0.15
Vanadium	mg/kg (ppm)	200 – 300	14597/IP501/470	300
Sodium	mg/kg (ppm)	100	AAS	30
Aluminium + Silicon	mg/kg (ppm)	80 (Al alone 30)	10478/IP501/470	15
Total sediment	m/m (%)	0.10	10307-2	0.10
Water	v/v (%)	0.50	3733	0.2
Flash point	℃	66	2719	60
Pour point	℃	24	3016	24

Remark: Data is obtained from International Standard Organization (www.iso.ch)

The source of HFO is crude oil with a natural sulfur content that varies in percentage from the origin of mining. When refine the remaining is heavier fractions of refinery products such as marine diesel fuels, plastics, and others. Globally on average HFO sulfur content is around 2.80%wt.

Sulfur is excellent for lubricant chemical properties because of the moving parts in the machinery. However, the reaction with water molecules produces sulphuric acid, which is highly corrosive and damages cylinder liners and piston rings.

3.1.1 Cylinder Lubricating Oil

The marine slow speed 2-stroke (long) diesel engines with a large bore that burns HFO containing sulfur require separate lubrication for the cylinder liner mostly called cylinder oil. This is different from system oil lubricating crankshaft and piston arm. Cylinder lubricating oil must attain the following purposes:

- Create and keep an oil film to protect metal physical contact between the cylinder liner and piston rings.
- Able to neutralize sulphuric acid (H_2SO_4) to prevent acid corrosion.
- Cleaning of deposit or carbon soot on the cylinder liner, and the piston ring pack.

It will prevent breakdown and damage that is caused by incomplete combustion and acidic compound residues. The design of a two-stroke crosshead engine makes no use of a scraper ring on the piston head and the cylinder lubricating oil is not recycled and reused in the engine system. For slow-speed marine engines using crosshead piston-cylinder, lubricating oil costs add to operating expenses because once used it becomes waste oil. To reduce cost and waste of resources the dosage of cylinder oil is very important for the daily running of the engine. Cylinder lubricating oil for slow speed large diesel engine basic characteristic is as follow:

- Viscosity grade SAE 50
- Base Number (BN) ranges from 20 to 150 depending on the amount of sulfur in fuel oil.
- Detergent additives. It must be able to clean the cylinder liner, piston ring pack and minimize deposit formation or accumulation.

During the period for this project monitoring, all 4 engines make use of the same cylinder lubricating oil of base number of 70 mgKOH/g and the specification is as follow in table 3.

Table 3 Cylinder Lubricating Oil Specifications (Source Exxon Mobil)

Lubricating Spec	Cylinder Oil
SAE Grade	50
Density at 15ºC	0.937
Flash Point, ºC, ASTM D 92	256
Pour Point, ºC, ASTM D 97	-9
Kinematic Viscosity, ASTM D 445	----
mm^2 /s at 40 ºC	222
mm^2 /s at 100 ºC	20
Viscosity Index, ASTM D 2270	104
BN, mg KOH/g, ASTM D 2896	70

The engines are designed with diaphragm and stuffing boxes to separate cylinder oil from mixing with crankshaft system oil. It makes it possible to independently lubricate crankshaft with system oil separately and cylinder liners and piston rings with cylinder lubricating oil. The diaphragm ensures cylinder lubricating is not mixing with crankcase system oil. This makes it possible to independently monitor metallic debris wear of cylinder liner and piston rings through a sampling of waste cylinder oil known as scrape-down cylinder lubricating oil. Table 3 indicates the chemical properties of cylinder lubrication oil used onboard for the ships for the main engine.

Also, because of severe contamination from fuel oil, cylinder lubricating oil detergent characteristics are extremely important for piston rings with cylinder liners cleaning. Cylinder lubricating oil must have sufficient viscosity, oxidation, thermal stability, corrosion prevention, antifoaming, and withstand extreme pressure in performance and biocides.

3.2 Drain cylinder lubricating oil sample Information

To guarantee data accuracy it is vital to label sample bottles. We are monitoring 4 ships' vital label information including ship name, output power, engine hours at sampling, type of lubricant, engine model, and date of sampling. Any mistakes made on labelling will cause analysis confusion and make an incorrect assessment and inaccurate monitoring.

Sampling test kits are routinely delivered to ships and contain all the equipment & bottles necessary for taking the samples. The sample labels are partly filled, and instructions and guidelines of sampling are always included to update the new crew. Ship crew must be changed at the end of their contracts and the replacement will board as a new crew. Due to the recycling of personnel instruction and guidelines is always included for the new personnel to do the drain cylinder oil sampling when sailing using the main engine. Samples are packaged and couriered to us for testing and analysis, but care must be taken to ensure that data received and label match appropriately. Due to health and safety precautions, it is compulsory to state the flashing point is greater than 60°C to avoid withholding the package because it is considered as flammable content. Figure 1 shows the oil sample in a bottle and the label.

Figure 1 Cylinder oil samples both new and used

The interpretation test results require knowledge about the cylinder liner and the piston rings of a 2-stroke large marine engine. This will allow good decisions on equipment on maintenance schedule and management of the engine. The historical data from cylinder liner and its operating conditions that is equipment in service, environmental information, and performance data are needed for daily monitoring of the marine engine. It is also important that a full and proper diagnosis can be achieved when conditions of sampling are the same and regular.

3.2.1 Sampling Intervals

Abnormality can be noted easily when test parameters are the function of time or operating hours of cylinder oil monitoring and analysis. This data is visualized to indicate the normal operating trends and abnormal equipment. The significant deviation from normal trends can be highlighted by graphical analysts so that the crew can carry out prognosis and diagnosis in a short time. When sampling for Condition Based Monitoring (CBM) the sampling frequency for the cylinder liner will vary according to the engine operating conditions such as combustion of fresh fuel oil, outside environment, and risk assessment of failing equipment for maintenance review. However, it is prudent to take samples monthly or less down 100 hours of engine operation. To explore CBM benefit the monitor results as to be a function of time and it is critical to take the cylinder oil samples at regular intervals.

3.2.2 Sampling Procedures

Scavenge drain oil is collected from each cylinder or in a common drain pipe collecting drain oil from all cylinder units. The design of the monitor engines only has a common drain pipe to collect directly from the cylinder liner after scraping down and the cylinder oil is not recirculated or reused in the engine. It is important to make use of clean collecting containers to avoid dilution and contamination because test reliability questioning leading wrong diagnosis and prognosis.

The scavenge drain pipe is equipped with the main valve and a sample valve branching off the vertical pipe that is between the engine and the main valve. The sample is drawn by closing the main valve and the pipeline will be filled up. Drain cylinder oil sample is collected by opening vertical branch valve to sample scrape-down drain cylinder oil.

3.3 American Ships and Oceania Ships Used Oil Samples

In this section the subject engine conditions at the time of sampling for each case study engine. The sampling engine must be running 85% above maximum continuous rating (MCR). The following tables showed readable data that was allowed to be used by the ship's management. The American ships have 2 ships which are called American Vessel 1 and 2 (AV1, AV2). Table 4 is the engine conditions at sampling as follow,

Table 4 Engine conditions @ sampling American Vessel 1 (AV1)

Total Eng. Hrs.	Temp°C	Scav. Air Press. (bar)	Power @ sampling (kW)	RPM @ sampling	Consumption Ltr/day	BN (Used Oil)	Fuel Sulfur %	Cal. Feed Rate g/kWh
113338	39	0.10	9727	105	442	60	2.64	1.77
114117	26	0.20	9878	106	431	50	3.03	1.70
114798	35	0.20	10029	106	432	60	2.69	1.70
115813	42	0.20	9887	106	431	61	1.88	1.68
116688	28	0.20	9632	105	432	52	1.90	1.75
117789	36	0.20	9321	105	425	52	2.96	1.78
118432	37	0.20	10070	104	410	62	1.83	1.51
119641	31	0.20	10570	104	411	62	2.76	1.52
120056	37	0.20	10050	104	410	62	1.83	1.51

Table 5 Engine conditions @ sampling American Vessel 2 (AV2)

Total Eng. Hrs.	Temp.°C	Scav. Air Press. (bar)	Power @ sampling (kw)	RPM @ sampling	Consumption Ltr/day	BN (Used Oil)	Fuel Sulfur%	Cal. Feed Rate g/kWh
111689	36	0.16	10146	106	432	62	3.30	1.66
111957	40	0.15	8390	98	432	63	3.30	2.01
112210	24	0.11	9156	95	288	63	3.30	1.23
112637	41	0.16	9879	107	432	63	3.30	1.71
113037	33	0.15	10016	105	457	63	2.69	1.78
113474	40	0.11	9239	100	352	63	1.96	1.49
114088	21	0.15	8866	101	432	62	2.58	1.90
114458	18	0.17	9559	103	452	63	1.96	1.84
114875	26	0.16	10133	103	525	62	2.58	2.02
115164	23	0.15	8734	103	534	62	1.60	2.38
115523	15	0.15	9206	102	526	63	2.58	2.23
115882	16	0.14	9280	104	506	66	2.58	2.13
116253	31	0.14	9440	104	528	70	2.79	2.18
116890	39	0.16	10285	106	526	62	3.02	1.99
117311	28	0.17	9709	106	511	64	1.97	2.05
117641	33	0.13	8457	100	478	66	1.97	2.20
117972	34	0.17	10240	106	473	53	2.96	1.80
118227	34	0.10	7584	96	427	68	3.02	2.18

The American vessels sailing only in the Northern Hemisphere, these ships do not deviate or change the pattern of voyage during the monitoring of main engine conditions. We can infer that the Northern Pacific Ocean environment will affect the engine conditions of combustion of fuel oil that contain sulfur. In the early chapters of this dissertation, we have discussed sulfur in fuel oil that caused acid corrosion or cold corrosion in cylinder liners that greatly influence the quantity of wear in drain cylinder oil.

To verify our hypothesis, we monitored another set of 2 ships that only sail to Southern ports. The ports are Australia and New Zealand ports, ships depart from Japan port. The official ship's names are not allowed to be used, so for project names are Oceania Vessel 5 (OV5) and Oceania Vessel 6 (OV6) respectively. The engine conditions at sampling are as follow,

Table 6 Engine conditions @ sampling for Oceania Vessel 5 (OV5)

Total Eng. Hrs.	Temp.°C	Scav. Air Press. (bar)	Power @ sampling (kW)	RPM @ sampling	Consumption Ltr/day	BN (Used Oil)	Fuel Sulfur %	Cal. Feed Rate g/kWh
71965	42	0.15	12203	102	408	36	2.49	1.30
72328	41	0.16	12098	102	408	52	2.49	1.32
72629	42	0.15	12012	101	408	47	2.49	1.30
72971	41	0.15	12211	101	408	52	2.49	1.32
73284	42	0.16	11820	101	396	32	2.49	1.31
73688	43	0.16	12059	102	384	45	2.49	1.24
73995	43	0.16	11853	101	384	36	2.49	1.55
74322	43	0.15	12038	101	384	36	2.62	1.50
74634	41	0.16	12113	102	449	45	2.40	1.45
74988	43	0.16	11882	102	436	43	2.93	1.43
75272	42	0.15	12379	102	408	52	2.40	1.33
75705	42	0.15	11969	102	408	50	2.49	1.29
75880	41	0.15	12019	102	408	47	2.79	1.32
76235	39	0.15	11837	103	384	38	2.54	1.27
76543	41	0.15	11913	102	384	45	2.54	1.26
76956	42	0.15	11803	102	384	45	2.54	1.27
77211	42	0.15	11820	102	384	45	2.53	1.27
77613	41	0.15	11782	102	408	50	2.53	1.35

Table 7 Engine conditions @ sampling for Oceania Vessel 5 (OV5)

Total Eng. Hrs.	Temp.° C	Scav. Air Press. (bar)	Main Eng.kW @ sampling	Main Eng. RPM @ sampling	Consumption Ltr/day	BN (Used Oil)	Fuel Sulfur %	Cal. Feed Rate g/kWh
71639	43	0.14	8474	99	384	43	3.03	1.77
72065	42	0.14	8523	100	384	54	3.03	1.76
72471	34	0.14	8551	99	384	47	3.04	1.75
72722	42	0.14	8534	100	384	45	3.04	1.75
73034	42	0.12	8534	99	384	38	3.18	1.75
73469	44	0.13	8316	97	384	34	3.18	1.75
73719	41	0.12	8530	99	384	50	2.65	1.76
74058	40	0.10	7902	92	384	47	2.65	1.90
74408	42	0.14	8553	99	432	43	2.66	1.99
74795	41	0.10	7959	92	384	52	2.45	1.88
75127	42	0.14	8675	101	408	52	2.45	1.83
75413	41	0.12	8249	96	384	43	2.72	1.82
75705	42	0.14	8675	101	408	43	2.45	1.83
76117	41	0.13	8604	100	384	61	2.57	1.74
76396	41	0.12	7577	96	408	45	2.57	2.10
76768	41	0.13	8307	96	338	45	2.54	1.58

3.4 Total Base Number Monitoring of Both Sailing Routes

The base number (BN) of the cylinder drain oil is affected by the fuel sulfur concentration. The cylinder oil BN for the monitored engine is 70 mgKOH/g (*see table 3*) and the cylinder oil feed rate varies depending on sulfur contents of fuel oil for combustion in the engine and rate is in g/kWh (*see tables 5 to7*). The higher concentration of sulfur in the fuel oil produced more acidic sulfur during combustion. The acid formed condenses on the liner surface and the alkali provided by the cylinder lubricating oil will neutralize the acid. From this, it is theoretically understandable that reducing fuel sulfur level or higher level of BN in cylinder oil and feed rate, the higher the level of BN in drain oil. The demand for optimizing neutralization and the demand for the appropriate oil film, that is the forming capability is a constant challenge for engine design as the sulfur content of the fuel varies from each point of bunkering locations. With a fixed BN for new cylinder lubricating oil the neutralization demand can be met by adjusting the feed rate, but the required oil film properties are proportional to engine operation which is difficult to attain. The subject ship engines' remaining alkali number is tested under the guidelines of ASTM D4739, and the results are graphically represented according to the sailing routes. The Northern Pacific Ocean ships are AV1 and AV2, while the Southern Pacific Ocean ships are OV5 and OV6. The figures are as follows.

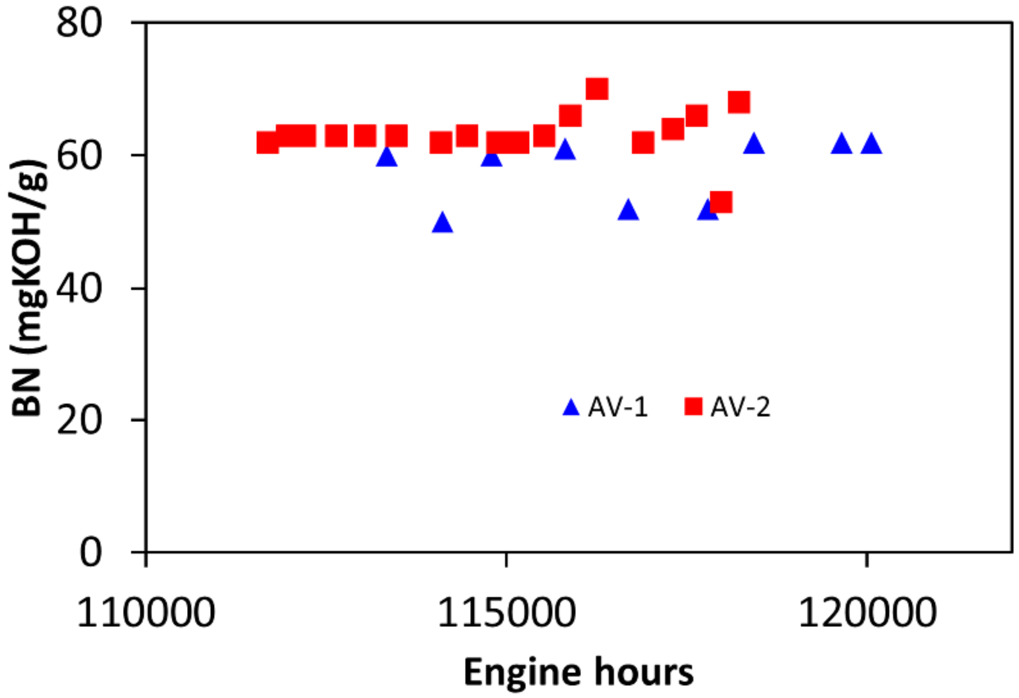


Figure 2 BN of Northern Pacific Ocean Ships and total engine hours

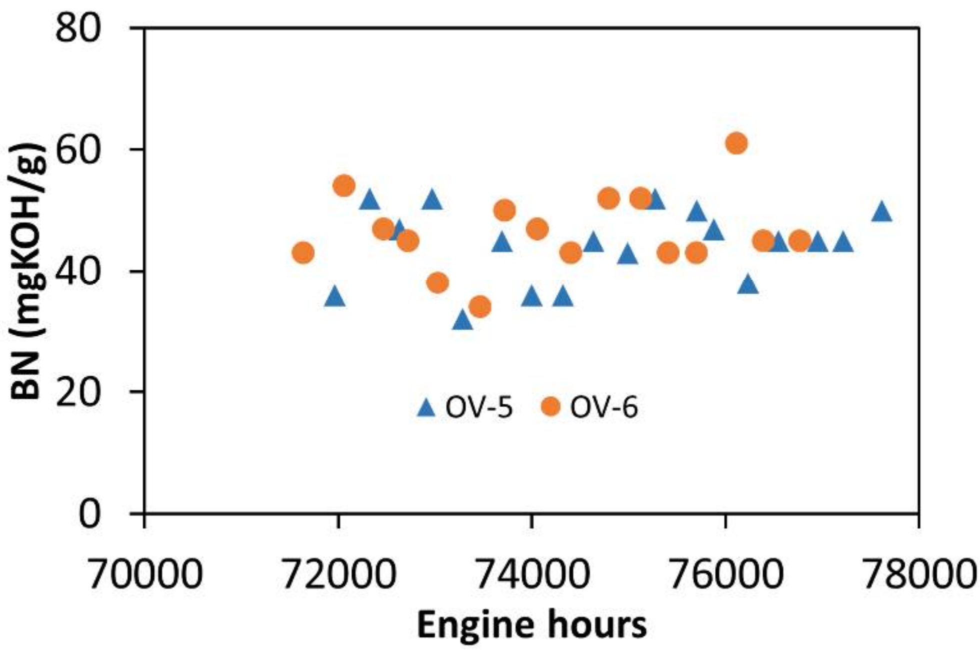


Figure 3 BN of Southern Pacific Ocean Ships and total engine hours

3.5 Wear Elements Comparison and Explanation

The goal is that individual cylinder liner wear conditions are monitored but the engine design is common drain pipe sampling is the only option to take drain cylinder lubricating oil. In the absence of common sampling, the variations in combustion and lubrication conditions affect the engine settings. This is reflected in fuel atomization and the sequence of ignition. During this project, the common sampling of the liners lubricating oil does help to evaluate the wear amount of cylinders liners and the overall performance of the engine in respect of output power.

Evaluation of wear conditions of marine engine cylinder liners using drain cylinder lubricating oil and engine performance data analysis makes it possible to monitor wear more regularly before overhauling. This method expanse maintenance management, timing, and cause of wear that is occurring can be traced and necessary actions or steps to minimize cylinder liner damage. Depending on the situation steps such as increasing the cylinder lubricating oil feed rate or stopping the engine to correct faulty equipment or isolation while continuing operation on auxiliary engines. Adjustment of the lubricant feed rate to minimize acidic corrosion by neutralization is imperative to the satisfactory protection of cylinder liners and piston rings.

The subsection highlight elements that indicate wear of liner, not the mechanisms. Cylinder drain oil reading and analysis of the total wear between cylinder liner and piston rings, it is known that the large portions of iron in oil sample is from wear between the rings and cylinder liner. Although Iron in scrape-down cylinder oil data is being collected continuously and monitored for both routes are Northern Pacific Ocean and Southern Pacific Ocean.

The drain cylinder oil samples were analyzed using JOEL X-ray fluorescence equipment model number JSX-3100RII in a 30kV tube and collimator of 7mm to count the number of metallic particles found in the oil samples at a rate of 100 seconds in the air. The equipment in figure 4 is an X-ray used for quantification of wear elements in a used oil sample.

Using XRF on drain oil samples from cylinder liner for condition-based monitoring can potentially facilitate the detection of engine deterioration during in-situ testing. By integrating trend data with equipment monitoring data, an effective monitoring system can be created and, such trend data will set standard guidelines for effective application of condition-based monitoring.

A fundamental parameter (FP) is used for determining element concentrations in oil samples. The use of FP calibration is required since multiple elements in oil samples will cause matrix effects (Criss J. W et al 1968)

$$C_i = K_i * I_i * M_{i\,s}, \qquad (1)$$

Where:

K_i is the calibration coefficient,

C_i is the concentration of the element in the sample,

I_i is the intensity of the XRF signal due to the element and

M_{is} is the matrix correction factor.

Elements found in oil samples are represented by the subscript i, while C represents their concentration. For calibration purposes, the coefficient K is the reciprocal of the element intensity energy level when the oil sample is pure, it is a single layer with no contaminants or metal fragments that can deflect X-rays.

Figure 4 JOEL X-ray equipment

The wear elements are the majority in the drain cylinder lubrication oil in both the Northern Pacific Ocean (AV1 & AV2) and Southern Pacific Ocean (OV5 & OV6).

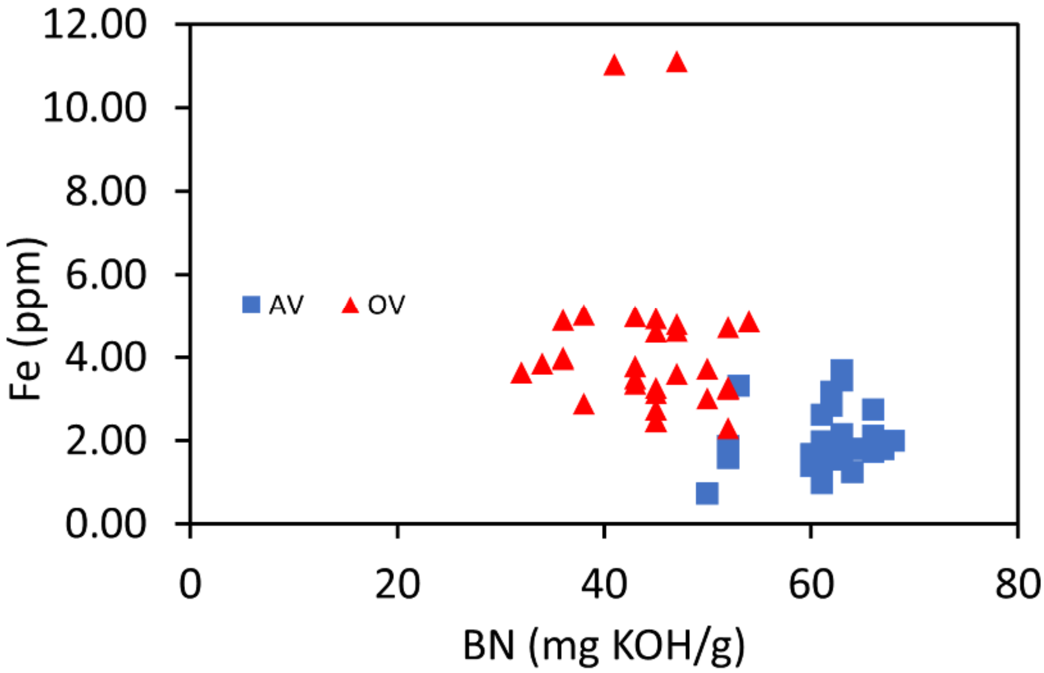


Figure 5 The Iron quantity and Base Number (Alkali) for all routes

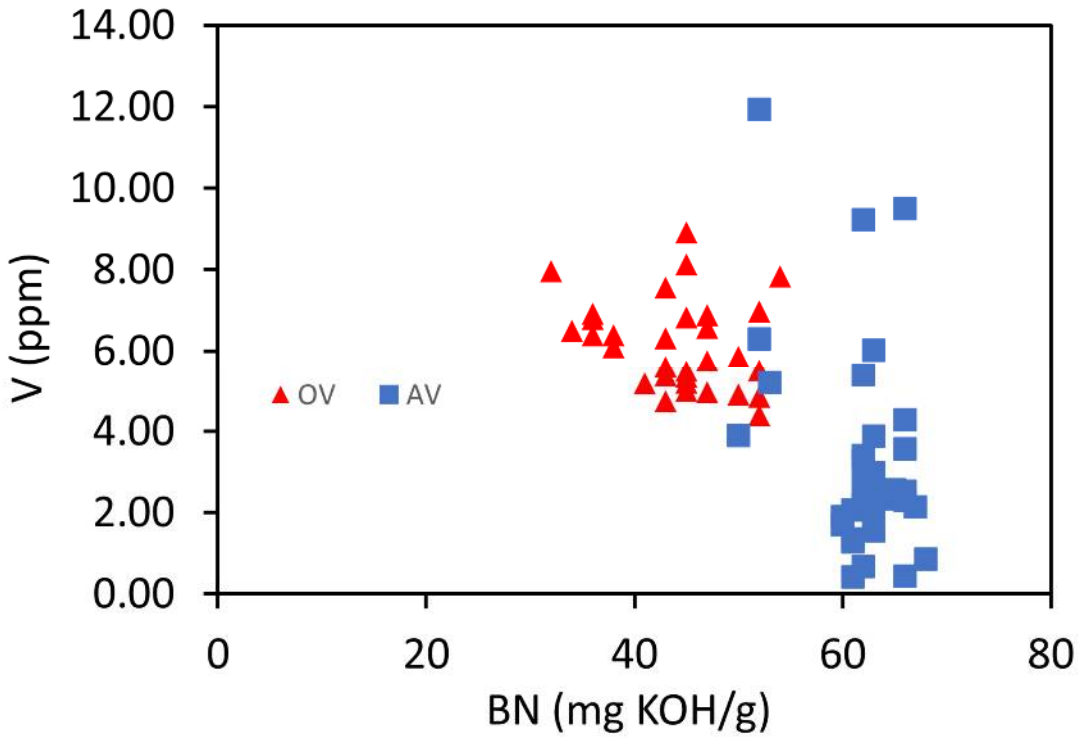


Figure 6 Vanadium quantity and Base Number (Alkali) for all routes

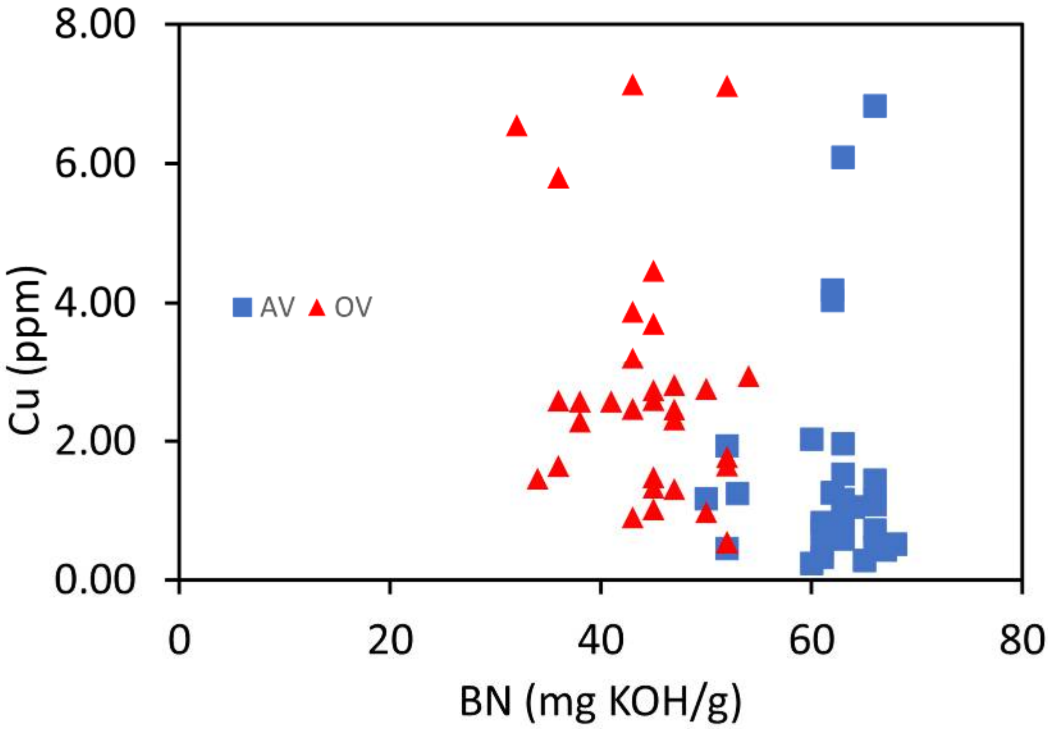


Figure 7 Copper quantity and Base Number (Alkali) for all routes

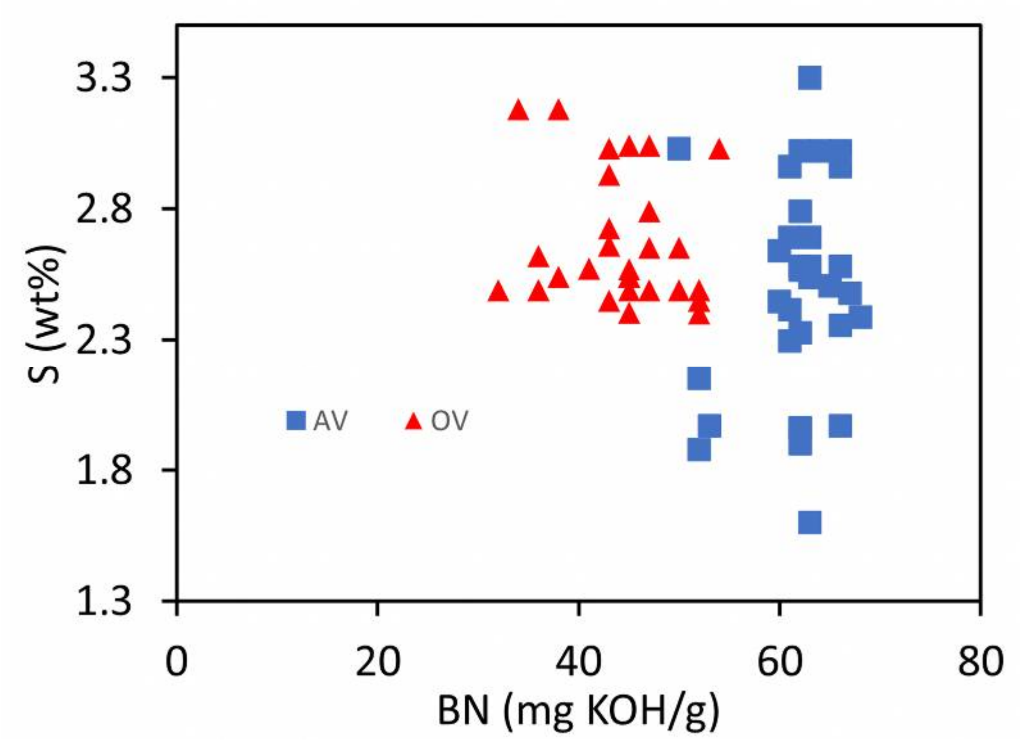


Figure 7 Sulfur quantity and Base Number (Alkali) for all routes

3.6 Summary of Monitored Results

The subject ships are Pure Car Carrier (PCC) operating in North America and Oceania. All the subject engines burn sulfur fuel oil ranges from 1.27 – 2.38 %(wt.). Fresh cylinder lubricating oil standard base number (BN) is 70 mgKOH/g for the engine. Typically, an inspection of cylinder liners and piston rings has a black stain and the ring pack showed signs of deposits from the exhaust phase of the cycle. Drain cylinder oil analysis showed that residual BN most at 60 mgKOH/g for the Northern Pacific Ocean ship (NPOS) while Southern Pacific Ocean ship (SPOS) between 40 and 55 mgKOH/g for the residual BN. The average RPM for SPOS is 100 and NPOS is 103 for the whole period of monitoring. There is a situation whereby the lubrication strategy is adjusting the feed rate to temporarily protect the cylinder liner from scuffing. Unfortunately, the opposite result is obtained whereby higher residual BN and abnormal wear occur thereby increasing the level of iron particles in drain cylinder oil.

The graph of figure 5 above shows the iron content and residual BN measured from the drain oil samples of both NPOS and SPOS. It can be seen clearly that the residual BN is higher for NPOS and lower the amount of iron that the wear is mitigated for these engines. For SPOS the opposite lower BN and higher iron in drain cylinder oil samples. The trend seems to favor higher residual BN to protect cylinder liner from metal-to-metal contact with piston rings but more information on operating and close findings on this phenomenon of both NPOS and SPOS.

3.7 Wear Discussion

The quantity of iron in the cylinder drain oil reflects the wear of the cylinder liners and piston rings. Wear assessment is by measuring the total iron worn out during the mechanical movement. Wear can be caused by adhesive, abrasive wear, or corrosion wear, must factors causing it such as cat-fines in the fuel, micro-seizures and/or scuffing, magnetic wear-particles. The wear particles by cold corrosion are oxidized form and cannot react to Particle Quantification Index (PQI) test. By onboard methods for detection is possible to use chemical reactions to detect iron oxides in drain cylinder oil samples. For the PQI test results is ferromagnetic and corroded iron can react to this test to quantify total iron wear from the cylinder liner.

Depending on the method of measurement, different results can be obtained, and it is advisable to consider all the methods to get a true picture of wear in the cylinder liners. For example, if the PQI method shows low iron, it must be complemented by results on analytical quantification of drain oil samples to evaluate the wear quantity. If the remaining BN is low, it could be acidic corrosion, and if the remaining BN is high the engine is likely to deposit is building around piston rings and piston grooves. Using only the remaining BN as a metric is not enough for condition monitoring of cylinder liner and piston rings.

To evaluate the degree of wear of the subject ships, based on the drain cylinder oil the project does not confirm wear mechanism and types of wear the analyzed results for iron readings from drain cylinder oil sample. The indicator of the total wear from Figures 5, 6, 7 highlights most elements from cylinder liner, piston rings, and fuel oil respectively. The greater quantity of iron in the cylinder drain oil is coming from wear between the rings and cylinder liner. Although Iron in cylinder oil samples is collected continuously and compared with sister ship sailing on the same voyage. There is little difference from each other, and it is non-sporadic in nature of wear of pistons rings and cylinder liners.

3.7.1 Cold Corrosion

Residual fuel contains a certain percentage of sulfur as a component of the fuel oil and prompted the development of alkali for cylinder lubricating oil which could neutralize the acid formed during combustion of fuel oil. The introduction of alkaline in cylinder oil means that corrosive wear in the diesel cylinder liner of an engine fluctuates when the sulfur content in the fuel ranges from 1.23% to 2.78%. The current study

Southern Pacific Ocean ship (see figure 5) indicated the wear pattern that may be attributed to acid corrosion (CIMAC 2017).

The acid condensation on the cylinder liner wall is influenced by the following:

1. *Fuel oil Sulphur percentage:* During combustion among the by-products is sulfur trioxide as gases and the further reaction produces acidic sulfur which condenses on the liner wall. Also, the acidic concentration is in proportion to the percentage of sulfur in fuel oil. The below chemical equation illustrates the process of sulfur figure 7 shows sulfur contents for the fuel oil used for both routes.

$$2SO_2(g) + O_2(g) \rightarrow 2SO_3(g) \quad (2)$$

$$SO_2(g) + H_2O(l) \rightleftharpoons H_2SO_3(aq) \quad (3)$$

$$SO_3(g) + H_2O(I) \rightarrow H_2SO_4(aq) \quad (4)$$

2. *Scavenge air:* Scavenge air temperature influences cold corrosion. Low scavenge air temperature increases the quantity of condensed water produced in the cooler, the water is likely got to the combustion chamber that eventually produces acidic compounds causing cold corrosion. The presence of water in the cylinder liner may cause limited lubrication and possibly seizures and scuff of the liner. When operating an engine with a low scavenge temperature, it is vital to ensure the cooler and mist catcher drain all free water promptly. On the other hand, high air temperature reduces the amount of

condensed water produced. The high air temperatures increase the inlet air (*see equation 1*) volume for a given mass and this may improve the scavenging of exhaust gas. Also, the merit of low air temperature is an improvement in engine efficiency because of compression and firing pressures for combustion.

3. *Liner wall temperature:* The increase of dewpoint because of the slow steaming of an engine means that piston stroke will be slow leading to a lower temperature than promoting cold corrosion. When the engine is at full speed cylinder liner temperature increases as a result acidic condensation is reduced cold corrosion will be mitigated. Also, it is required that cylinder lubricating oil maintain an acceptable lubricant oil film at higher or lower liner wall temperatures.

3.7.2 Incomplete Combustion Conditions

The troubles that are related to poor or incomplete combustion are enormous and complex. It can vary with individual engine cylinders and the environment of operation. The most significant problem of incomplete combustion is the fouling of an engine. The fuel injectors, exhaust ports, and turbocharger failure contribute to burning fuel oil inefficient combustion (Eid S Mohamed 2018). Marine fuel oil is blended of cracked residual with higher aromatics carbon mass, meaning without catalytic element ignition is difficult.

Other challenges are engine knocking, uneven combustion, ignition delay, and steep ignition pressure gradient. As a result, increased engine components fatigue, excess thermal load, and higher exhaust temperature. The long-term effects are fouling and building of deposit will occur when the engine is operated at low steams or low loads.

Conditions of influencing incomplete combustion are as follow:

- Fuel injection timing depending on cylinders sequences
- Incorrect fuel oil boiler temperature and pressure setting
- Poor atomization of fuel oil by a faulty injector
- The presence of fuel asphaltenes cause un-atomization
- Excessive catalytic elements in fuel oil

Any combination of the above stated will disrupt the combustion of fuel oil and lubricating oil film because of fuel chemicals' contents. This results in a high thermal load of the liner wall delay combustion of fuel oil charge and increasing iron (Fe) in the drain cylinder oil samples (J. Keller 2009). Although we cannot specify reasons for the project engines rather consider the likely reasons such as inconsistency of fuel oil chemical contents. This can happen when asphaltenes are found in fuel oil, viscosity variations, and mechanical malfunctioning of a fuel injector or the nozzle holes.

Incompletely combustion fuel is scavenged by the cylinder lubricating oil and detected in the drain cylinder oil samples of **Vanadium** and increase in Viscosity, as well as by other factors that serve as indicators for incomplete combustion of fuel oil. As fuel oil is injected at a certain rate into the cylinder and cylinder lubricating oil is injected simultaneously, if the quantity of unburned fuel is 0.1% of the injected fuel oil resulting in a dilution of about 12% of the cylinder lubricating oil. The dilution will infringe cylinder lubricant oil film by un-combusted fuel oil from a faulty injector or other factors. This is expected to reduce the lubricating properties of the cylinder lubricant oil and cause an increase in abrasive wear. Poor ignition or combustion of fuel oil cause delay burning, and this may also be detected in drain cylinder oil sample calcium concentration in the drain oil.

Incomplete combustion for the subject ships is accessed by the **Vanadium** in the drain cylinder oil in figure 6 with residual BN of oil samples. It is observed that Southern Pacific Ocean Ships may have incomplete combustion of fuel oil and no report of fuel injector malfunctioning during the period of monitoring the engines. This may have contributed to the wear increase of iron (Fe) element from cylinder liners for the Southern Pacific Ocean ships (OV) in the graph of figure 5. It is known that the lubrication characteristics of cylinder oil film deficiency caused an increase in the iron (Fe) in the drain cylinder oil. A very minor change in combustion conditions for the cylinders unit can cause a significant increase of iron (Fe) element because of deterioration in fuel oil combustion.

It is also reasonable to assume that incomplete combustion affects neutralization of acid produced, note that the dew point of acid is a function of sulfur in the fuel, so the gas pressure and temperature of cylinder liner surface which condensed on the influence dew point that acid condensation occurred and increased the corrosive wear that damaged the cylinder liner surface. This iron (Fe) is detected in the drain cylinder oil samples. Finally, the coincidence of high Vanadium and high iron (Fe) suggests that occurrence of inferior combustion, fuel dilatation, and hence abrasive wear occurred caused by deficient cylinder lubrication oil film.

3.7.3 Piston Rings Abrasion

When wear does occur the increased iron (Fe) in the drain cylinder oil, in many instances corresponds with increased **Copper**. This shows that abrasion between the piston rings and cylinder liner wall, and as the brass rubbing strip wears down. Piston rings abrasion against the liner surface is also seen to occur whenever there is an accumulation of deposit on the piston top-land. Abrasive wear between piston and liner surface can be traced in drain cylinder lubricating oil samples as an indicator in figure 7 for copper and base number (BN) of oil samples. Although, deposits can only be confirmed by physical examination of piston top-land which disturbs the lubricant film and may cause scuffing. Based on inspection reports the deposit has accumulated on the piston top-land leading to movement restriction of the ring, affecting the piston movement alignment according to inspection reports issued by Southern Pacific Ocean Ships (OV) engineers.

Though my thesis does not specify the normal or abnormal level of copper in drain cylinder oil samples to flag engines for emergency maintenance work from the study of comparison it can be inferred that Southern Pacific Ocean Ships experienced more wear quantity of copper during the operating the engines. To affirm the prognosis of incomplete combustion in this study we consider copper element among monitor elements in drain cylinder lubricating oil for the study.

4. Machine Learning Model and Monitoring
    4.1 Gaussian Graphical Model (GGM) approach
        4.1.1 Kullback-Leibler Divergence
    4.2 Data validation from GGM
    4.3 Collaboration of samples data with GGM
    4.4 Model application

Chapter 4

Machine learning Model and Monitoring

Data from a marine diesel engine on cylinder liner wear process is monitored by measurement using a micrometer gauge. The top section of the cylinder liner is the maximum wear area that usually occurs because of high-thermal load and tribological stresses during the ignition phase of the engine. Excessive wear of cylinder liners is among the major reason for mechanical failures of 2-stroke slow marine diesel engines. The fact is almost all failures occur in every single stroke, once the wear exceeds a specified threshold it becomes obvious through cylinder oil sample analyst. The wear in cylinder liner is mostly caused by abrasive particles or soot between the piston ring surface and cylinder liner surface. The mode is produced during combustion of heavy fuels oil and cylinder lubricating oil degradation, when the oil film thickness is below expectation the soot particle formed from combustion can cause 3-body abrasive wear. That is metal-to-metal contact and solid particle in between the sliding surface. Even though metal-to-metal do occur, it damaged both the liner surface and rings surface. This wear occurs because the soot particles solidify and become harder to cause 3-body abrasive wear on the engine parts.

Model is useful on the decision to inspect and maintenance schedule management of marine diesel engine. Several models can be used for monitoring mechanical wear and failure probability before exceeding the threshold leading to complete mechanical failure. We make use of the Gaussian Graphical Model (GGM) on the oil samples from the monitored ships. Gaussian Graphical Model process has been broadly applied in modeling machinery or equipment reliability. This is to access and predict equipment reliability, maintenance, and repair-replacement policies. Also, because of multi-variety elements, GGM is more flexible in its model utilization. GGM can have a monotonic trend for modeling engine operating times that will need both repair and non-repair failed equipment parts. In policy management measures the repair and replacement model where based reflect on the Gaussian model process while reactivation depends on repair times after failure event according to work. A GGM for obtained or analyzed results in the view of inspections and preventative for cylinder liner for an engine. A Gaussian process on the maintenance model is correlating and interpretation of oil sampling of ships for this project.

When processing data that include anomalies in an event the raw data from the statistic and information-theoretic analysis will reveal the information on abnormal parts. For example, cluster analysis for the whole raw dataset samples that include anomalies, by partitioning into small populations or datasets will make the comparison easier with the normal dataset. By the statistical processing or information analysis testing with proximity reveal the characteristic of abnormal data, which makes such a method quite appealing for the inspection of both cylinder liner and piston rings. Moreover, anomalies with different data sizes have different analytic distributions and characteristics that may require deeper data observation. More also, anomaly distribution data do not usually follow a specific known pattern.

Also, GGM can employ Kullback-Leiber Divergence (KLD) on anomaly detection for interpretation of data and applicable interphase. The anomaly detection in cylinder liner inspection may be modeled that support the adoption in an application domain. The simple form of anomaly detection can support distinguishing the abnormal data from the normal data distribution. Data with anomalies are close to each other from a KLD point of view. On the other hand, the abnormal ones are far apart from the normal clusters. When there is a baseline the dataset from the normal event makes it possible to compute the KLD from analyzed oil samples data. The anomalies can be detected, and baselines establish in subject ships monitored.

Kullback-Leiber Divergence (KLD) is used for anomaly detection in data series generated by drain cylinder oil samples analysis. In this work, the cylinder liner generated wear particles that are modeled to access engine performance based on the samples collected from the engine and analyzed using the X-ray equipment machine. The KLD maps the wear elements by using the value of ray intensity signal measurement that gives approximate element molecule in a drain cylinder oil sample (Criss J. W et al 1968). With the cylinder inspection, an algorithm of the generated data from a sampling of oil work analysis can detect cylinder liner mechanical anomaly during operation.

The KLD is an algorithm based on the assumption's distribution of the analyzed cylinder oil sampling data. It is adapted to include distribution models whenever they are available for a specific wear quantity. The KLD naturally measures the discrepancy in the data information content between various data sets, thereby detecting an anomaly, and does not require knowledge about the nature of the wear anomaly or the engine characterization.

The aim of this chapter is an application of a Gaussian graphical model (GGM) on wear sequence on cylinder liner and piston rings. We make use of it to assess the ship's performance using the drain cylinder lubricating oil to analyze the failure mode of an engine (Wang et al 2012).

In the field of condition monitoring and diagnostic engineering of marine engine cylinder liner and the piston rings there are thermal, sound sensors monitoring the liner walls performance and drain oil analysis of the machinery. In this project we focus on the internal combustion of the engine, researching factors that contribute to the wear of cylinder liner as the main goals. This chapter supports developing an algorithm using Gaussian Graphical Model for condition monitoring.

4.1 Gaussian Graphical Model (GGM) approach

To start a structure learning program taking closer to consideration of Gaussian graphical model, and assume a random variable X_i for $i \in 1 \dots . n$ are normal distribution, $X_i \sim N(\mu_i, \sigma_i^2)$, while the vector of X of the n random variables of X_i have a multivariate distribution. By letting $X \sim N(\mu, \sum)$. $\sum$, will be invertible in positive symmetric, it can be rewritten as $\sum \; = K^{-1}$, where K is a precision matrix and probability density function of Xas follow:

$$p(x|\mu, \Sigma) = \frac{1}{(2\pi)^{n/2}|\Sigma|^{1/2}} \exp\left[-\frac{1}{2}(\mathrm{x} - \mu)^T \Sigma^{-1} (\mathrm{x} - \mu)\right] \qquad (1)$$

$$p(\mu, K) = \frac{|k|^{1/2}}{(2\pi)^{n/2}} \exp(-\frac{1}{2} \textstyle\sum_i q_{i\,i}(x_i)^2 - \sum_{i<j} q_{i\,j} x_i x_j) \qquad (2)$$

The term $q_{i\,i}(x_i)^2$ is the node potential of $x_i$and in another is $q_{i\,j} x_i x_j$ is the edge potential of x_i, x_j. This makes it possible to estimate the coefficient of the precision matrix. There is a merit of computing in the precision matrix because of the possibility of the covariance matrix that makes it possible to correlate the network at zero element $\sum_{i,j} = 0$ showed that X_i and X_j are marginal independent without other variables (Friedman J et al 2008). In such an independent method, it indicates that 2 random variables are not active trails without the nodes.

This precision matrix indicated a sophisticated and likely relationship between the random variables. For the coefficient in 0 meaning that the 2 variables are only conditionally independent that acknowledge other nodes. The conditional independent is expected to be real variables and important to structural learning. Therefore, the graph is without edge connection of nodes, and this makes it more convenient to illustrate it as follows in this example.

K =

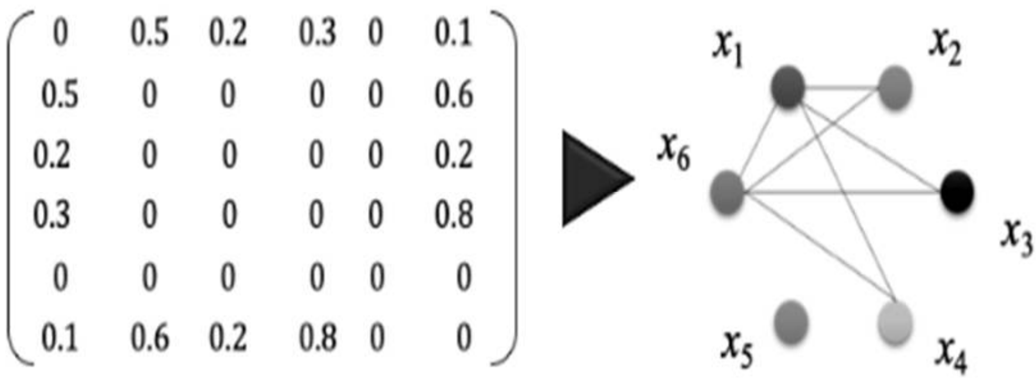


Figure 1 GGM example with Precision matrix K Relationship

Gaussian Graphical Model is used to model the network of interest, and the estimating the precision matrix can be used to do the LASSO regression of the nodes and repeat it for each other as seen in figure 1. For the regression at each node, it is formulated by solving the following:

$$\hat{x} = \arg\min(x)\|Y - Zx\|^2 + \lambda\|x\|_1 \quad (3)$$

The dimensional vector N is Y with each entry as a node at s certain dimension from the sets of data considered. The data have P nodes which are shown at the right in figure 1, and Z is $N \times (P-1)$ in dimensional matrix with each column. While X is P – 1 the dimensional weight vector that we estimated. Also, the last term l_1 in the equation is a sparse penalty term enforcing the sparsity. Ideally, the above regression makes it possible for each node to repeat itself and eliminate 0 value edges. There are several assumptions associated with sparse regression as follow:

- Covariates are not dependent
- Irrelevant covariates will not be correlated with relevant covariates
- The samples quantities values can be converged

For this project, Gaussian Graphical model is an ideal machine learning computation because of real applications on a precision matrix that include multi variates. And most nodes are readily connected and dense, which makes them tractable and interphase friendly.

4.1.1 Kullback-Leibler Divergence

Kullback-Leibler Divergence (KLD) is a measurement of the information that is relative to the entropy. In a set of normal data, the KLD will be relatively small, while the opposite in anomalous data shows high KLD. The threshold does not require categorization to define or prior knowledge about the data. This makes it possible to define threshold when using Gaussian Graphical Model for machine learning. Based on this study from the drain cylinder oil sample result will be used for anomaly detection during engine operation. As many elements in the sample can be estimated by Gaussian distribution, though it is continuous random variables. Using the estimation KLD is used to find the anomaly in subject ships. The application of KLD has merit on anomalies size assessment for the inspection of a marine 2-stroke speed engine.

There are 2 random variables of $p\ and p'$ with a finite-dimensional set, then the system settings of p in p' is defined below:

$$H(p||p') = \sum_{i=1}^{N} D(x_i) \log \frac{P(x)}{p'(x)} \qquad (4)$$

The $H(p||p')$ measured the regularity of sequential dependency and equate it to 1. If the random variable is determined by other variables to make independent that is separate. For the 2 dependent random variables f $(p\, and p')$ the system measures in random and reduced uncertainty variables in the set. It is a mutual exchange of information between the random variables. Whereby setting a threshold for selection of anomaly data from subject ships when exceeded the value. In addition, the system conditions will reflect the dependencies of the random variables and their relationship between the time series of sampling. Another merit is on the sample irregularity results that can cause unpredictable outcomes in condition monitoring of marine engines. Therefore, it is important to establish a baseline for anomaly detection for ships according to the environment of operation.

To finalize the KLD for the 2 random variables from the above system set is defined as follows

$$KL\ (p||p') = \int dx\ p(x) \ln \frac{p(x)}{p'(x)} \tag{5}$$

Because of the 2 random variables, covariance can be further expanded as below

$$a_i = \int dx_{-i}\, p(x_{-i}\,|D_A) \int dx_i\, p(x_i|x_{-i}, D_B) \ln \frac{p\ (x_i\,|x_{-i},D_A)}{p\ (x_i\,|x_{-i},D_B)} \tag{6}$$

In this project, KLD was used on drain cylinder oil samples elements to determine the possible standard of wear for the ships. The model computation helps to anomaly score each ship and compare them.

4.2 Data validation from GGM

The goal is to pinpoint the anomaly in ships operation. These abnormal conditions can be further isolated, investigated, and identify as the samples being tested. Before application on the X-rays test results from the subject ships, it is necessary to validate the Gaussian Graphical Model application.

The algorithm presented is an inverse covariance matrix to estimate while running Gaussian Graphical Model on results. For this purpose of validation, we make use of denotation as follow:

$$N = \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

The diagonalize matrix will be

$$\begin{bmatrix} I & -BD^{-1} \\ 0 & I \end{bmatrix} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} I & 0 \\ -H^{-1}G & I \end{bmatrix} = \begin{bmatrix} A - BD^{-1}C & 0 \\ 0 & D \end{bmatrix}$$

Where $XYZ = W \Longrightarrow Y^{-1} = ZW^{-1} X$,

$$N^{-1} = \begin{bmatrix} I & 0 \\ -D^{-1}C & I \end{bmatrix} \begin{bmatrix} (N/D)^{-1} & 0 \\ 0 & D^{-1} \end{bmatrix} \begin{bmatrix} I & -BD^{-1} \\ 0 & I \end{bmatrix}$$

$$= \begin{bmatrix} (N/D)^{-1} & -(N/D)^{-1}BD^{-1} \\ -D^{-1}C(N/D)^{-1} & D^{-1} + D^{-1}C(N/D)^{-1}BD^{-1} \end{bmatrix}$$

The above validate the precision matrix and covariance matrix as discussed in the earlier paragraphs. And for the Gaussian Graphical Model, it can be validated by Gaussian density as follow

$$p(x|\mu, \Sigma\ ) = \frac{1}{(2\pi)^{n/2}|\Sigma\ |^{1/2}} \exp[-{}^{1}/_{2}\,(x - \ \mu)^{\intercal}\,\Sigma^{-1}(x - \ \mu)]$$

And this can be rewritten for the Gaussian Graph as

$$p(\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} |\mu, \Sigma) = N \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} | \begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix}, N \begin{bmatrix} \Sigma_{\ 11} & \Sigma_{\ 12} \\ \Sigma_{\ 21} & \Sigma_{\ 22} \end{bmatrix}$$

With the above validation, the proposed computation of selected elements (node) can be resolved using the Gaussian Graphical Model for drain cylinder oil samples analysis by XRF.

4.3 Collaboration of samples data with GGM

These are the wear elements identified in the drain cylinder oil when analyzed using XRF. For the cylinder liner, the majority composition is iron (Fe) and copper in piston rings surface material. The monitoring is regular and continuous for the maintenance strategy, and the elements are listed in table 1 and the source of the wear.

Table 1 Elements in Drain Cylinder Oil and Wear Source

Elements	Sources
Ca, Zn	Oil Additive
Fe	Cylinder Liner Wall
Cu	Piston Rings Materials
V, S, Ni	Fuel oil
Ag	Bearings Materials

For each ship drain cylinder oil samples collected with XRF analysis these are represented in the graph in the following figures:

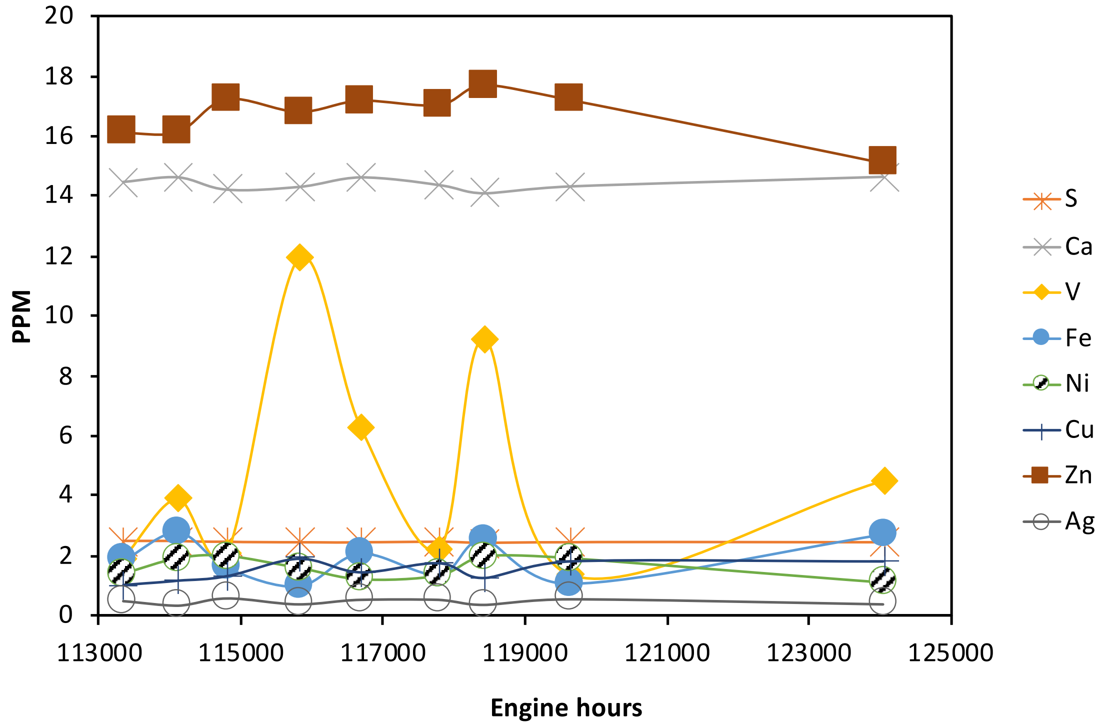


Figure 2 The graph of AV1 wear elements and engine hours

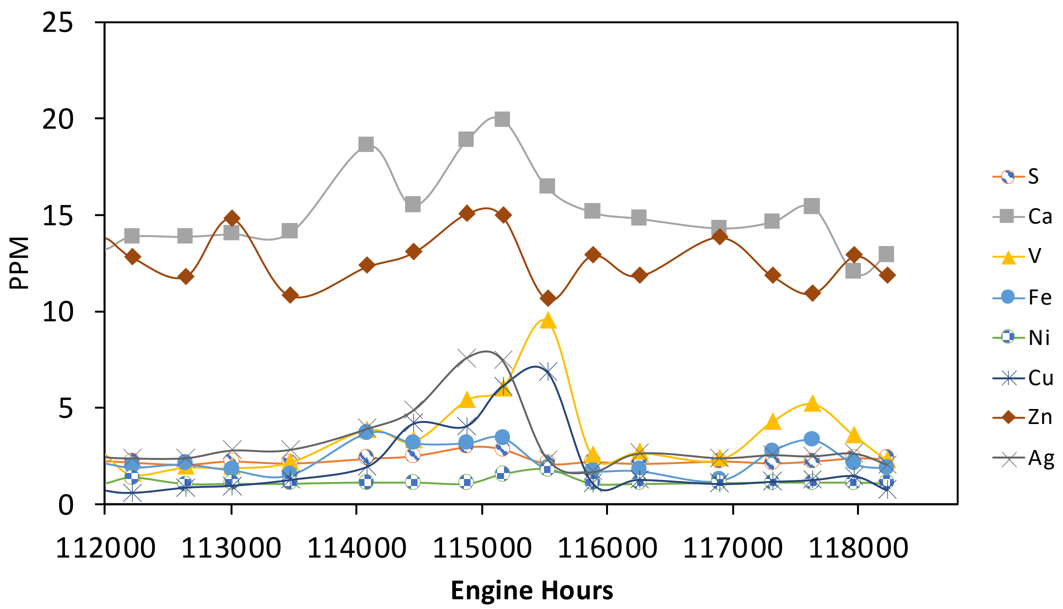


Figure 3 The graph of AV2 wear elements and engine hours

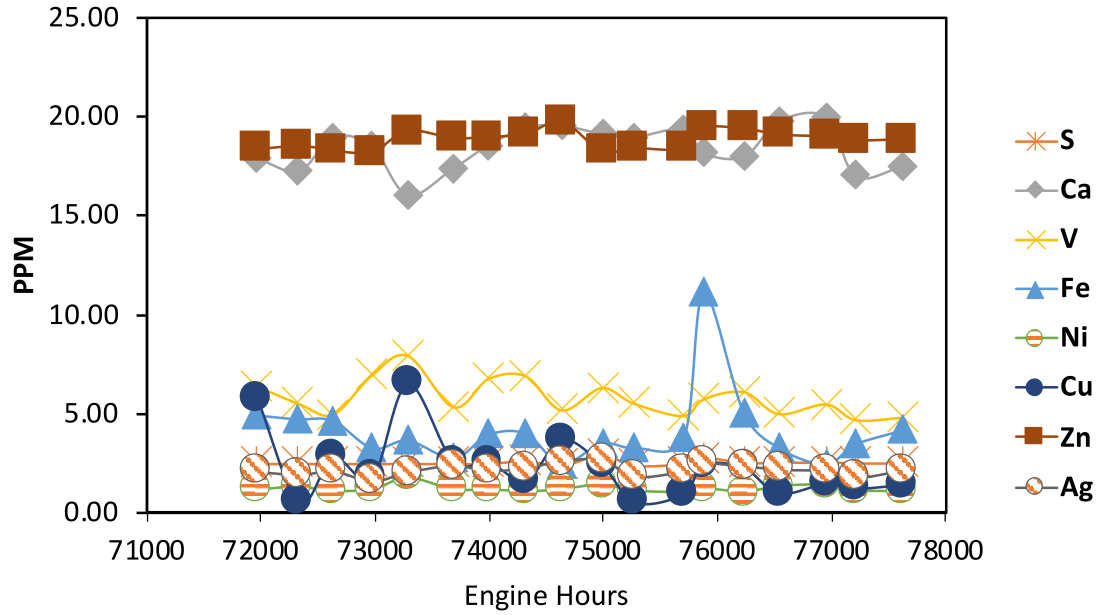


Figure 4 The graph of OV5 wear elements and engine hours

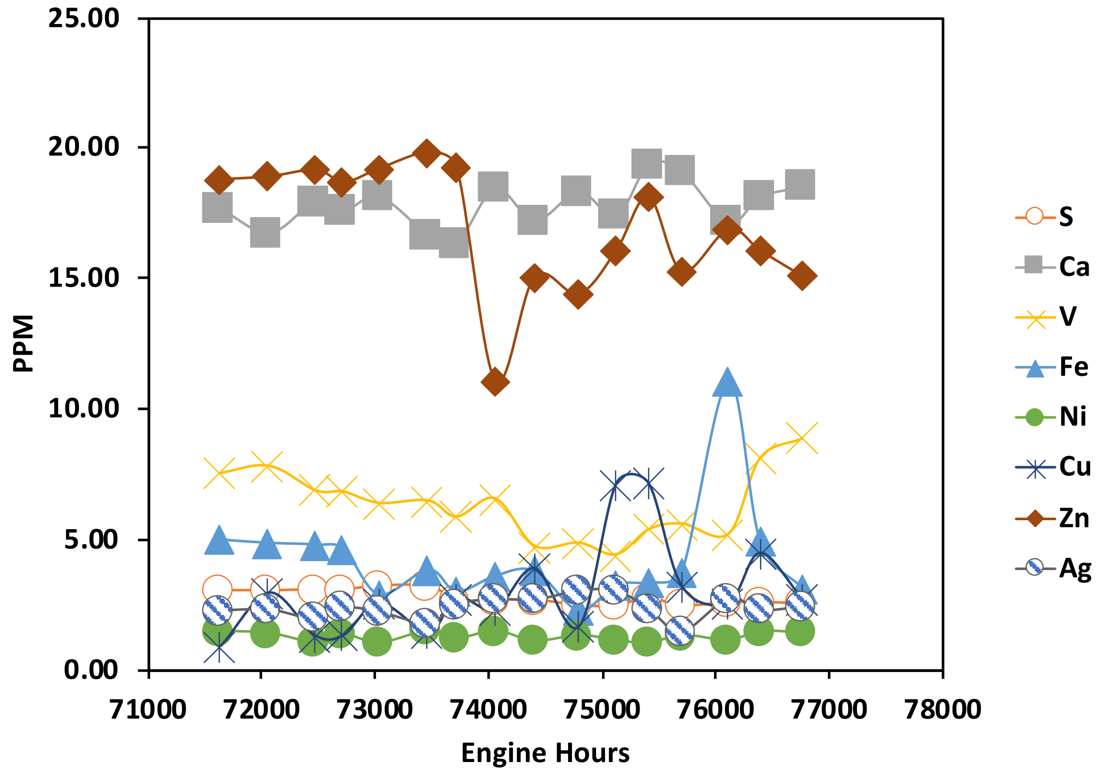


Figure 5 The graph of OV6 wear elements and engine hours

The next procedure is using Gaussian Graphical Model to compute the elements such as Sulfur, Calcium, Vanadium, Iron, Nickel, Copper, Zinc, and Silver in drain cylinder oil samples. We find the correlation between elements using the regression method as discussed above and, this makes it possible to eliminate zero value for the element. From the 8 elements (S, Ca, V, Fe, Ni, Cu, Zn, Ag) the matrix $\hat{x}$ will 8×8-dimensional matrix and the hypotheses of zero and non-zero conditions.

To map analyzed results data after using the Gaussian Graphical Model regression to align data 2 integers that each data set associated with the raw data results. This is the point where Kullback-Leibler Divergence (KLD) is required to correlate and build function when considering the random variable for each element. The KLD will measure the discrepancy between a node and over all nodes in the set. The process is step by step in repetition for each node and mapping of correlation will be drawn in the below figures for each subject monitored ships.

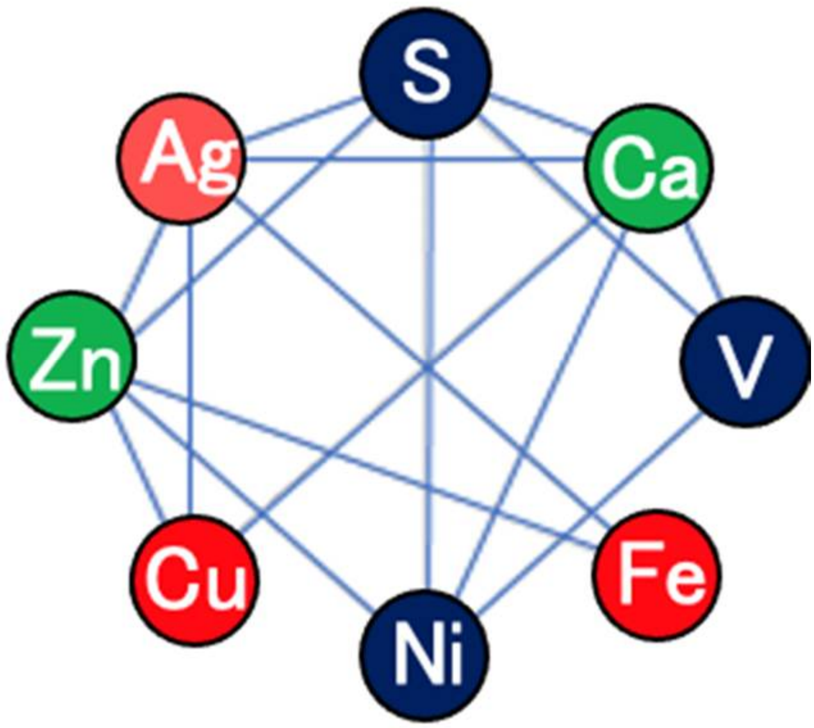


Figure 6 The GGM for AV1

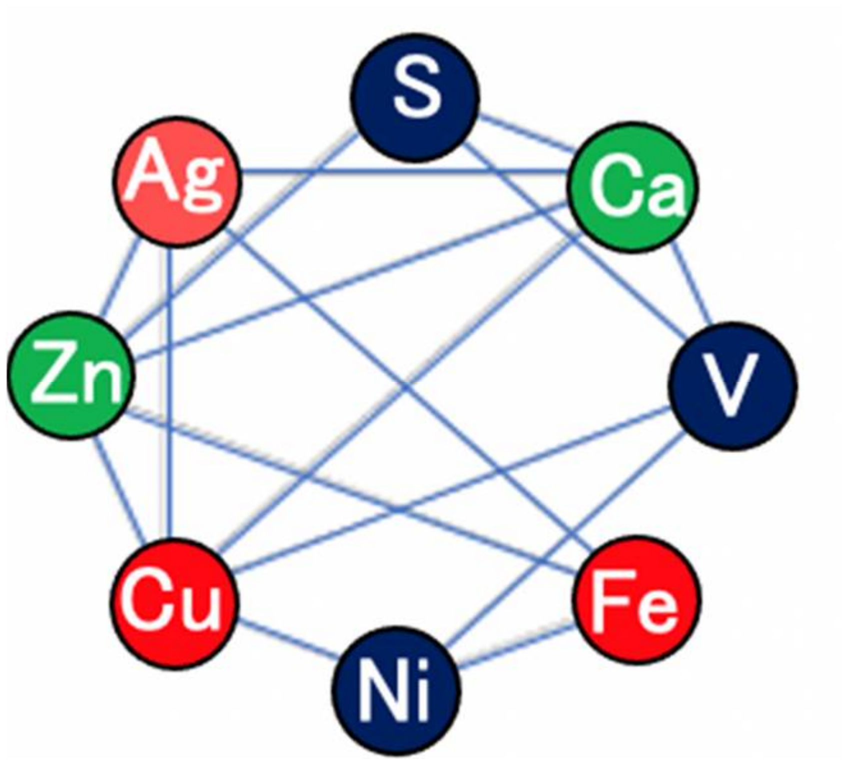


Figure 7 The GGM for AV2

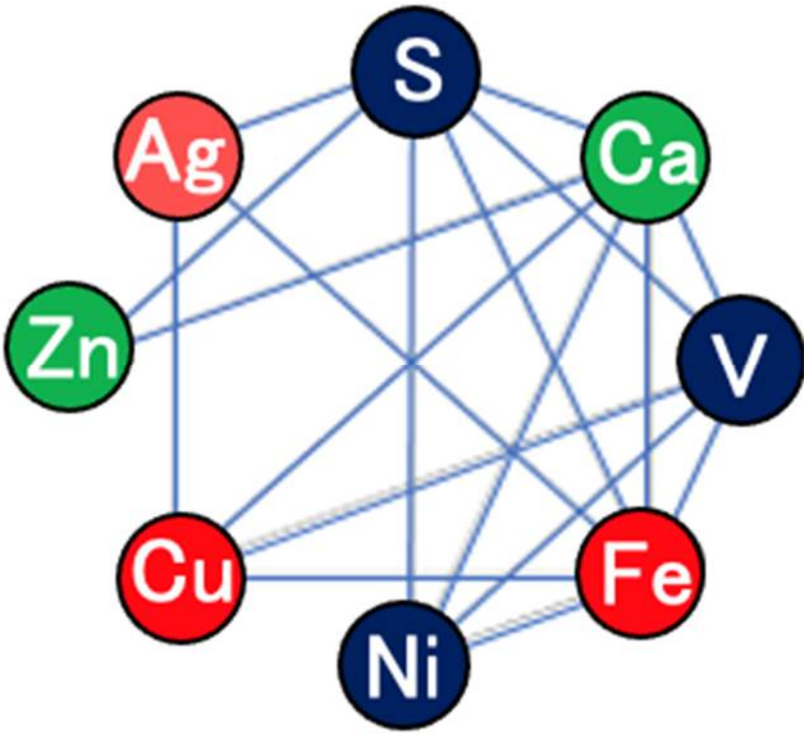


Figure 8 The GGM for OV5

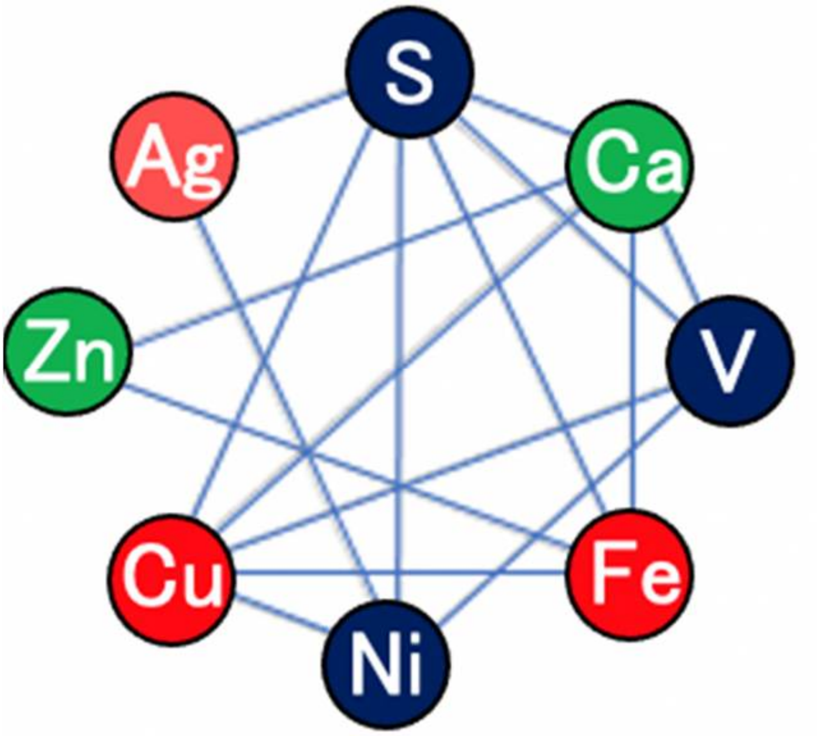


Figure 9 The GGM for OV6 using KLD

4.4 Model application

With the Gaussian Graphical Model, isolated elements in drain cylinder oil samples were computed with aid of Kullback-Leibler Divergence for each monitored ship. This section focuses on anomaly detection for each ship based on the analyzed oil samples collected during the sea operation. To proceed KLD filter outlined anomaly in the data set distribution. The merit of not depending on assumptions on the data distribution can be offset by the histograms.

The algorithms of GGM are unsupervised for anomaly detection for the model application. Using the histogram-based score will be in a combination of multivariate and univariate methods. This allows applying histogram-based anomaly detection to the unsupervised dataset. The frequency of samples is used to estimate the density of the dataset, and by proximity methods, the distance nodes can be computed by each instance of abnormality.

A histogram is a model splitting the dataset into different groups. Through several splits that are drawn at random to partitions algorithm for a large group is likely to be anomalies and by correlating nodes in multiple times then the anomaly can be detected in oil samples.

To apply it on monitored ships conditions-based monitoring, the recursive data was split in the dataset. Each decision is according to the kurtosis score and a value of random selective support. A kurtosis split is selected by the attribute (correlation) from dataset X. Each element parameter has max data h, and the attributes are binary which the node is either zero or one. This gives the kurtosis split into 2 sides or set. As a result, when the element analysis reached a peak, it may be a negligible contribution of external influence on the score. In some instances, the values are far from the mean distribution when probability mass is concentrated that is cluster or tail distribution mass of the dataset. We used kurtosis score measurement on the concentrated sampling hours during the monitoring based on the drain cylinder oil sample analysis from XRF.

By introducing a logarithm on the kurtosis score support focusing on the magnitude or threshold for the dataset and get eliminate influence from any small changes on the score. By this, we can measure clusters on the trail where the occasional values are far from the distribution. It is easy to depict normal and anomalous density functions in the dataset. Whereby d is dimensional, and n is samples number and to computes the kurtosis scores for the attributes and kurtosis sum as follow:

$$K_s = \sum_{a=0}^{d} \log[KX_a + 1] \qquad (a \in d) \qquad (7)$$

By selecting a random value from test result data represented using b

Therefore, according to the selected random the kurtosis split (a_s) for minimum and maximum is

$$a_s = argmin(\sum_{a=0}^{i} \log[KX_i + 1] > b) \tag{8}$$

We can have two subsets going by kurtosis split requirement at min and max values. With the kurtosis, scores define and established, for each ship sample that was analyzed by XRF, and the data obtained. We define anomaly score v with respect to the histogram as:

$$v = \sum_{i=0}^{d} \log(\frac{1}{hist(v)}) \tag{9}$$

hist(v) value is normal(max=1), and as the density decreases values increase from zero.

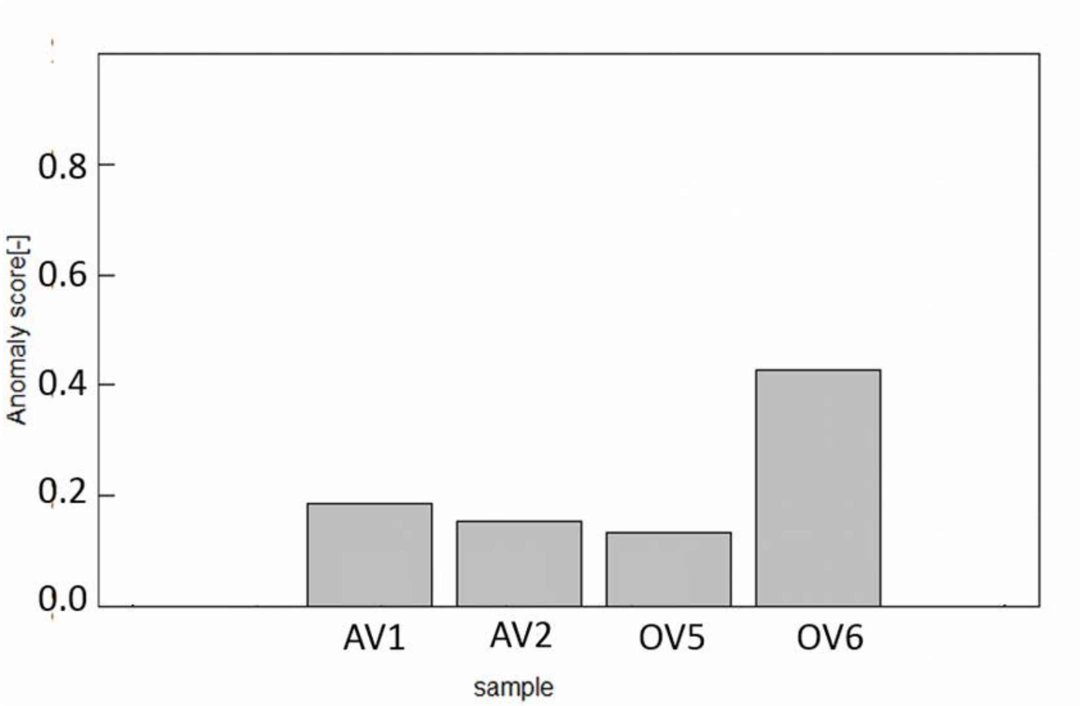


Figure 10 Anomaly scores for each ship

As discussed in the preceding paragraph about anomaly score for each monitored ship. The figure 10 histogram is for all monitored ships samples data. As explained above data computed indicate that the threshold anomaly score is 0.2 for the total samples collected for the conditions-based monitoring of marine ship engines. This figure showed that ship AV1, AV2, and OV5 are operating within the standard of GGM algorithm and data verification.

Using the machine learning method gives the data test results a more concise interpretation for condition-based monitoring. The drain cylinder oil samples from these ships AV1, AV2 and OV5 contain wear particles that are observable through XRF analysis. But the correlation between these elements cannot be established or linked without the aid of a machine learning algorithm.

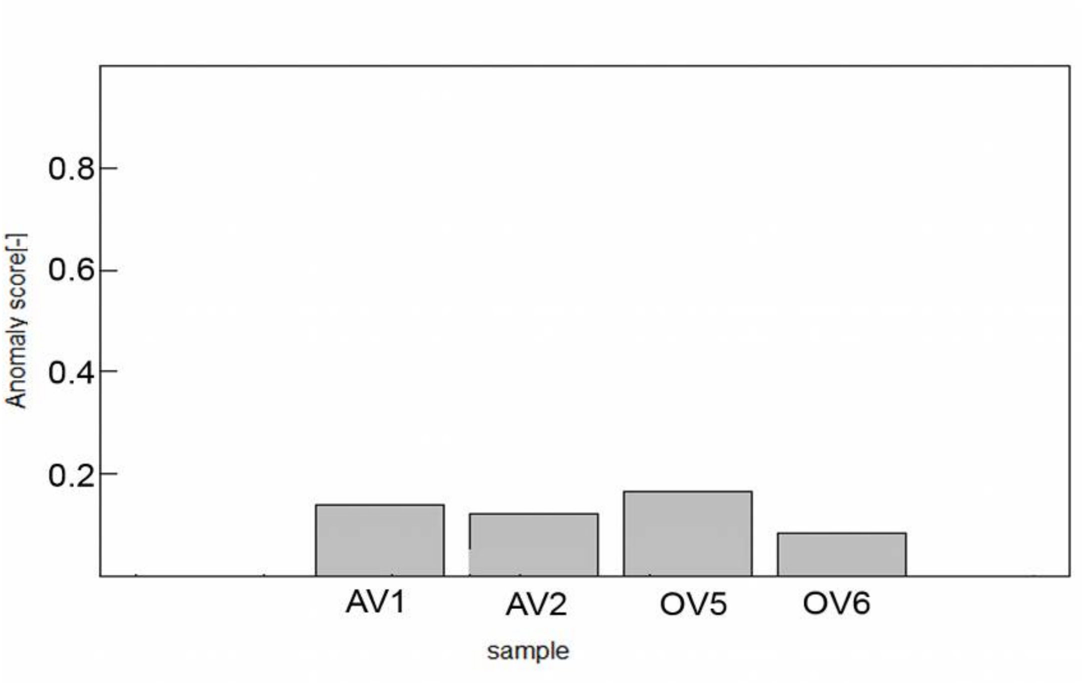


Figure 11 Anomaly scores for ships with exemption

The anomaly score of the ships is further analyzed the cluster intensity in the dataset. To proceed on investigating the OV6 anomaly score we exempt some wear elements to examine the influence on the anomaly score. All the preceding steps were repeated, and Sulfur and Calcium were observed to make difference in the OV6 anomaly score as shown in figure 11. Please note this figure 11 is exemption data for control machine learning on subject ships for conditional-based monitoring.

Despite exemption on dataset elements other ships such as AV1, AV2, and OV5 anomaly scores are not influenced or discrepancy in the output. From figure 11 and algorithm analysis exempting Sulfur and Calcium is not possible in operating a marine 2-stroke slow-speed diesel engine because Sulfur is found in fuel oil and Calcium in an additive in Cylinder Lubricating oil. The most important is how the engine was able to combust a mixture of fuel oil and Cylinder lubrication oil under the environment of operation. The key depends on the percentage of water molecules in the in-let air to the combustion chamber of the engine. When the air contains more water molecules it is likely to contribute to corrosive corrosion of cylinder liner according to the below chemical reaction.

$$SO_{3(g)} + H_2O_{(I)} \rightarrow H_2SO_{4(aq)}$$

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

As presented in this chapter using GGM on the unsupervised result of an XRF data. The analyzed result of a drain cylinder lubricating oil can be used in the machine learning algorithm to build a model by KLD. Also, the ship operation condition-based monitoring was evaluated by a novel anomaly detection method using the histogram. With the result and control machine learning specifically identify elements correlation that contributes to wear of a marine diesel engine cylinder liner.

5. Ships Maintenance and Management Approach

5.1 Assessment of Cylinder liner wear

5.2 Condition Monitoring for Engine Maintenance with Machine Learning

5.2.1 Maintenance Decisions

Chapter 5

Ships Maintenance and Management Approach

We have been discussing condition-based maintenance (CBM) from the preceding chapters and in this chapter also focuses on a new maintenance strategy that uses the analyzed data by the algorithm and physical measurement to monitor cylinder liner conditions during this project monitoring of a ship. The aim is to improve the operating life of marine diesel engine cylinder liner maintenance action. The CBM support maintenance policy can be implemented when there is data deviation corroboration of the subject cylinder liner. The steps of CBM on cylinder liners are highlighted in the managing technical tools utilization and the equipment operating conditions evaluating techniques. The view is to maximize the total lifetime operating hours of equipment and mitigate the risk of mechanical failure. It is important to observe the health conditions of cylinder liners when the data deviated which will prompt actions to extend the remaining life of the equipment using the necessary technical tools available.

Cylinder lubricating oil analysis helps to quantify, identify, and evaluate subject equipment health conditions while in operation. CBM on cylinder liners using drain cylinder oil enables prediction and proactive maintenance policies, and to mitigate deterioration of cylinder liner early implementation of action elongates the remaining running life of the equipment. As a result, avoidance of potential catastrophic equipment failure is possible. Decisive maintenance actions have a tremendous impact on failing cylinder liner during operation, and on the other hand, unproductive decisions often lead to adverse mechanical failure of marine engines. This contributes or leads to economic loss, environmental damages, and worst scenario loss of crew's life. For successful maintenance policy-making on cylinder liners, wear data and technical information about the conditions of operation are vital for implementing those policies. Therefore, the period, accuracy, and reliability of decisions centered guided knowledge information derived from the condition-based monitoring of cylinder liners. The importance cannot be underestimated because of emergency can present itself during operation, whereby economic objectives may delay the implementation of maintenance policies in that challenging situation. A merchant ship marine engine, the technique of maintenance is the operate-to-failure approach that is equipment until mechanical failure occurred. In every 2 years interval, a compulsory inspection of the entire ship's equipment is required by maritime laws and regulations. At the *dry dock* for a ship, all machinery is assessed for safety certification to sail for another limited period. But this cannot equalize condition-based monitoring on cylinder liners that can support maintenance policies.

Using CBM to correlate wear of cylinder liners and quantification of major elements is possible through state of the art of CBM applicable techniques. The practicality of CBM using algorithms application to extract data to support maintenance policies and decision inspire to further expand the knowledge about it. The study has classified methods for maintenance policies solely based on statistic methods, machine learning, and physical inspections to make prognostic decisions on equipment. These approaches aim to quantify the remaining life of cylinder liner in operation. Another approach presented for CBM in the earlier chapter is model-driven methods for prognostic on cylinder liners based on oil analysis.

The remaining part of the paper discussed the physical measurement of cylinder liners and collaborating wear quantity of iron from drain cylinder oil samples. The final sections presented a machine learning approach on a ship XRF results. (Shiraiwa et al 1966)

5.1. Assessment of Cylinder Liner Wear

The marine engine cylinder liner for a ship sailing in the Northern Pacific Ocean was assessed by physically measured and almost the same interval drain cylinder oil was sampled before opening for measurement. In this chapter, we presented the overhaul of cylinder liner details and estimation of iron particles in the drain cylinder oil samples. The cylinder liner thickness is measured using liner diameter measuring instrument is of micrometer-scale like a rod shape. The data obtained are recorded in the form to calculate the wear down of cylinder liner. This format form was shared for only AV1 sailing in the North Pacific Ocean as shown in figure 1 below.

REPORT OF INSPECTION

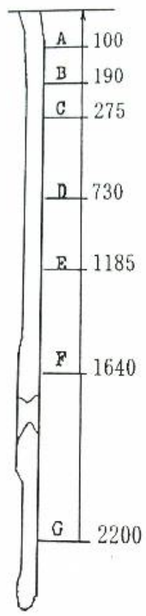
Name of vessel :	AV 1	Date of Inspection: 22 May 2019 Part name: UEC60LSA
Engine name :	MAIN ENGINE	Master : Capt. ******
Subject :	Measurement of cylinder liner inner diameter	Chief Engineer : **********

M.E total RH	120056Hrs	RH since last OH	3355Hrs

Design Diameter	600.00 - 600.11
Use Limit	**604**
Standard Gauge	600.04

Unit: 600 + 1/100 mm

Cylo. No.	No.2		No. 2		No. 2	
Position	F-A	P-S	F-A	P-S	F-A	P-S
A	600.03	600.03	601.66	600.71	601.67	600.83
B	600.08	600.50	**602.74**	602.66	**604.16**	602.88
C	600.03	600.03	**602.03**	602.11	**603.32**	602.29
D	600.1	600.03	601.03	601.96	601.78	601.09
E	600.15	600	600.69	600.05	601.14	600.72
F	600.01	600.1	600.60	600.67	600.76	600.55
G			600.18	600.18	600.37	600.24



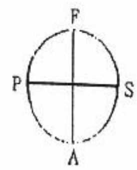


Figure 1 Sample of wear down physical measurement record form

The work is done when the engine temperature permit to work in a tight or confine space. Steps begin with a covering of the stuffing box, removing liner rings, and cleaning of carbon deposits on the top surface. The piston will be lower to the bottom dead center for the cylinder liner inner thickness can be measured from the top dead center to bottom dead center. A ladder is lower for the crew to be able to do the thickness measurement. Figure 2 ~ 3 showed method measurement work.

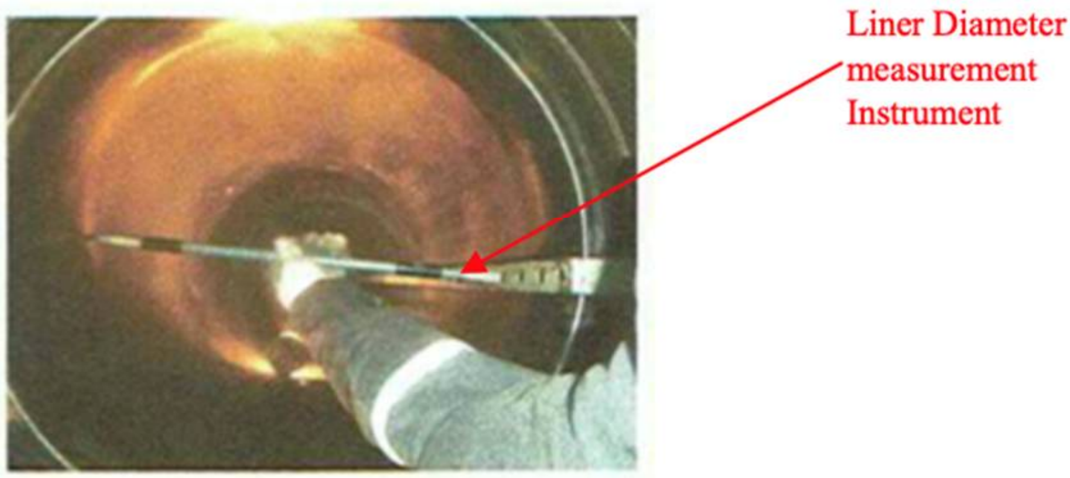


Figure 2 Display Liner Diameter Measurement Instrument

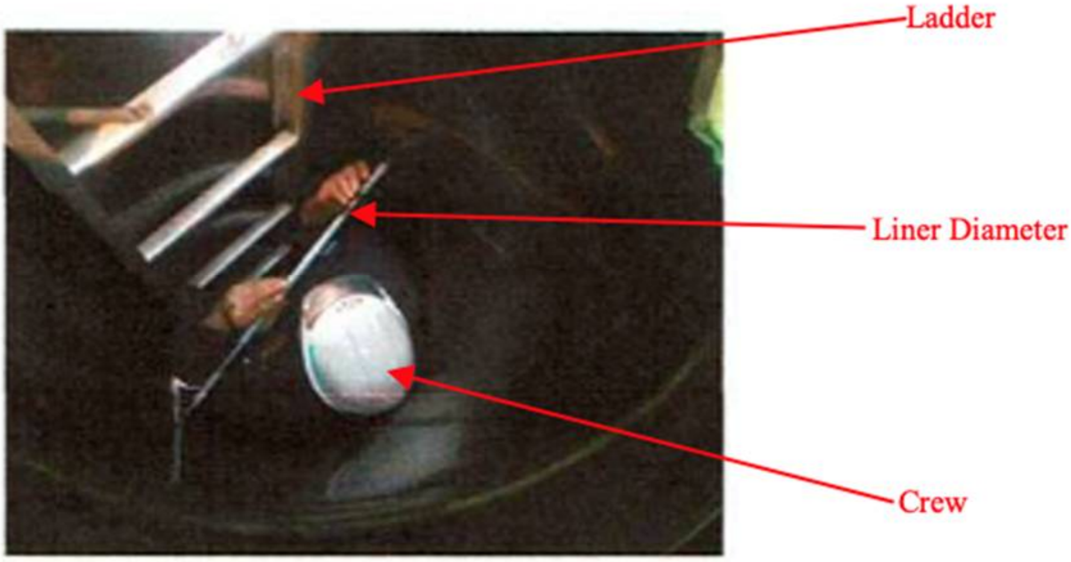


Figure 3 Crew measuring Cylinder Liner Inner Thickness

The environmental effects on cylinder liner wear rates are estimated in our case study ship. Drain oil samples were collected from the ship engine at regular intervals of 1000 hours of continuous engine operation, the cylinder drain oil samples were analyzed by XRF. The results indicated the presence of wear metals from cylinder liner and piston ring materials including the fuel oil elements. The wear of a unit cylinder liner is measured at an average of 1000 hours of operation and the cylinder liner inspection measurement is roughly 1,000 hours of operation. Using the deferential wear down of cylinder and analysis of Iron trend in drain cylinder oil sample is represented in figure 4.

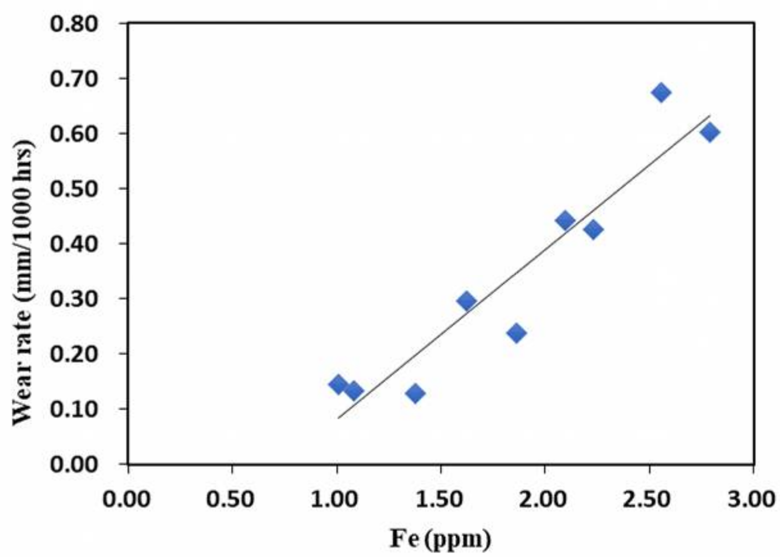


Figure 4 The relationship of wear rate by measurement and sampling tracing

The relationship between average wear rates obtained through physical measurements and XRF results for the iron (Fe) concentration in drain oil samples are as shown in figure 4 there is a correlation between the physical measurements and the XRF results. We make use of XRF results to estimate the quantity of wear thereby equalizing it with iron quantity. It is a reasonable method to evaluate cylinder liner degradation when deciding on engine maintenance.

In some practical manners, obtained results are within the expected trend to estimate the wear amount of iron from the cylinder liners in operation. Having analyzed drain oil samples close to the time interval for overhaul maintenance work and collect instant data from XRF equipment. Although used oil samples contain a complex compound of iron that formed as an impurity in samples, this adds a margin of errors to the iron intensity data that make estimate the wear progression of the cylinder liner. However, estimation is plausible using this method on drain cylinder oil samples that contain iron impurity.

5.2. Condition Monitoring for Engine Maintenance with Machine Learning

We utilize statistical machine learning to interpret XRF results variable relationship as shown in chapter 4. This chapter explained how a Gaussian graphical model (GGM) matrix was used for the machine learning on wear elements. Each element is in bidirectional conjunction in a drain oil sample that is likely to be relative, and the model was simplified to algorithmically learn each wear element's characteristics. This makes it possible to evaluate the case study ship's cylinder liners according to their wear element quantities and other elements present in drain cylinder oil.

The goal is to compute element anomaly correlations. And once the correlation is established table 1 will be used to identify the source of wear elements for prognosis and target maintenance work. See chapter 4 of table 1 lists the elements found in cylinder drain oil samples and the sources of each element. As indicated in table 1 there are various elements classified according to their source.

Given each element as data sets

$$\mathfrak{D} \equiv \{X| \in \mathbb{R}^M,\ \ n = 1,2,\ldots\} \qquad (1)$$

$\mathfrak{D}$ represent data set, n is the number of samples, X denotes scalar matrix while M is elements in a set.

To get Gaussian Graphical Model we penalized the results to maximum likelihood using equation 8. In the equation log was introduced and where $\wedge$ is the precision matrix.

$$(X|0,\wedge^{-1}) = \frac{\det(\wedge)^{1/2}}{(2\pi)^{M/2}} \exp\left[-\frac{1}{2}X^{(\wedge X)}\right] \qquad (2)$$

before proceeding, data measured must be standardized(S).

$$(X|0,\wedge^{-1}) = \text{In}\det(\wedge) - \text{tr}(S\wedge) \qquad (3)$$

tr is matrix trace i.e., sum over the diagonal element, while ρ is finite. The penalized likelihood for each element is

$$f(\wedge, S, \rho) = \ln det\wedge - tr(S\wedge) - \rho\ \|\wedge\|_1 \qquad (4)$$

Equation (3) is a convex objective function and we used it to solve variance elements in the model. It was classified according to the source to better understand the mechanical wear in the internal combustion chamber.

The graphical representation of elements correlation model first step is to learn the sparse data and then compute it for each variable.

1. Input
    - The data set for elements and the target elements in oil samples

- Oil sample data is penalized using equation (4)

2. Output: individual element where 1 represent correlation while 0 is non-correlation as below,

	S	Ca	V	Fe	Ni	Cu	Zn	Ag
S	1	1	1	0	1	0	1	1
Ca	1	1	1	0	1	1	0	1
V	1	1	1	0	1	0	0	0
Fe	0	0	0	1	0	0	1	1
Ni	1	1	1	0	1	0	1	0
Cu	0	1	0	0	0	1	1	1
Zn	1	0	0	1	1	1	1	1
Ag	1	1	0	1	0	1	1	1

3. Gaussian Graphical Model

Using drain oil samples data and each element was scored for correlation and represented by a graphically model of drain cylinder oil samples from monitored engine in operation as shown in chapter 4 figure 6.

For the condition-based monitoring using the GGM for correlation assessment, there the assessment was performed on each element and the algorithm output to correlate each element relationship. As shown in table 1 classified elements according to the source and based on XRF data on drain cylinder oil was used GGM to establish cylinder liner degradation status. In chapter 4 figure 6, there is a correlation between additive elements (Zn & Ca) and fuel oil elements indicating that incomplete combustion contributes to cylinder liner wall degradation.

Based on the report from AV1 physical observation lacquer deposits were observed at the cylinder liner, piston, exhaust valves, and exhaust pipe of the engine and this is caused by incomplete combustion of the fuel oil. By the engine report, our Gaussian Graphical Model is affirmed on the elements forming lacquering on the equipment. The degradation by wear of cylinder liner is confirmed as zinc (Zn) and iron (Fe) are linked and same situation with copper (Cu), calcium (Ca), and silver (Ag). As these elements bond together solid particles and lacquering of cylinder liner wall is visible during an inspection and total landing piston ring peeling was observed.

5.2.1 Maintenance Decision

Machine learning contributes to maintenance decisions by focusing on elements correlation as shown in chapter 4 figure 6. This helps to diagnose cylinder liner degradation during operation (Andrew K.S et al 2006). The combination of machine learning and wear rate of cylinder liner determines the maintenance decisions, and in the case study to ensure engine reliability we include wear rate estimation at every interval of 1000 hrs. of operation as shown in figure 4. The iron particle in the oil sample continues to rise as the cylinder liner wear amount measured continues to climb. This allowed us to observe and link factors causing cylinder liner degradation patterns by correlating each element (Susan Alaswad et al 2017).

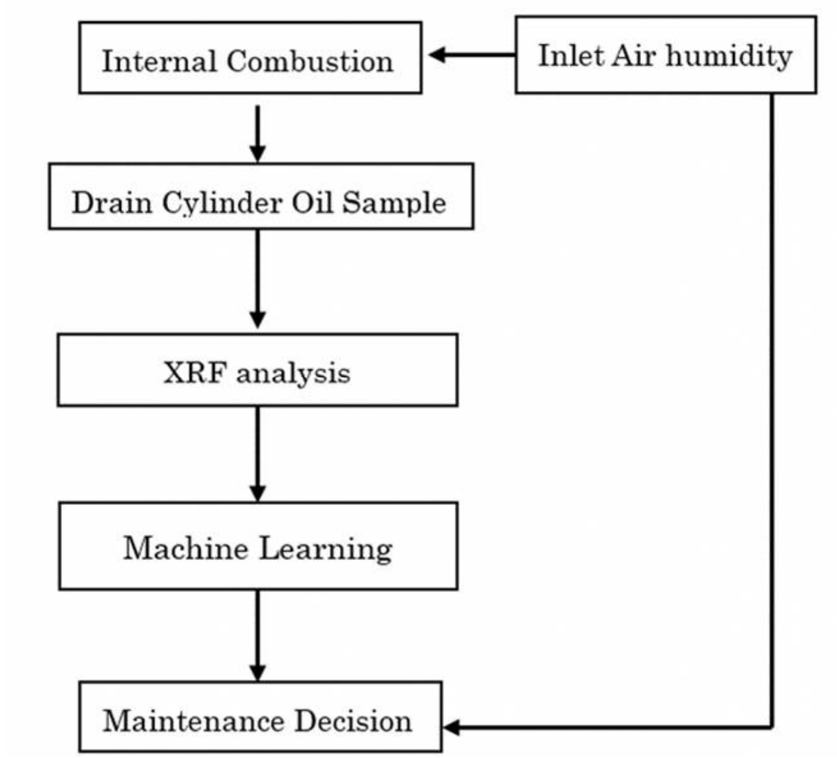


Figure 5. A proposed onboard maintenance decision-making framework

Figure 5 shows the framework of our new approach to cylinder liner condition-based monitoring. This new framework adds environmental conditions as factors to consider when making cylinder liner maintenance decisions. For internal combustion engines that need a high volume of air for their combustion, the atmospheric water vapor is amplified in higher latitude territorial waters. Since the analysis result of drain oil alone is not enough without interpretation for maintenance decisions, as the result establishing a wear elements relationship will make this result practicable. Therefore, with a machine learning application on XRF sample results to rate the engine performance and secondary the operating conditions. Our new monitoring system and machine learning analysis approach, in which environmental data is used to support maintenance decision-making purposes, can be expected to contribute to flexible and adaptive engine maintenance planning.

6. Conclusion and Future work

6.1. Conclusion

6.2. Future work

Chapter 6

6.1 Conclusion

In this project condition-based monitoring of 2-stroke slow-speed marine diesel engine cylinder liner. The drain cylinder oil samples are the key to condition-based monitoring. This cylinder lubricating oil is used only once and is not recirculated in the engine system. For condition-based monitoring of the engine cylinder liner included the possibility of environmental effect in this project, whereby comparing Northern Pacific Ocean ships with Southern Pacific Ocean ships. Through this process wear particles quantification was done on drain oil samples for comparison and monitored the environmental effect. The health of the engine cylinder liner can be determined by our project as XRF results are built to the dataset for machine learning by the algorithm. The maintenance decisions can be based on solid data that will benefit the engine cylinder liner, detect early deviation, and possible elongation of the remaining useful life of the equipment. Using in operation is a benefit for this project to study condition-based monitoring of stroke slow-speed marine diesel engines because it confirms that condition-based monitoring can be deployed to avoid sudden mechanical failure that can be an economical loss. Though efforts were made to sample all ships for the same quantities and operating hours ship operating schedule there is an in-balance between ship's sampling quantities and operating hours. Currently, oil samples analysis is done by shore laboratory, and no onboard testing is performed. The lab test report can take days before issuing the reports on used oil samples.

Through this project of condition-based monitoring of cylinder liners and piston rings of 2-stroke slow-speed marine diesel engine concluded as follow:

- There is significant wear quantity in ships sailing in Southern Pacific Ocean than Northern Pacific Ocean ships
- XRF analysis of drain cylinder oil detected all elements in the sample oil
- Based on samples results dataset was built for machine learning
- The machine learning algorithm is significant in the interpretation of the dataset
- All subject ships were anomaly scored and only OV6 ship scored beyond the threshold of 0.2
- Further investigation on the OV6 anomaly score indicated that Sulfur and Calcium contributed to the anomaly score of 0.4. The anomaly score was reduced to roughly 0.1 without Sulfur and Calcium in the algorithm matrix.
- It was concluded that incomplete combustion of fuel oil for ships sailing in the Southern Pacific Ocean causes *corrosive corrosion* of the cylinder liners and excessive Calcium will also be deposited in the piston groove. This deposit

becomes solidify particles that caused a “third wear” mechanism, that is between metal-to-metal contact solidify particles will stay in between.

- Finally, wear estimation of cylinder liners through iron (Fe) in drain cylinder lubricating oil. The cylinder liner overhaul is tedious work when measuring the diameter to calculate the teardown of cylinder liners. Using accumulated drain cylinder oil sample analysis, the iron quantity is significant to estimate the remaining useful life of marine engine cylinder liner in operation.

Condition-based monitoring on cylinder liners for marine 2-stroke slow-speed diesel engines is not currently adopted for maintenance decisions for the engine. This dissertation proposes a maintenance framework is based on *trend analysis, correlation analysis, machine learning, and wear estimation.*

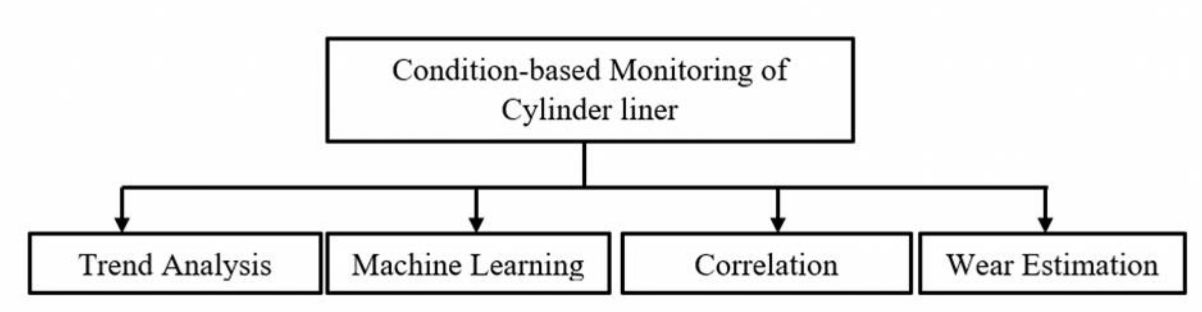


Figure 1 Summary in the flowchart for condition-based monitoring

6.2 Future Work

Our challenge on this project is that there is no collaboration with the ship's managing company. As a result, our proposed contribution could not be adopted when deciding on maintenance for the ships. Testing equipment is not allowed on board for analyzing drain cylinder lubricating oil, this makes it difficult to obtain data immediately after sampling drain cylinder oil. The condition-based monitoring of cylinder liner is not real-time work and time lag from sampling engine hours to analyzed results available created the time lag.

However, for the application to be useful for a real-time maintenance decision there must be an agreement for collaboration and funding of this project. And for the in-service ship’s engine, there is a need to alter the scavenge space drain pipe for continuous sampling of drain cylinder oil. Onboard testing equipment is required to run samples analysis when the engine is in operation.

The advance of the internet of things (IoT) will benefit both crew and shore data centers for collecting accumulated datasets from the marine engine and drain cylinder oil samples analysis. The data center will share real-time with the maintenance team to assess the current operation and be able to identify, isolate and repair failing equipment when anomaly operating. IoT is required for future work on this project.

There are other data needed to study the effect of environment on cylinder liners and piston rings such as percentage of molecules in air at the entrance of combustion chamber, ocean humidity of voyage, and sharing of GPS from starting port to the next port. As the marine engine for 2-stroke slow-speed become larger the design will be complex. Condition-based monitoring of the cylinder liner will be vital for the maintenance management of the engine.

Future work will investigate the above unavailable data that will better this work making it more dependable to apply on marine engine maintenance. The baseline has been established and repeatable method data collection on the engines is possible.

References

Pevzner, L.A. (1998a), Aspects of marine low-speed, cross-head diesel engine lubrication, Lubr. Eng., 54, 16-21.

Yan Liu, Zhong Liu, Youbai Xie, Zhigang Yao. “Research on an on-line wear condition monitoring system for marine diesel engine” Tribology International 33 (2000) pp 829-835

Phue DO VAN, Eric LEVRAT, Alexandre VOISIN, and Benoit IUNG “Remaining useful life (RUL) based maintenance decision making for deteriorating systems” 2nd IFAC Workshop on Advance Maintenance Engineering Services and Technology. Universided de Sevilla, Sevilla Spain. November 22-23, 2012.

Eid S Mohamed “Performance analysis and condition monitoring of ICE piston-ring based on combustion and thermal characteristics” Applied Thermal Engineering 132 (2018) 824-840

Sergey Victorovich Sagin and Oleksandr Vladymyrovich Semenow “Marine Slow-Speed Diesel Engine Diagnosis with View to Cylinder Oil Specification” American Journal of Applied Sciences 2016, 13 (5): 618-627

Doug Woodyard “Pounder’s Marine Diesel Engines and Gas Turbines 8th edition 2004”

Y.Iwai, T. Honda, T. Miyajima, S.Yoshinaga, M. Higashi, Y. Fuwa. “Quantitative estimation of wear amounts by real time measurement of wear debris in lubrication oil” Tribology International Online 43 (2010) 388-394

G O Chandroth, A J C Sharkey and N E Sharkey “Cylinder pressures and vibration in internal combustion engine condition monitoring”
Source: www.dcs.shef.ac.uk/research/groups/neural/

Oihane C. Basurko, Zigor Uriondo. “Condition-Based maintenance for medium speed diesel engines used in vessels in operation” Applied Thermal Engineering 80 (2015) 404-412

J. Keller, V. Fridrici, Ph. Kapsa, J.F. Huard "Surface topography and tribology of cast iron in boundary lubrication" Tribology International 42 (2009) 1011-1018

Susan Alaswad, Yisha Xiang "A review on condition-based-maintenance optimization models for stochastically deteriorating system" Reliability Engineering and System Safety 157 (2017) 54-63

Andrew K.S Jardine, Daming Lin, Dragan Banjevic "A review on machinery diagnostics and prognostics implementing condition-based maintenance" Mechanical Systems and Signal Processing 20 (2006) 1463-1510

N.K. Myshkin, L.V. Markova, M.S. Semenyuk, H. Kong, H.-G. Han, E.-S. Yoon "Wear monitoring based on the analysis of lubricant contamination by optical ferroanalyzer" Wear Journal 255 (2003) 1270-1275

CIMAC Working Group 8 "Cold Corrosion in Marine Two Stroke Engines"
Marine Lubricants 2017 CIMAC Guideline (1st edition)

Wang, W., Hussin, B. and Jefferis, T., A case study of condition-based maintenance modeling based upon the oil analysis data of marine engines using stochastic filtering
Int. J. Production Economics, 136, pp.84-86（2012

Baurko, O. C. and Uriondo, Z., Condition-Based Maintenance for medium speed diesel engines used in vessel in operation, Applied Thermal Engineering, 80, pp.404-412（2015）

Friedman, J., Hstie, T. and Tibshirani, R., Space inverse covariance estimation with the graphical lasso, Biostatistics, 9（3）, pp.423-441（2008）

Sherman, J., The theoretical derivation of fluorescent X-ray intensities from mixtures, Spectrochim. Acta., 7, pp.283-306（1955）

Sherman, J., Simplification of a formula in the correlation of fluorescent X-ray intensities from mixtures, Spectrochim. Acta., 7, pp.466-470（1959）

Shiraiwa, T. and Fujino, N., Theoretical Calculation of Fluorescent X-Ray Intensities in Fluorescent X-Ray Spectrochemical Analysis, Jpn. J. Appl. Phys., 5, pp.886-899（1966）

Criss, J. W., Birks, L. S., Calculation methods for fluorescent X-ray spectrometry empirical coefficients vs. fundamental parameters, Anal. Chem., 40, pp.1080-1086（1968）

河村恒夫，潤滑油中の摩耗粒子解析による設備の診断技術，コペルニクス vol.3 pp.9-12（1994）

山田洋，菅原広，羽根田誠，永井義和，シリンダ油ドレンによる機関摺動部の状態監視，日本舶用機関学会誌，p.476（2000）

増子昭義，斉藤一郎，浜川論，松崎昭，エネルギー分散型蛍光 X 線法の石油への応用（第 3 報）ファンダメンタルパラメーター法による油中多元素同時定量，石油学会誌，Vol.30，pp.337-341（1987）

井手剛，杉山将，異常検知と変化検知，pp.127-144，講談社（2015）

熊谷将也，松本亮介，疎構造学習およびグラフ畳み込みニューラルネットワークによる異常検知，さくらインターネット株式会社（2018）

井手剛，依存関係スパース性を入れる- グラフィカル lasso の話，IBM Research，岩波データサイエン Vol.5，pp.423-441（2016）

羽生田清，潤滑油の性状測定とその重要性，日本マリンエンジニアリング学会誌，第 45 巻，第 1 号，pp.53-54（2010）

花島脩，シリンダーの潤滑（3）- オイル・ストレスと高湿度下のスカッフィングの原因，日本マリンエンジニアリング 学会誌，第 47 巻　第 5 号，pp.76-82（2012）

Broszeit, E., Friedrich, C. and Berg, G. Deposition, properties, and applications of PVD CrxN coatings. Surface and Coatings Technology, 11(1999)5, pp. 9–16.

Affenzeller, J. and Gläser, H. Lagerung und Schmierung von Verbrennungsmotoren (Bearings and lubrication of internal combustion engines / in German). Die Verbrennungskraftmaschine, Neues Folge, Band 8. Vienna, Austria, 1996, Springer-Verlag. 397 p. ISBN 3-211-82577-0.

Glaeser, W. A., and Gaydos, P. A. Development of a wear test for adiabatic diesel ring and liner materials. ASTM 1993, Proc Symp wear test selection for design and application, Dec 2, 1992. Miami, FL, USA, ASTM Philadelphia PA, 0066-0558 ASTTA8, ASBN 0-8031-1856-2, pp. 1–16.

Publications

- Ayo FAMAKINWA, Ryoma AIHARA, Tadahiro SHIBUTANI. The Effect of Voyage Path on Condition Based Monitoring of Cylinder Liners. Journal of the Japan Institute of Energy, Volume 100, Issue 4, 2021 Pages 22-28 Online ISSN: 1882-6121
  https://doi.org/10.3775/jie.100.22

- Ryoma AIHARA, Ayo Famakinwa, Tadahiro SHIBUTANI. Proposal for Condition-based Maintenance Method using Lubricating Oil Analysis and Machine Learning. Volume 59, Issue 6, 2020 Pages 416