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GUIDELINES FOR DIESEL ENGINES LUBRICATION

OIL DEGRADATION

The International Council
on Combustion Engines

Conseil International des
Machines à Combustion

CONSEIL INTERNATIONAL
DES MACHINES A COMBUSTION

INTERNATIONAL COUNCIL
ON COMBUSTION ENGINES

CIMAC is an international organisation, founded in 1950 by a French initiative to promote technical and scientific knowledge in the field of internal combustion engines (piston engines and gas turbines). This is achieved by the organisation of congresses and working groups.

It is supported by engine manufacturers, engine users, technical universitites, research institutes, component suppliers, fuel and lubricating oil suppliers and several other interested parties.

The National Member Associations and previous CIMAC Recommendations still available are listed in the back of this publication.

This document has been elaborated by the CIMAC Working Group „Marine Lubricants“ and approved by CIMAC in April 2004.

Foreward by the President

The CIMAC Recommendations are produced by the CIMAC Working Groups in which experts in the various fields of combustion engines, contribute voluntarily, to formulate the related documents.

The CIMAC Recommendations serve not only to consolidate the knowledge and expertise in a particular field, but are also aimed to be of practical importance for engine users, manufacturers and related equipment suppliers.

The present Recommendations on “Guidelines for Diesel Engine Lubrication-Lubricating Oil Degradation” is targeted to all people related to large engines in marine propulsion, land-based power generation and railroad industry.

This Recommendation is one further product of the CIMAC Working Group No. 8. “Lubricants”, which can boast a very wide participation of experts from CIMAC Members and has been very fruitful in producing Recommendations over the past years.

I wish to congratulate the Working Group No. 8 “Lubricants” for this fine document, which I trust will be useful for the combustion engine community all over the world.

Prof. Nikolaos P. Kyrtatos
April 2004

GUIDELINES FOR DIESEL ENGINE LUBRICATION

LUBRICATING OIL DEGRADATION

OIL DEGRADATION

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OIL DEGRADATION

PREFACE

This document brings together insights into mechanisms and phenomena of oil degradation resulting from stress of the lubricant in large 4-stroke (medium speed and high speed) and 2-stroke diesel engines. Its objective is to contribute to the understanding of the complex processes resulting in oil degradation and thereby, to a degree, enable control of them so that the engines, their treatment systems and the lubricant itself remain in an acceptable condition for an acceptable period.

The intended readership of this document are all people related to *large* engines in marine propulsion, land based power-generation and railroad industry - for example users and producers of equipment, students and newcomers to the industry etc.

1. INTRODUCTION

The lubricating oil for a diesel engine needs a variety of properties. It must be able to clean engine components and keep them clean, it must neutralize acids, transfer heat, fight rust and corrosion in addition to its main job of lubricating the engine for a very long time [1, 2]. Since lubricating oil is a product influenced in its quality by a variety of stresses, monitoring of the oil quality, adequate oil maintenance, as well as its timely replacement if needed (partially or totally) must be ensured. Also, the selection of the type and grade of lubricant to be used should be based on the relevant engine operating conditions and service conditions.

This document discusses the types, causes and counter measures of degradation of large engine lubricants during service. ”Oil degradation” in this document means the change in physical and chemical properties of the lubricants during service that result in deterioration of performance. The change in oil quality is the result of a) accumulation of contaminants including combustion soot, acidic combustion blow-by products, raw residual fuel, water, etc., and b) the influence of high temperature, aeration and NOx.

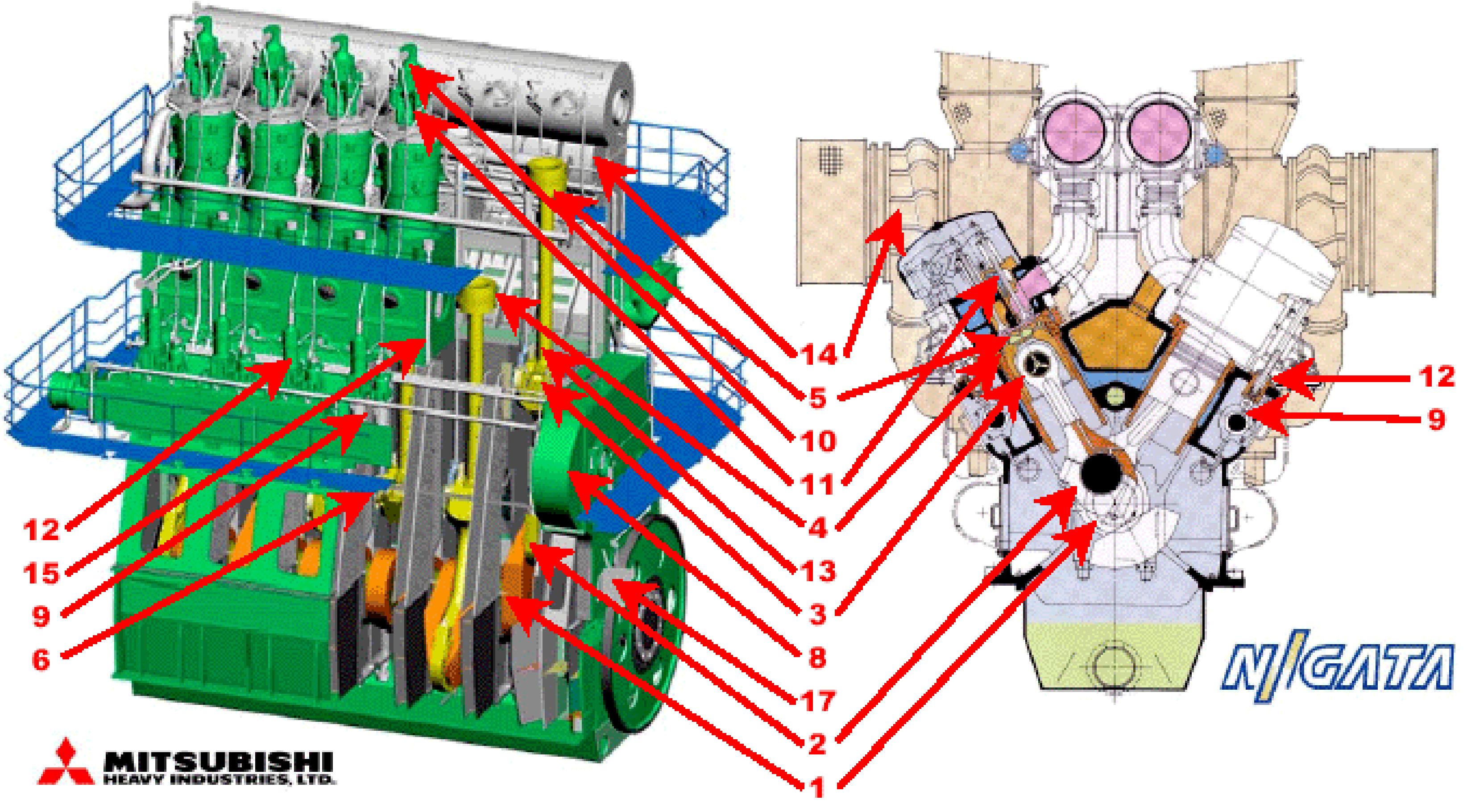
This document gives advice on how to maintain oil properties within acceptable limits.

2. STRESSES IMPOSED ON THE ENGINE OILS BY ENGINE COMPONENTS

This section compiles a list of the different stresses a lubricant experiences in an engine. It also serves as a guide for engineers to understand why attention needs to be paid to lubricant properties as part of routine engine maintenance. Some of the components mentioned in this section are marked in Fig.1 which shows a typical “Crosshead” and “Trunk Piston” diesel engine. [3].

Stresses on the lubricant are listed in Table 1. A lubricant can degrade through a number of routes, therefore users need to be aware of how engine operation can affect lubricant properties and the importance of carrying out maintenance and preventive work to minimize engine wear and malfunctions.

Figure 1: Engine Components relevant for Lubrication [3]



Mitsubishi UEC68LSE: 2-stroke, Crosshead Low Speed Diesel Engine

Niigata: 4-stroke, Medium Speed Diesel Engine

(Courtesy of Mitsubishi Heavy Industries and Niigata Power Systems)

Table 1: Stresses on Lubricating Oils of Large Diesel Engines

No.	Engine component :	Function of the oil :	Oil type used in crosshead engine :	Oil type used in trunk piston engine :	Stresses on oil :
1	Main bearing	Lubrication, cooling	System oil	System oil	Load, heat
2	Crank pin bearing	Lubrication, cooling	System oil	System oil	Load, heat
3	Crosshead and conrod Bearings	Lubrication, cooling	System oil	System oil	Load, heat
4	Cylinder liner, piston ring and piston ring groove	Lubrication, wear control, sealing, cleaning, neutralization,	Cylinder oil, highly alkaline	System oil, medium alkaline	Load, heat, dirt, acids
5	Piston undercrown	Cooling, cleaning	System oil	System oil	Heat, dirt
6	Crosshead guides and Shoe	Lubrication	System oil	-	Load, heat
7	Thrust bearing	Lubrication	System oil	System oil	Load, heat
8	Camshaft drive gear	Lubrication	System oil	System oil	Load, heat
9	Cam, roller, roller guides	Lubrication	System oil	System oil	Load, heat, fuel
10	Exhaust valve drive gear	Hydraulic action, lubrication	System oil	-	Load, heat
11	Exhaust valve shaft, valve guide	Lubrication, sealing, neutralization	Cylinder oil or system oil	System oil	Load, heat, dirt, acids
12	Fuel injection pump	Lubrication, sealing	System oil	System oil	Load, dirt, fuel
13	Piston rod stuffing box	Lubrication, sealing	System oil and cylinder oil	-	Load, dirt, acids
14	Turbo charger rotor bearings	Lubrication, cooling	System oil or turbine oil	System oil or turbine oil	Load, heat
15	Tie rod	Damping	System oil	-	Load, heat
16	Axial/torsional vibration dampers *	Damping	System oil	System oil	Load, heat
17	Turning gear	Lubrication	Grease / Oil		Load

* Some torsional vibration dampers operate with their own dedicated oil

3. PRINCIPAL FUNCTIONS OF ENGINE OILS

Basically, the principal functions of the engine lubricant are as follows. See also [4]:

1. Reduce friction
2. Minimize wear of engine components including corrosive wear
3. Removal of heat
4. Protection of engine components against harmful deposits
5. Sealing

Apart from these basic functions, the lubricants are also expected to control against any deposit formation in the lubrication system (circulation lines, check valves and sight glasses).

In merchant marine terminology as shown in Table 2, diesel engine lubricants are classified as follows:

1. Cylinder oils
2. System oils for crankcase lubrication of crosshead engines
3. Crankcase oils for medium or high speed trunk piston engines

Table 2: Diesel Engine Classification

Diesel Engine Classification	Rotational Speed (rpm)
Crosshead	Below 300
Medium Speed Trunk Piston	Below 1000
High Speed Trunk Piston	Above 1000

Note : There are some older design engines of the two-stroke (trunk-piston) type with rpm of above 1000.

4. TYPES OF LUBRICANT FOR LARGE DIESEL ENGINES AND THEIR REQUIREMENTS

Different physical properties and performance levels are required for different lubricants depending on the applications. A discussion on oil degradation is, therefore, dependent of the lubricant type and applications.

Requirements of large diesel engine lubricants are shown in Table 3.

Table 3: Requirements of Diesel Engine Lubricants

	Crosshead Engine		Trunk Piston Engine - Medium Speed	Trunk Piston Engine - High Speed
	Cylinder oils	System oils		
Wear Control (Rings /Liners)	*		*	*
Thermal and Oxidation Stability	*	*	*	*
Piston Deposit Control				
Ring grooves, Lands,	*		*	*
Undercrown		*	*	*
Detergency/Dispersancy (Engine cleanliness)	*	*	*	*
Retention of Alkalinity		* (against water wash)	*	*
Water Separability		*	*	
Rust Inhibition	*	*	*	*
Filterability		*	*	*
Free of gelling tendencies	*	*	*	*
Load-carrying property for reduction gears			*	
Load-carrying property for valve-train area			*	*
Load-carrying property for hydraulic functions		*		

4.1. Crosshead Engine Oils [5]

Crosshead engines generally burn residual fuels. In this type of engine, separate systems are used for:-

- cylinder lubrication (which is a total-loss system) and
- crankcase lubrication

Different properties are required for the oils used for these two applications. Further information on crosshead engine oils is discussed in detail in CIMAC No.15 [2].

4.1.1. Cylinder Oils

One of the most important properties of the cylinder oil is a high alkalinity to combat the corrosive sulphuric acid derived from combustion of sulphur in the fuel; this fuel sulphur can be up to around 5 per cent (m/m). See Table 6. Because cylinder lubrication is a “total-loss” / ”once through” system, the cylinder oil is less extensively covered in this document.

4.1.2. System Oils

The crankcase of the crosshead engine is separated from the combustion side. The division is achieved by a piston rod gland. Although in principle the system oil is not directly exposed to contamination by combustion by-products or used cylinder lubricant, in practice some leakage/contamination through the piston rod gland does happen. In addition, whilst some crosshead engine designs with water cooled pistons still exist, most of the recently introduced models have pistons cooled by the system oil.

System oils possess a degree of alkalinity reserve together with dispersant properties. System oils used in engines with oil cooled piston may be exposed to high piston undercrown temperatures. In these circumstances enhanced thermal and oxidative properties of the system oil are also required. Such alkaline system oils have the advantage that they protect the internal engine parts against corrosion by strong acids which may enter the oil by leakage of used cylinder oil draining through the piston-rod gland. Their dispersancy properties minimize sludge deposits and keep the piston undercrown, piston under-space (crosshead gland) and the crankcase clean. Notwithstanding these properties, such oils are usually designed to have good water and sludge separation properties so that water and sludge contaminants may be readily removed by normal shipboard purification processes. Normally the system oil is not designed for oil change at regular intervals.

4.2. Medium Speed Trunk Piston Engine Oils [5]

Medium speed trunk piston diesel engines employ a single lubrication system for the entire engine, however, in some instances the cylinders are also fitted with lubrication quills, through which oil is fed. Nevertheless even in these cases, splash-lubrication also contributes significantly to the amount of oil on the cylinder walls. Whilst the need for extreme pressure (EP) / anti-wear properties is less marked than for high speed engines, these properties are often incorporated in order to widen the shipboard application of this class of oils to other equipment such as reduction gears. Multigrade oils find little application in this class of engines.

Some medium speed trunk piston engines burn distillate fuel and their lubrication requirements are similar to those for high-speed trunk piston engines burning this type of fuel. But, most medium speed trunk piston engines are normally designed to burn residual fuel containing sulphur up to 5.0% m/m, and need crankcase lubricants with an appropriate level of alkalinity – i.e. having suitably high Base Number (BN) - to neutralise the corrosive combustion acids that may contaminate the oil. Medium speed trunk piston engine oils contain additives imparting a high level of oxidation and thermal stability, detergent / dispersant characteristics, protection against corrosion of both ferrous and non-ferrous materials and anti-foam characteristics. Medium speed trunk piston engine oils generally contain relatively little or no ashless dispersant additives since they can negatively affect water separation performance.

The crankcase oil in a trunk piston engine is continuously exposed to combustion products, whereas – apart from unavoidable indirect contamination – the system oil in a crosshead diesel engine is not.

The alkalinity reserve of the new lubricant is selected on basis of engine design, typical sulphur content of the fuels to be burnt and the oil consumption rate. The latter is determined primarily by the engine design and secondly by operating conditions. In any case, the engine builders should be consulted for their guidance [6- Section 4.1.2]. In the case of low to very low oil consumption (0.50 down to 0.10 g/kWh), the engine builder’s requirement for adequate service BN translates into a demand for lubricant BN grades as high as 50-55. The key deciding factor for such higher BN grades is the impracticality or undesirability of frequent oil changes to maintain service BN above the minimum limit [6– Section 4.3.2].

It is well known that BN providing additives also often give detergency power to the oil. In addition, certain alkaline additives also contribute to the anti-oxidation capacity of the oil. It is therefore important to observe the BN of the oil in service not only as a measure of neutralizing capacity, but also as a measure of its detergency power and anti-oxidation reserve. However, the above varies and depends greatly on additive technology.

Trunk piston engine burning residual fuels should be fitted with a centrifuge purifier/separator which help clean its lubricating oil. Under normal conditions of oil consumption, trunk piston engine oils do not require oil changes for a very long time, perhaps up to several years for large engines, provided that a) the centrifuge capacity is not too small and kept in correct operation, b) combustion conditions are normal and c) the oil is not contaminated with raw residual fuel. A trunk piston engine oil is therefore required to have at least moderate dispersancy properties and an excellent water separation characteristics such that contaminants/water transported by the lubricant to the purifier can be effectively removed.

However, as the power output of modern trunk piston engine increases, together with trend towards lower oil consumption, the interval of oil change is being shortened. Further information on medium speed trunk piston engine oils is discussed in detail in CIMAC Recommendations No.13 [1] and No. 7 [7].

4.3. High Speed Trunk Piston Engine Oils

High speed trunk piston diesel engines employ a single lubrication system for the entire engine. Their lubricants must be capable of working under adverse conditions that promote oxidation / nitration and thermal breakdown of the oil, and that lead to oil contamination, especially by soot and other combustion products. Corrosive products may be present in the oil, resulting from both:

- oil oxidation (weak acids that corrode bearings in particular) and
- strong acids from combustion of sulphurous fuels. The strong acids are corrosive to ferrous components, such as cylinders and piston rings.

To provide satisfactory lubrication under these conditions, the crankcase oils must contain detergent/dispersant, acid-neutralizing (alkaline) and anti-oxidant additives. Anti-foam additives, pour-point depressants and anti-wear (extreme-pressure) additives for valve trains are also commonly used. Multigrade oils are occasionally used for small high speed trunk piston engines and they usually contain polymeric viscosity index improvers, as well as specialised mineral oils or synthetic oils with an inherently very high VI. High-speed trunk piston engines burn distillate fuels without exception.

High-speed trunk piston engines require their oil to be changed at the regular set intervals; this helps control oil stress from both operating conditions and engine design. Economical pressure on the operators is relatively low due to the small oil sump size. In most cases, the oil is simply treated with a filter without centrifuge purifier due to limited engine room space. Therefore, the oil is required to have excellent dispersancy properties, which helps suspend/control insolubles, but which also means it is poor in water separation characteristics. Hence when contaminated with water, the oil can easily become a stable emulsion to the extent it needs renewal.

The main characteristics of the various lubricants are summarised in Table 4.

Table 4: Summary of Main Characteristics of Lubricants for Large Diesel Engines

	Trunk Piston		Crosshead
	High Speed Trunk Piston Engine Oils	Medium Speed Trunk Piston Engine Oils	System Oils
Fuel Type Mainly Used	Distillate Fuels	Residual Fuels	Residual Fuels
Key Treatment System for Lubricants	Filter	Centrifuge and Filter	Centrifuge and Filter
Dispersant Properties of Lubricants	Excellent	Moderate	Moderate
Water Separation Tendency of Lubricants	Very Poor Can emulsify easily.	Excellent	Excellent
Oil Change	Renewed at Regular Intervals	Basically No	No

Based on the fundamental requirements for large diesel engines shown in Table 4, the commercial grades are categorised in Table 5 and 6.

Table 5: Categories of Lubricants for Large Trunk Piston Diesel Engines

Application Type				Typical Lubricant Properties	
Engine Speed	Fuel	Fuel Sulphur Content %	Lube Oil Cleaning	Viscosity Grade	BN, mg KOH/g 1)
High	DMX DMA DMB DMC	<2.0	Filter	30-40	8-30
Medium			Centrifuge and Filter		
Medium	RMA RMB RMD RME RMF RMG RMH RMK	<2.5	Centrifuge and Filter	30-40	15-40
		>2.5			20-55

1) BN recommendations include those from the following engine builders:
Caterpillar, MAN B&W (incl. Holeby, Alpha Diesel), MTU, SEMT Pielstick, Wärtsilä

Table 6: Categories of Lubricants for Crosshead Diesel Engines [8]

Lubricant Type	Typical Lubricant Properties		Comments on Base Number (BN) of Cylinder Oil when Engine is Running on Fuel with Following Sulphur Level:		
	Viscosity Grade	BN, mg KOH/g	Consistently High Sulphur	Consistently Low Sulphur	Switching Between High and Low Sulphur
Cylinder Oil	50	70	OK	May be OK	May be OK
		30-50	Not OK	OK	Not OK
System Oil	30	5-12	-		

Note: Avoid running-in on low sulphur fuel with 70 BN cylinder oil if possible [8]

5. CAUSES OF OIL DEGRADATION

5.1. General

The fact that large engines are tending towards higher power output places greater physical and chemical stresses on the lubricant. In addition, low oil consumption, smaller oil capacities and the requirements for long oil drain intervals compound these stresses. Another major contribution to oil stress is from higher temperatures, leading to a) increased oxidation and nitration, b) higher levels of insolubles and wear metals and c) increased engine deposits.

The critical aspects of lubricant performance that need to be improved or maintained are shown in Table 7 [9].

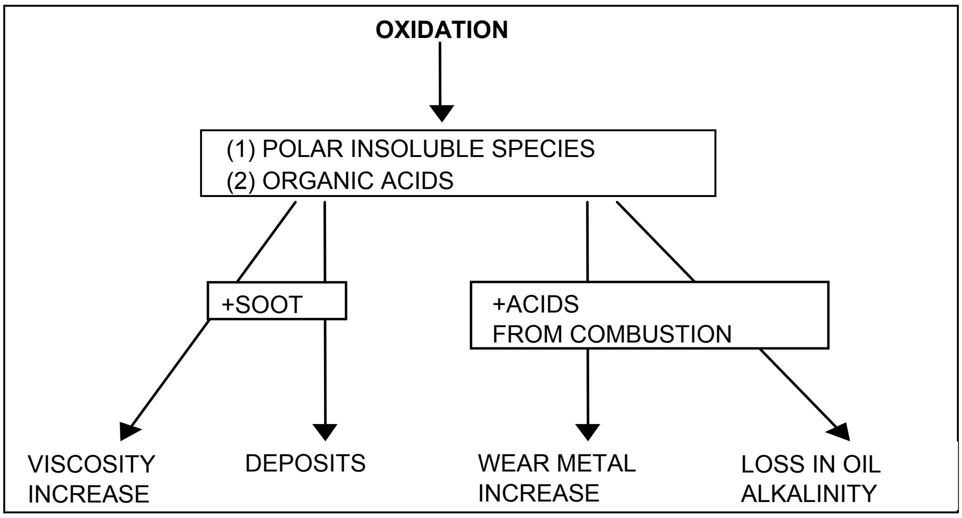
Table 7: Critical Areas of Lubricant Performance [9]

- Viscosity control
- Alkalinity (BN) retention
- Engine cleanliness control (piston undercrown in particular)
- Insolubles control
- Wear protection (oval shape wear of liner in particular)
- Oxidation stability
- Nitration

These performance aspects are of importance during service and are monitored through oil properties such as viscosity and alkalinity. Loss of control of oxidation stability, and/or alkalinity retention and and/or soot content will result in viscosity increasing beyond the condemning limits.

Oil oxidation is a complex process. It occurs through reaction with oxygen at elevated temperatures and leads to changes in oil properties illustrated in Fig.2 [9].

Figure 2: The relationship between oxidation and in-service oil properties [9]



5.2. Factors Affecting Oil Degradation

The following parameters of engine design and operating condition affect oil degradation:

5.2.1. Specific Lube Oil Consumption (SLOC, g/kWh) [10, 11]

Specific lube oil consumption (SLOC) is defined as oil consumption in grammes per hour per unit of output in kilowatt of the engine. In this document, lower oil replenishment / top-up is a direct consequence of lower SLOC.

The oil consumption of conventional trunk piston diesel engines has been in the range 1 -1.5 g/kWh, however new engine designs have an oil consumption typically in the range 0.2 - 0.8 g/kWh. This reduction in oil consumption results from the incorporation of “special” rings which are inset into the upper part of the cylinder liner. These “special” rings are described as flame rings, anti-polishing rings, carbon-cutting rings, burner rings, fire rings, calibration rings, piston cleaning ring or scuff rings. Such “special” rings, installed at the top of the cylinder liners, give a controlled clearance with the piston crown. Consequently, the crown land deposit is reduced to the extent that, when the piston tilts during thrust and anti-thrust motions, rubbing of the crown land against the cylinder liner surface is minimal. Bore polish caused by the carbon build-up is thereby prevented. With less or no bore polish, and with significantly reduced hot carbon wiping the cylinder liner, the oil consumption will be significantly reduced.

Another explanation of reduced oil consumption is the improved gas sealing of the ring pack against the cylinder liner due to better distribution of gas pressure to the back of the piston rings. The improved gas distribution is the direct consequence of the cleaner piston crown land brought about by the application such “special” rings.

The reduced oil consumption will directly influence oil degradation through reduced oil top up. This will be reflected by e.g. an increase in viscosity, and a reduction of BN. Therefore, considering all other parameters, the oil consumption must be seen as the key factor influencing oil degradation.

5.2.2. Specific Lube Oil Capacity (or Sump Size) - kg/kW

The specific oil capacity (or sump size or oil charge) is defined as the nominal quantity (kg) of lubricant circulated in the engine per unit of output (kW). The specific oil capacity is about 0.5 - 1.5 kg/kW in engines of dry sump design. Engines of wet sump design generally have a specific oil capacity of 0.1 – 1.0 kg/kW.

As shown in Figs.9(a)(b)(c) in Section 7.2, the specific oil capacity does not directly affect the maximum or the equilibrium level of the oil deterioration. However, the specific oil capacity influences the speed with which a lubricant deteriorates during service. The smaller the specific oil capacity is, the faster the oil degradation attains an equilibrium level.

5.2.3. System Oil Circulation Speed

Lubricants are subjected to degradation by the blow-by gas, including soot and NOx, during the residence time in the crankcase. Thus the time required for each circulation of the total oil volume affects the speed of oil degradation.

The time required for one circulation of the total bulk oil is about 1.5 – 6 minutes with the trend towards smaller oil volumes and therefore shorter circulation times.

5.2.4. NOx Content in the Crankcase Atmosphere and Influence on Lubricant [12, 13]

Note that this section is more relevant to gas engine oils than diesel engine oils.

It had been recognised in the past that the NOx level in the crankcase of trunk piston diesel engines was very low. This is supported by the data shown in Table 8(b). These data suggest a ratio of the NOx in the exhaust gas to that in the crankcase atmosphere of 30 - 50 : 1.

Table 8(a): Engine Conditions when measuring NOx data [13]

The Engine Conditions	
Speed, rpm	1400
Torque, Nm	360
Air Temperature, °C	80
Air Pressure, kPa	270

Note : NOx concentrations were measured in blow-by gases and in exhaust gases of a small AVL-Caterpillar 1G single cylinder test bench engine burning heavy fuel oil under full load conditions.

Table 8(b): Results of the NOx Measurement [13]

	Blow-by	Exhaust
O_2 , %v	20.5	11.3
CO_2 , %v	0.2	7.4
CO, ppm	75	> 2,500
CH, ppm (propane)	166	155
NOx, ppm	10.3	500

Although engine specific parameters such as injection characteristics, the air/fuel ratio, engine speed and load conditions may contribute to the NOx concentration in the crankcase, an increase of the mean effective pressure alone should result in a greater NOx content in the crankcase [14].

In consequence, it is evident that the NOx content in the crankcase of highly rated marine diesel engines cannot be neglected when assessing its impact on the degradation of the lubricant. However, it has a less significant impact on the degradation mechanism of diesel engine oils (than gas engine oils) because in diesel engine oils, sulphur derived acids (rather than NOx) are the main source of acidic products.

NOx produced by oxidation of atmospheric nitrogen during the combustion process plays a role in lubricant degradation. One concern with NOx has been its influence on the viscosity increase of the lubricant and total acid build-up. Field data collected in the past on certain engines [15] had shown that a good correlation can exist between nitration levels (measured by infrared analysis of oil samples) and the viscosity increase. The nitration rate directly correlates with the viscosity increase observed. More severe nitration also causes an increased acid number and a higher nitrogen content of the lubricant.

Lubricant degradation by NOx may proceed by two main paths [12] :

- The first one is the normal oxidation of lubricants. Here NOx behaves as a precursor and catalyst promoting an oxidative reaction. NOx is very reactive in creating nitrites, nitrates and nitro-compounds. These are sources of free radicals that usually initiate oxidative reactions.

- The other path involves the direct nitration of the lubricant and its oxidation products to produce mainly soluble organic nitrate and, to a lesser degree, nitro-compounds. These nitration products are unstable and subsequently undergo polymerisation to form products which are similar to those obtained from oxidation. Hydro-peroxides and alcohols formed during the oxidation are converted to nitrates by reaction with NOx as well. These contribute to a high increase in acidity and viscosity of the lubricant. If allowed to accumulate, products derived from both degradation pathways eventually agglomerate, become insoluble, and appear as deposits on engine parts [12].

When using infrared spectroscopy to determine the cause of lubricant degradation, the absence of nitration peaks does not necessarily mean that nitration did not play a major role. This is because organic nitrates are thermally unstable so that, if a nitrated oil is exposed to excessive heat, the nitrates will be decomposed. It was reported that nitrates – found stable for several hours at approx. 90 °C – were almost completely destroyed when a sample of the oil containing these nitrates was heated to approx. 150 °C for 2 ½ hours [12]. It should be noted that at typical crankcase temperatures, NO is the major NOx component.

5.2.5. Fuel Contamination in Trunk Piston Engines [16, 17, 18]

As fuel injection pressures have increased so has the risk of crankcase oil contamination by fuel. A recent review of the implications of such contamination has highlighted the most critical areas to be adversely affected by fuel initiated deposits [16]. Typically where the engine operates with residual fuel oil these are the fuel pumps, where plunger sticking or seizure can make the engine inoperable, and piston undercrowns where deposits result in a decrease of the cooling efficiency of the lubricant. Increases in piston crown temperatures have resulted in piston seizures or burn-throughs. A widely used term in the marine industry to describe residual fuel derived deposits in the cooler parts of the engine is “Black Sludge”. Black sludge comprises mainly asphaltenes precipitated from the oil phase. This should not be confused with the black sludge phenomenon of automotive gasoline engines, which is caused by nitro-oxidative degradation of the oil. Viscosity and AN of a used oil also increase following the contamination by residual fuel. Reduced flash points can result from cases of contamination by fuels having low flash points, particularly distillate fuels.

5.2.6. Deposition Tendency on the Cylinder Liner Wall

Deposits in the combustion chamber (includes cylinder liner) can derive from excess of lube oil and/or unburnt fuel. These deposits are scraped down by the piston rings and lead to higher levels of insolubles and viscosity in the oil. Countermeasures to reduce these deposits includes reduction in SLOC (after consultation with OEM) and improvement in fuel combustion.

5.2.7. Metals in Lubricant Systems

Copper in particular acts as a strong catalyst for oxidizing the lube oil. Copper and copper alloys in total have an extremely deleterious effect on lubricants. Microscopic particles of wear metals, particularly copper and iron, in used oils also work as oxidizing catalysts.

5.2.8. Oil Top-up Intervals

The quantity of oil in a lubrication system is prescribed by the design of the engine installation. It should not be allowed to vary too much from this design capacity. The level of oil should be checked regularly and frequently, and fresh oil should be added before the quantity in circulation falls below 90 % or better, below 95 % of the design capacity. A sudden introduction of large quantity fresh oil can sometimes cause the precipitation of asphaltenic or resinous oxidation products (“sludge”). The reason is that in general, used oil is capable of keeping higher concentrations of these materials in solution or suspension. The tendency to precipitation in fact tends to be heightened by a temperature difference between the hot oil in service and the cold oil from the storage tank [19]. Foaming is another possible ill-effect of topping-up with too much fresh oil at once [19].

5.3. Summary of Factors Influencing Oil Degradation

Not all factors affecting oil degradation could be mentioned in paragraph 5.2. Therefore attempts have been made to systematically compile all potential factors that could influence oil degradation in tabulated form. Tables No.9(a) and 9(b) therefore give an overview of the mechanisms for oil degradation due to stresses, influenced by further factors such as engine design and operating conditions. [20]

Table 9(a): Summary of Physical Factors in Oil Degradation [20]

LUBRICANT DEGRADATION					
Factor	**Type**	**Route**	**Effects on lubricant**	**Detection**	**Consequences for the engine**
Engine power		KWh/g of oil correlates with oil properties (eg BN) and determines oil drain interval	Measured by OSF* (Oil Stress Factor, see 6.1.1)	Used oil analysis	Increase in kWh per gram of oil gives reduced oil life
Contamination	Gaseous	Air	Air entrainment (foam)	Air release & foam test	Cavitation failure in bearing
		Combustion gases	Oil degradation	FTIR*	Reduced oil life
		Reaction products	Oil degradation	FTIR*	Reduced oil life
	Liquid	Water	Emulsion leading to additive loss	ICP*	Reduced corrosion protection
		Fuel	Change in viscosity; volatility; insolubles	Flash point; viscosity; VI; insolubles	Risk of crankcase explosions; bearing wear and damage; deposits on engine components
		Cylinder oil drain	Increase of viscosity & BN	Viscosity and BN	potential bearing problems
	Particulate	Dust	Increase in insolubles	ICP*; Insolubles	Risk of abrasive wear
		Wear debris	Catalytically induced oxidation	ICP* elements; ferrography*	Reduced oil life; wear
		Soot	Oil thickening	Viscosity; insolubles	Filter life; centrifuge discharge rate; wear
Thermal	Heat	Volatility*	Oil thickening	Viscosity	Increased oil consumption; potential wear
		Accelerated additive depletion	Oxidation	Viscosity; AN	Reduced oil life
	Hot surfaces	Piston crown and formation of corrosive eutectics*; piston undercrown; ring belt area	Oxidation	Viscosity; AN	Reduced oil life; deposits on piston crown and exhaust valves; hot corrosion and metal loss
Mechanical		Shear	Reduced molecular weight	Viscosity; GPC*	Lower bearing load capacity due to thinner oil film thickness
		Wear	Particulate debris	Elements; ferrography; insolubles; viscosity	Prediction of potential engine damage

* see Glossary

Table 9(b): Summary of Chemical Factors in Oil Degradation [20]

LUBRICANT DEGRADATION					
Factor	**Type**	**Route**	**Effects on lubricants**	**Detection**	**Consequences for the engine**
Oil chemistry	Chemical reactions	Oxidation	Oil thickening; molecular structure changes; loss of anti-oxidants; colour change ; deposit precursors	AN; insolubles ; GPC* FTIR* viscosity	Metal corrosion (Cu, Pb, Sn); filtration/centrifuge loadings; deposits; lacquers.
		Nitration	Deposit formation	FTIR*	Deposits
		Polymerisation	Deposit formation	Insolubles	Deposits
		Precipitation*	Increase of insolubles	Insolubles	Deposits
		Neutralisation	BN reduction	BN	Potential corrosion
Surface reactions	Physisorption*	Interface ; gas / liquid	Loss of additives : foaming	ICP* ; element analysis	Reduced oil life; accelerated wear; engine deposits
		Interface ; liquid / liquid	Emulsion formation	Emulsion tests	
		Interface ; liquid / solid	Soot and asphaltene peptisation*	Blotter spot tests	
	Chemisorption*	Interface; liquid / solid	Potential loss of EP/AW additives*		Wear protection potentially reduced

* see glossary

6. LUBRICANT PERFORMANCE IN SERVICE AS INFLUENCED BY DEGRADATION EFFECTS

It is instructive to consider what happens to the lubricant during its passage through a diesel engine and what impacts it is exposed to. These can be summarised as follows:

6.1. Engine Impacts

It appears convenient for the user to quantify the “Oil Stress” imposed on the oil in use by considering the key operating conditions of his particular engine.

6.1.1. Lube Oils for High and Medium Speed Trunk Piston Diesel Engines

A equation for an “Oil Stress Factor” (OSF) as proposed in [10,11] is shown as follows:

$$OSF = 1/R * \{ 1 - e^{[-Rt/V]} \} \qquad (1)$$

Where OSF: Oil Stress Factor (kWh/g)
R: brake specific oil consumption (g/kWh)
t: oil charge life (hour)
V: oil charge (g/kW)

As shown in Table 10(a)(b), the Oil Stress Factor OSF can be used as a convenient tool for assessing the economical advantages using lubricants of different BN. Fig.3 demonstrates the relationship between OSF and oil life.

Figure 3: Oil Stress Factor for Medium and High Speed Diesel Engines [10, 11]

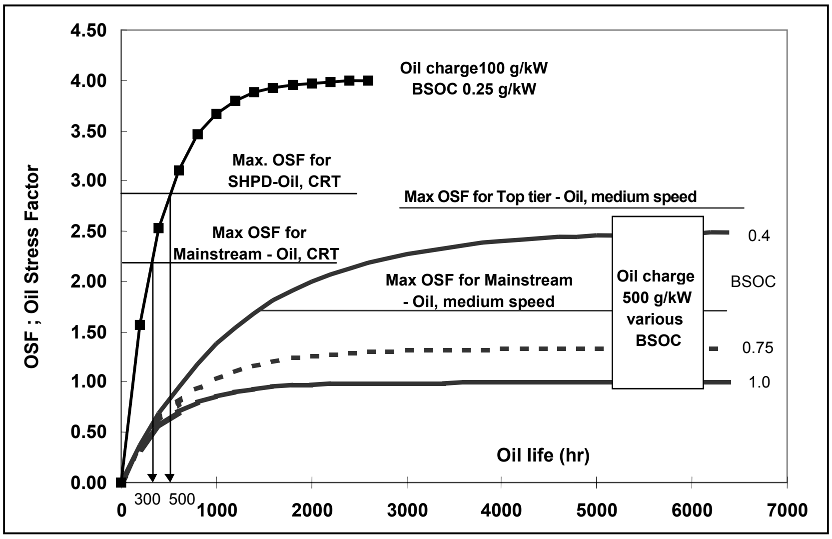


Table 10(a): Comparison of Economics between Oils of different OSFs [11]

Parameter	Units	Oil A	Oil B
Engine Power	KW	2,000	2,000
Oil OSF limit	kWh/g	2.0	2.6
SLOC	g/kWh	0.4	0.4
Sump size	g/kW	550	550
Time to reach OSF limit (oil charge change)	Hr	2,200	Infinite
Oil consumed in 7000 h	Kg	9,100	5,600
Effective oil consumption rate	g/kWh	0.65	0.40

Table 10(b): BN levels for Oils having different OSF limits [11]

Parameter	Unit	Oil A	Oil B
Fuel sulphur	% m/m	2.0	2.0
Fuel consumption	g/kWh	195	195
y Factor *)	%	0.0555	0.0555
Fresh oil BN	MgKOH/g	30.0	40.0
BN at oil change	MgKOH/g	14.8	no change
BN at equilibrium	MgKOH/g	11.1	21.1

*) y = factor indicating the fraction of Sulfur that actually enters the lube oil film in the form of condensed sulphur oxides

6.1.2. Oils for Two-Stroke Crosshead Diesel Engines

So far there is no literature introducing a similar model of “Oil Stress Factor” for slow speed engine oils. See also [21].

Operators often demand a reduction in system oil consumption for cost savings. Lower system oil consumption may lead to faster/greater contamination of the system oil, resulting in frequent partial oil replacement or condemning of the oil charge.

Operators should monitor viscosity, BN and insolubles to assess degree of oil degradation / contamination for deciding oil refreshment. A reasonable degree of oil refreshment / top-up helps to reduce oil stress.

6.2. Physical Stresses [20]

The most important physical stress to be mentioned is heat. Pressure may be considered as well in combination with heat when it comes to assess load carrying capacities and mechanical shear. This is considered by OEMs when selecting adequate viscosities.

6.3. Chemical Stresses [20]

Chemical stresses result from reactions, caused by the exposure of the lubricant to combustion gases in the following areas :

- the cylinder liner walls,
- the piston ring pack and
- the crankcase interior.

Chemical changes to the lubricant can also work in a positive sense – e.g. tribo-chemical reactions occur during the relative motions of metallic component surfaces which results in an anti-wear film being formed.

6.4. Physical Contamination [20]

Physical contamination can arise from soot, water, fuel, airborne dust and from particles generated as the lubricant carries out its functions, for example during the neutralisation of mineral acids. Contamination can also occur by wear particles that may accelerate chemical degradation through catalytic activity.

6.5. Oil Film Thickness [20]

The rate of oil degradation and the mechanisms involved vary in relation to the oil film thickness. Under thin film conditions the oil may degrade faster [20].

7. THE MECHANISM OF OIL DEGRADATION & MEASURABLE RESPONSES TO STRESSES

The impact of stresses is such that the original properties and the performance of the lubricant will change. This can be observed in terms of viscosity changes, volatility losses, oxidation, nitration, acid formation, BN depletion [21], additive adsorption onto metal surfaces and soot particles, incompatibility with fuel components, etc.

Therefore, in this document, oil degradation is assessed and determined by the analysis of the changes in the physical and chemical properties of the lubricants in use. This is normally carried out by regular routine analysis at laboratories. The improved ability of a lubricant to resist undesirable changes induced by stresses forms the basic target for the development of enhanced quality oils.

7.1. Changes in Oil Viscosity

Kinematic viscosity is a measure of the resistance to gravity flow of a fluid, the pressure head being proportional to its density. Dynamic viscosity is the ratio between the applied shear stress and rate of shear. This measures the resistance to flow of a liquid and is commonly called the viscosity of the liquid. Internal resistance results from two origins:

- The first one is the cohesion of molecules or, the forces of molecular attraction between the molecules composing the fluid.

- The other is the internal resistance caused by the inertia force of molecular agitation.

Viscosity is the most important property of a lubricating oil. Viscosity determines not only the internal friction, but also the load carrying ability and the oil film thickness between bearing surfaces. This will influence the bearing temperature and the oil quantity transported to the piston undercrown for cooling, and to the cylinder liners / piston rings. It affects also the oil spreadability.

The viscous property of a fluid asserts itself only when the fluid is in motion. Viscosity is dependent on temperature and in the case of liquids it decreases with temperature. This explains why the “classification” of a lubricant into a viscosity category always needs reference to the temperature at which the viscosity is measured. For example, the SAE Viscosity Classification for engine lubricants is specified by the viscosity determined at 100 °C. (See Table 11). To assess oil thickening due to oxidation viscosity at 40 °C is often measured, whilst thickening effects due to insolubles are indicated through viscosity changes measured at 100 °C.

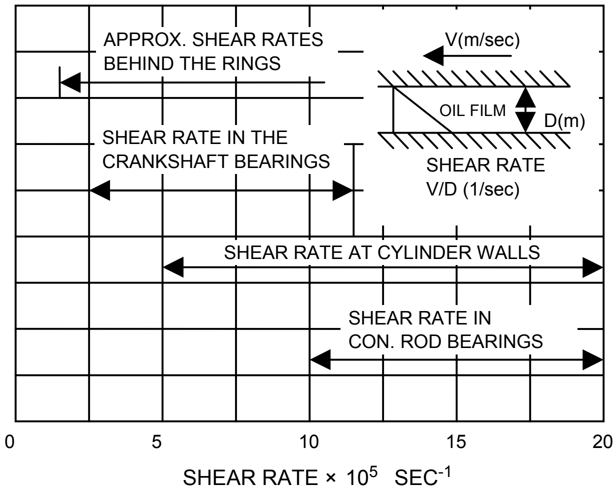
Table 11: SAE J 300 Viscosity Grades for Engine Oils (December 1995 Revision)

SAE Viscosity Grade	Low Temperature (°C) Cranking Viscosity in (cP) max.	Low Temperature (°C) Pumping Viscosity in (cP) max. with no yield Stress	Kinematic Viscosity (mm^2/s) @ 100 (°C)		High – Shear Viscosity (cP) @ 150°C and 10^6 s^{-1} min
			min.	max.	
0W	6200 @ -35	60,000 @ -40	3.8	—	—
5W	6600 @ -30	60,000 @ -35	3.8	—	—
10W	7000 @ -25	60,000 @ -30	4.1	—	—
15W	7000 @ -20	60,000 @ -25	5.6	—	—
20W	9500 @ -15	60,000 @ -20	5.6	—	—
25W	13000 @ -10	60,000 @ -15	9.3	—	—
20	—	—	5.6	< 9.3	2.6
30	—	—	9.3	< 12.5	2.9
40	—	—	12.5	< 16.3	2.9 (0W-40, 5W-40, and 10W-40 grades)
40	—	—	12.5	< 16.3	3.7 (15W-40, 20W-40, and 25W-40, 40 grades)
50	—	—	16.3	< 21.9	3.7
60	—	—	21.9	< 26.1	3.7

For a range of lubricants (multigrades, HVI lubricants) the viscosity is dependent on the shear rate. For others it is not, or in a limited temperature range only. A fluid whose viscosity is independent of the shear rate is defined as a Newtonian fluid. A fluid whose viscosity varies with changes in shear rate is referred to as a non-Newtonian fluid.

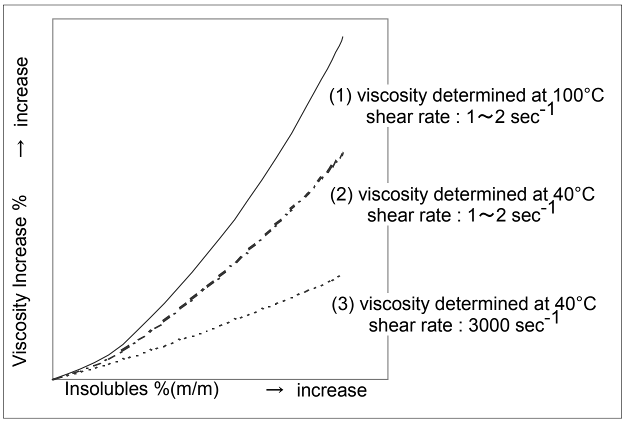
Since the kinematic viscosity of an oil is determined using a glass capillary viscometer having a very low shear rate (say 1 - 2 s^{-1}), specific rotary viscometers are required to measure the viscosity of lubricants under conditions relevant in the bearings of internal combustion engines. Here the shear rates are extremely high, say (10^6 s^{-1}). Typical shear rates of lubricated engine components are shown in Fig.4.

Figure 4: Shear Rates of Lubricated Parts in Engines



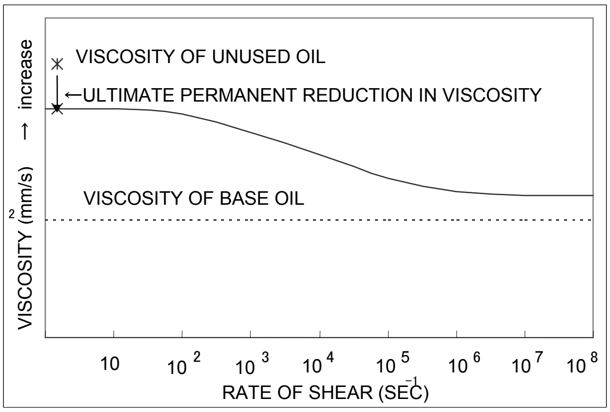
Although fresh oils – categorized as SAE single viscosity grades – are Newtonian fluids these, when heavily contaminated in use, may show non-Newtonian behaviour. Therefore, the viscosity of oils in use for the bearings of running engines may be lower than the viscosity determined in the laboratory under low shear conditions. For engines with a relatively small minimum oil film thickness in the bearings it is, therefore, not recommended to reduce the viscosity of the oil in use further by topping up with fresh oils of lower viscosity. Fig.5 illustrates the effect of insolubles on the viscosity at different temperatures and shear rates [22, 23].

Figure 5: Insolubles and Viscosity Increase



Multigrade oils, e.g. SAE 15W/40, are formulated with VI–improvers consisting of long chain polymers. Multigrade oils are frequently used for automotive derived high speed diesel engines. These oils are “non-Newtonian” in that their viscosity falls as the rate of shear increases (See Fig.6). A further complication is that VI-improvers suffer, to a degree depending on their characteristic, a permanent initial loss of effectiveness due to thermal and mechanical stresses. A drop in viscosity at an increased shear rate is referred to as “temporary”. This drop must be considered in addition to the “permanent” loss of viscosity associated with the initial partial breakdown of the “VI-improver”. At a very high shear rate the temporary viscosity loss may be quite large. Therefore, before applying multigrades in marine diesel engines with critical bearings, it is recommended to carry out field tests to confirm safe applicability.

Figure 6: Relationship between Viscosity and Shear Rate in an Oil Containing VI-Improvers [24]



For the lubrication of medium and low speed diesel engines multigrades are rarely used. Therefore, the impact of shearing (permanent and temporary) can be rated as less meaningful.

The viscosity of a system oil may change in service due to a variety of reasons as mentioned in the subsequent paragraph. Accordingly, any change in viscosity should be considered in relation to other parameters, such as AN for oil oxidation, insolubles and water content for contamination, and others (including fuel contamination). If, however, these test data reveal nothing unusual, a change in viscosity may simply indicate an admixture of lubricating oils with a higher or lower viscosity being added to the system.

Reasons for Viscosity Increases

The reasons for a viscosity increase – apart from a reduction of the lubricant's temperature – are as follows:

(i) Low oil replenishment. This is of particular importance, because it exaggerates the severity of all other processes mentioned below. The lube oil volume should never be allowed to drop below 90 % or better, below 95 % of the design capacity.

(ii) Oxidation. This results from heat combined with the presence of oxygen. It is aggravated when the lubricant is contaminated with raw fuel (eg containing unstable olefinic components) or partially oxidized fuel components. Furthermore, the catalytic activity of wear metals, particularly copper and iron, can accelerate oxidation rates. Copper plated surfaces, such as the copper flash (for preventing seizures) on piston skirts can have a similar effect.

(iii) Nitration. This occurs mainly due to high NOx contents of blow-by gases passing the crankcase. This is more relevant to gas engine oil than diesel engine oils.

(iv) Contamination by highly viscous residual fuels. Further increases in viscosity will occur if coagulation of asphaltenes from residual fuels takes place within the oil in use.

(v) Contamination by highly viscous lubricants, e.g. waste cylinder oil from the scavenge space of cross head diesel engines contaminating crankcase system oil through the stuffing boxes. In trunk piston diesel engines with cylinder lubricators, one grade (normally SAE 40) of engine oil should be used for the feed of the quills and for the top up of the crankcase, in order to avoid undesirable influences on the viscosity.

(vi) Oil insolubles. Significant increases of insolubles in used oils can result from poor combustion, faulty operation of purifiers, insufficient capacity of purifiers, filter elements not being replaced, insufficient capacity of filters, and also the ingress of sulphuric acid into the oil due to low cylinder liner temperature, poor mechanical condition of the engine,etc.

(vii) Increase of sooty insolubles in the oil in use due to high oil consumption. High oil consumption via the combustion area can lead to more soot formation from burnt lubricant. Soot adhered to the cylinder liner surface is scraped/washed down into the crankcase if there is excessive oil on liner surface.

(viii) High volatility lubricant (dumb-bell blends). This is less critical with higher viscosity single grade oils, i. e., SAE 40 and above.

(ix) Contamination with water.

Countermeasures Against Premature Viscosity Increase of the Oil in Use :

The following suggestions should be considered for preventing a premature viscosity increase of an oil in use:

(i) Adjust oil level to that recommended by the engine builder.

(ii) Avoid raw fuel contamination.

(iii) Reduce as far as possible the NO_x concentration in the crankcase. This is more relevant for gas engines than diesel engines.

(iv) Make sure the oil treatment system, in particular separators, centrifuges, filters, etc. is correctly sized/installed and diligently operated. For a 4-stroke engine, the complete oil volume should pass through the treatment system at a frequency not less than the minimum specified by the OEM (this "minimum" can be typically 4 to 6 times [25] per day, depending on the OEM and the engine/fuel/operating conditions, ie the soot generation tendencies)

(v) Avoid the use of copper and copper platings where possible in the design of the lubrication system and in pipe work.

(vi) Keep the engine, in particular the entire lubrication system, in good mechanical condition.

Reasons for a Viscosity Decrease

A decrease in lubricant viscosity may present a higher risk to the engine than an increase in viscosity. Levels may be reached where full film lubrication is no more possible, particularly in bearings. The causes of a viscosity decrease are as follows:

(i) Increase of the oil temperature for a variety of reasons.
(ii) Dilution by light fuels, low viscous lubes and / or cleaning fluids.

Countermeasures Preventing Viscosity Decrease of the Oil in Use :

(i) Control oil temperature to design value.
(ii) The diligent elimination of all causes for contamination by light fuel and / or cleaning fluids.

7.2. The Formation of Insolubles

The control of the insolubles level in a used oil is important for satisfactory lubrication of an engine and long term engine reliability. It requires an integrated view of the engine, the oil quality being used, the used oil condition and the effectiveness of the lubricant maintenance system. This in particular is relevant when the oil consumption is reduced and the drain interval extended.

What are Insolubles ?

It has been shown already that greater stresses will inevitably result when at higher levels of oil contaminants. The level of contamination is expressed as insolubles content of the oil. Many types of contaminants [23] are found in used oils which can be detrimental to varying degrees. Contamination may lead to oil thickening and/or increased engine wear, and/or may lead to the formation of deposits in the engine and in lubricant filters. This will impair the efficiency of engine operation.

The following section discusses harmful effects of lubricant contamination during engine operation. Various factors that have an impact on the oil contamination are identified and will be considered in a mathematical model. A series of tests in a direct-injection diesel engine fitted with a centrifugal lubricant filter confirms the validity and usefulness of the model (Figs.7 and 8) [26].

The entire process of insolubles formation is not completely understood, even though it is one of the key factors in determining the quality of an oil in use. This is due to the complex nature of the impurities. A wide spectrum of differences in particle size, shape, density and chemical composition is found, depending on engine type, load, fuel (combustion) characteristics, lubricant quality and grade, and engine service status. Analytical work has shown that soot and calcium sulphates are the main components of the insolubles found in diesel engines running on residual fuels [26]. A typical result of a chemical analysis on separator sludge shows that 20% is soot, 65% is inorganic calcium salts and 10% is hydrocarbons. The remainder consists of degraded additives and other inorganic components [26]. The degree of contamination is normally determined by measuring the quantity of insoluble matter in the oil. The numerical result, reported as “insolubles content”, varies with the analytical method used. Some techniques rely on solubility in certain solvents and / or on filtration through micro-pore filters. Other methods use chemical flocculents and a centrifuge. Sometimes infrared spectroscopy or optical microscopy is used. It is clear that with such a variety of techniques, some confusion can occur as to what “insolubles” actually are.

When reporting the insolubles content the method used must be reported. To avoid any confusion, this document refers to insolubles as measured according to the ASTM D893 procedure, which is explained in CIMAC Recommendation No. 13 [1]. (Note studies / debates on alternative proven methods are actively being pursued by CIMAC and CEC).

Data in many publications support the qualitative statement that insolubles in lubricants have an adverse effect on engine operation and life [27]. When trying to quantify this effect, the data become more elusive or even contradictory. However, the data published in [27] show the relationship between cylinder liner wear and the volume of extracted separator sludge. They demonstrate that in this test effective particle removal was able to reduce liner wear down to 0.01 mm per 1000 hours. Another report [28] links bearing wear to combustion soot becoming embedded in the soft overlay of the bearing shells. Oil contamination is reported to lead to piston groove and land fouling [29]. This trend was confirmed in service trials, particularly for piston undercrown areas [26]. Heavy contamination reduces filter life. However, other factors do play a role as well. Such factors could be the particle size of oil contaminants and their affinity towards the filter medium. It is evident that there is a correlation between insolubles and various engine performance aspects (Figs.7 and 8). It is, furthermore, justified to assume that there is actually a cause / effect relationship. The key uncertainty, however, arises when it comes to the definition of safety margins and the maximum contamination levels that can be tolerated.

Figure 7: Effect of Lubricants Insolubles Content on Engine Cleanliness (DI Caterpillar Laboratory Engine) [26]

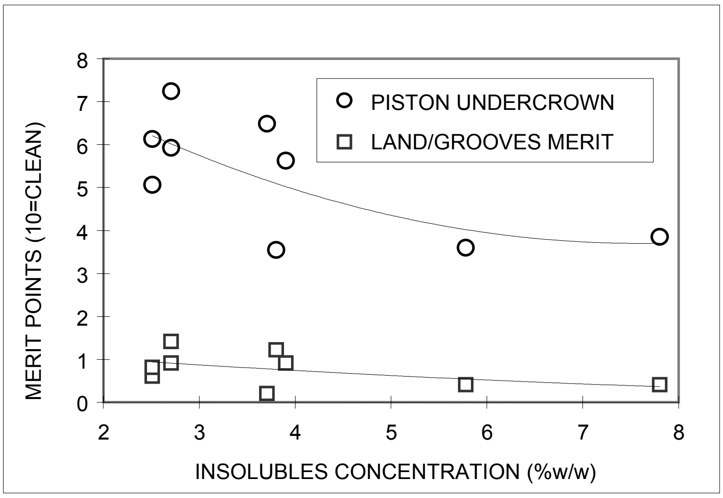
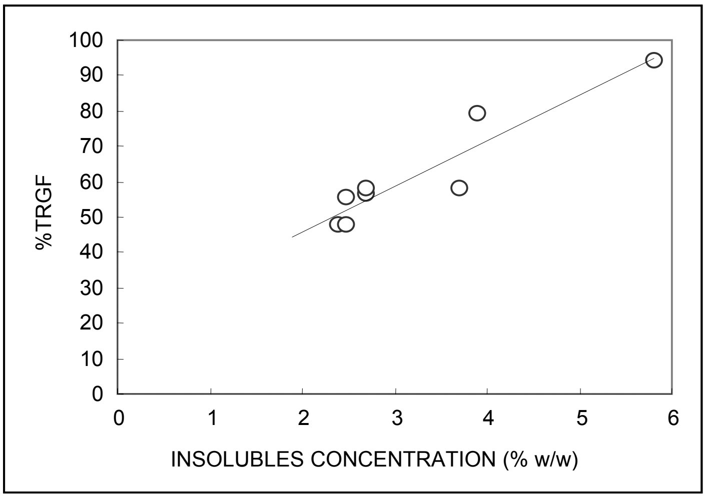


Figure 8: Effect of the Insolubles Content on Top Ring Groove Filling in a DI Caterpillar Laboratory Engine [26]



<u>Factors controlling the Soot Contamination</u> [26, 31, 32, 33]

As shown before, many factors can contribute to soot contamination. These factors can be grouped into three main categories:

(i) Engine design parameters
(ii) Oil treatment system
(iii) Operational parameters

These three categories are discussed below:

(i) Engine design parameters: Major factors are the combustion chamber and injection equipment design, the compression ratio, etc. The quantity of blow-by gas is important and hence also the piston crown / cylinder liner clearance. Furthermore, the soot enters the lubricating oil mainly via thermophoretic deposition on the cylinder wall [30]. The speed of the engine controls the exposure time of the lubricant to the combustion gas. A high stroke/bore ratio enhances the fuel/lubricant interaction and thus the risk of lubricant contamination. The oil consumption, which itself is influenced by various factors, must be grouped into this category as well. The combined action of all factors named above plus many others yields a wide variation of oil contamination levels, which can easily differ by more than 100 per cent. Usually, the insolubles production ranges from 10 to more than 100 mg/kWh for engines running on residual fuel [32]

(ii) Oil treatment system: This subject relates to the dimensioning and layout of the oil cleaning system, e.g. filters and/or separators in the form of full flow or bypass units, and the percentage of the nominal capacity the filters or centrifuges are operated at. It is generally recommended that separators and filters should operate at 25% max of their nominal capacity to obtain maximum efficiency.

(iii) Operational parameters: These also have a great effect. Other parameters unchanged, the soot production increases roughly in proportion to the fuel consumption or power output. Additionally, fuel quality, lubricant grade and quantity, and separator operating conditions (temperature), play a major role. Here, the mechanical condition, the wear profile and also reasons for the restriction of engine speed, such as hull fouling etc. must be mentioned. The impacts of several of these factors have been reported. [31, 33, 34, 35, 36, 37, 38]

Trunk piston diesel engines burning residual fuel are usually operated with separators in a bypass configuration. These separators have to remove water, soot and other contaminants from the oil. The oil acts as transport medium for insolubles produced in the engine, and carrying the insolubles to the separator for disposal. The degree of engine fouling is determined by the concentration of insolubles and by the oil's tendency to form deposits. As a consequence it is assumed that the efficiency of the separator has an influence on engine cleanliness.

A model has been developed where the lubricant is considered as a fluid circulating from the sump to the engine, from the engine to the separator and back again into the sump. For details see Appendix 1 and [26]. In this model it is assumed that the amount of soot is influenced by:

(i) The production rate of insolubles.
(ii) The fraction of these insolubles deposited on engine surfaces, particularly on the cylinder liner surface.
(iii) The fraction of these insolubles removed by filters and centrifuges
(iv) The loss of oil (and contaminants) by combustion and in the separator.
(v) The lubricant quality

The Model relates insolubles levels to a number of these parameters via a mathematical formula. The main findings/recommendations from applying this Model are:

a) where no centrifugal separator or oil filtration is present or active, a very high insolubles levels will occur which will equilibrate at a level dependent on the oil consumption rate. The lower the oil consumption rate the higher the level of insolubles at equilibrium. See Figs.9(a), (b) and (c).

b) In view of the serious impact of high levels of contaminants on engine condition it is essential that such material is removed as effectively as possible. Correct operation of centrifuge and filters is vital to ensure that insolubles levels are kept below acceptable maximum levels (i.e. below condemning limits specified by the engine manufacturer). One aspect of efficient centrifuge operation is centrifuge capacity which is referred to previous Section 7.1 under “Countermeasures Against Premature Viscosity Increase of the Oil in Use”.

Figure 9(a): Factors influencing the rate of insolubles build-up.

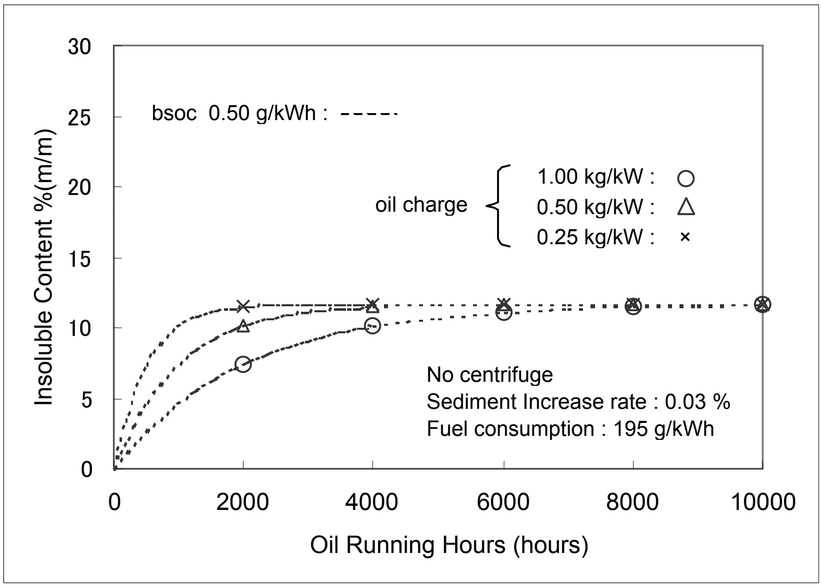


Figure 9(b): Factors influencing the rate of insolubles build-up .

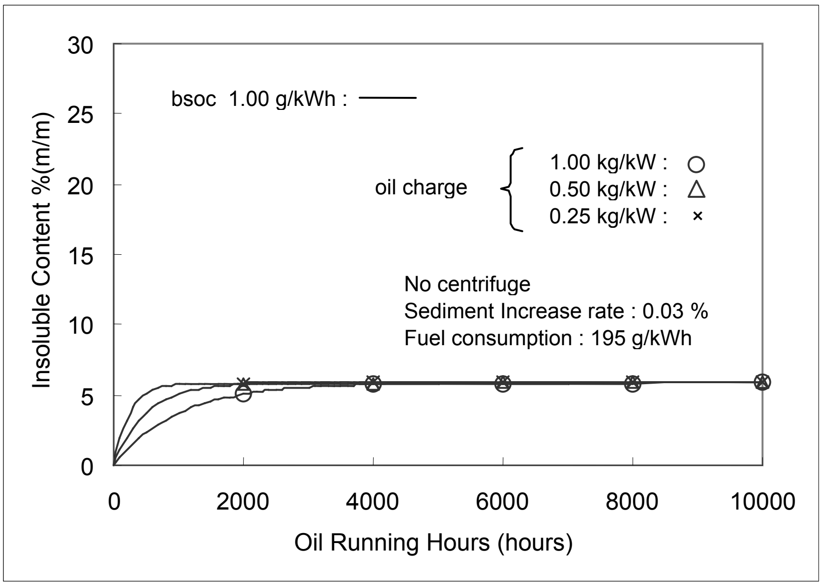
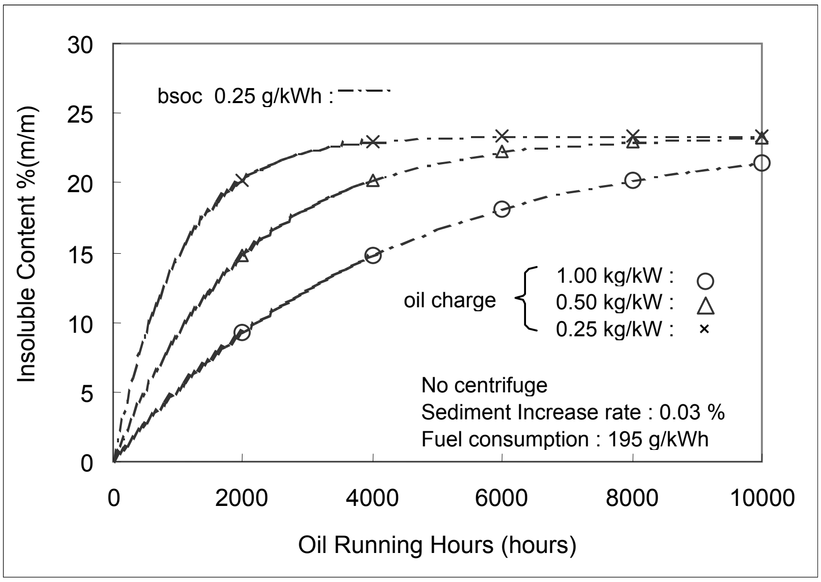


Figure 9(c): Factors influencing the rate of insolubles build-up.



7.3. Changes in BN (Base Number)

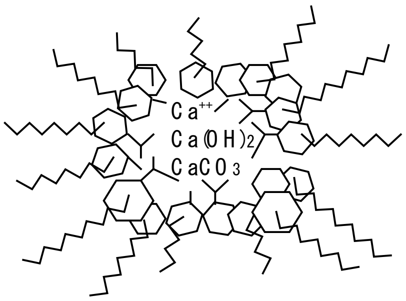
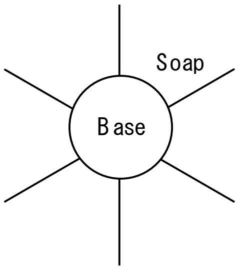
The BN of trunk piston engines oils decreases during service. The BN depletion can be predicted using a knowledge of (a) how the engine stresses the lubricant, known as oil stress (see Section 6.1) and (b) conversion of sulphur in the fuel to base depleting acids. But before going into more detail we will first explain exactly what is meant by BN.

What is Lubricant Base? [10, 11]

BN is determined by titration of lubricant against an acid. It is a measure of the acidity neutralisation potential of a lubricant, expressed as the amount of a typical reference base to which the lubricant is equivalent. For example one gram of a lubricant with BN 20 mgKOH/g will neutralise the same amount of acid as would be neutralised by 20 mg of the reference base or alkali, which is potassium hydroxide (KOH).

The primary function of the various alkaline detergent additives used in marine lubricants is to add neutralizing capacity to the oil [39]. Inorganic salts like calcium carbonate ($CaCO_3$) and calcium hydroxide ($Ca(OH)_2$), which provide BN are held in the oil by calcium detergents of organic sulphonates, (sulphurised) phenates or salicylates.

These additives are present in the oil in the form of very small particles. A typical overbased detergent additive particle is shown in Fig.10 and summarised in Table 12. The typical size of an additive particle is less than 20 nm, which is too small to interfere with even very thin oil films. Large bore medium speed engines with minimum oil film thickness of a few microns have been shown to have an extremely long bearing service lifetimes, even when using BN 50 lubricants, which have relatively high amount of additive particles.

Figure 10(a): Simplified chemical structure of an Overbased Detergent Micelle	**Figure 10(b): Schematic Drawing of an Overbased Detergent Micelle**
	

The various types of detergents (or "soaps") provide to a greater or lesser extent the detergency which keeps engine components clean, as well as additional anti-oxidant properties, dispersancy and protection against corrosion. The inorganic salts cannot exist in the oil alone (if the detergent is used up, the inorganic part would precipitate). The ratio of inorganic to organic material defines what is known as the degree of overbasing.

The BN of the oil, although related to, is not directly proportional to such properties as detergency or anti-oxidancy. The degree to which BN is a measure of its detergent power and anti-oxidant reserve depends greatly on additive technology, and for any new lubricant product it has to be verified by engine tests.

Table 12: Generalised Detergent Composition

Organic Substrate (Soap)	detergency, anti-oxidancy and dispersancy
Inorganic Core (Base)	(a) base to counteract acid combustion products (b) some anti-wear properties

Changes in BN due to reaction with acid

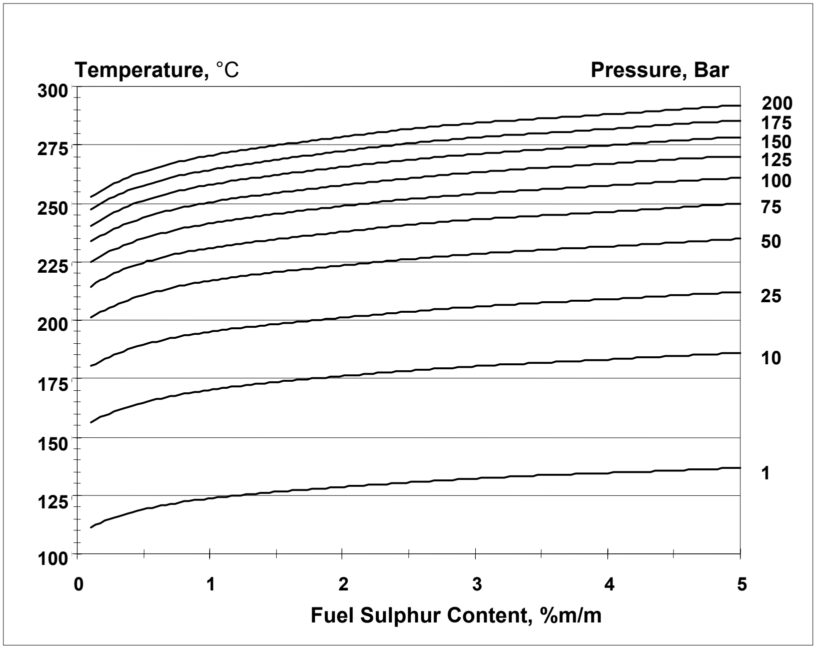
The inorganic core of the detergent additive is primarily responsible for neutralizing the two types of acids that are found as contaminants in the lubricant: 1) inorganic acids, such as sulphur and nitrogen acids from fuel combustion and 2) organic acids from oil and fuel oxidation. The neutralisation results in a consumption of BN additive and thus a drop in BN. The major reduction of BN in oil is related to the sulphur in the fuel. The amount and concentration of sulphuric acid condensing on the oil film depends on:

i. fuel sulphur content
ii. combustion gas water content
iii. surface temperature
iv. engine factor (design, load, speed, pressure, bore,….)

Fuel sulphur content and water content in the combustion gas influence the dew point of sulphuric acid at the elevated combustion pressures in diesel engines. Although difficult to measure in practice, calculations show that elevated pressure has a very significant effect. The sulphuric acid dew point curve as a function of pressure and fuel sulphur content can be found in [40](Fig.11). Dew point also varies with sulphuric acid concentration, and therefore the surface temperature will determine the actual concentration of the sulphuric acid which condenses on any given surface in the combustion chamber.

determine the actual concentration of the sulphuric acid which condenses on any given surface in the combustion chamber.

Figure 11: Acid Dew Point Curve [40]



Predicting the rate of BN reduction

Equations (1) and (2) can be used to estimate the BN of used trunk piston engine oils at time t:

$BN_t = BN_0 - 0.35 * S * F * y * OSF$ **(1)**

Where BN_t : Base Number(BN) at oil life of t hour (mgKOH/g)
BN_0 : BN of the fresh oil (mgKOH/g)
S : fuel sulphur content (% m/m)
F : specific fuel consumption (g/kWh)
y : the percentage conversion of sulphur into species neutralised by the basicity of the oil (%)
OSF : Oil Stress Factor (kWh/g) (See equation (1) in Section 6)

At some point the BN will stop falling and reach an equilibrium level. The BN_{EQ} can be computed by using the equation:

$BN_{EQ} = BN_0 - 0.35 * S * F * y / R$ **(2)**

Where BN_{EQ} **:** Base Number (BN) after an indefinite long time period (mgKOH/g)
R **:** actual specific oil consumption (SLOC), (g/kWh)

Factor “y” in both equations (1) and (2) can be estimated by the following equations (3) and (4).

$y = (BN_0 - BN_t) / (0.35 * S * F * OSF)$ **(3)**

Under equilibrium condition of BN, factor “ y “ is given by equation (4).

$y = (BN_0 - BN_{EQ}) * R / (0.35 * S * F)$ **(4)**

Figs.12 to 15 illustrate the effects of varying the parameters in equations (1) and (2):

Figure 12(a): Effect of SLOC (Fresh Oil : BN 30)

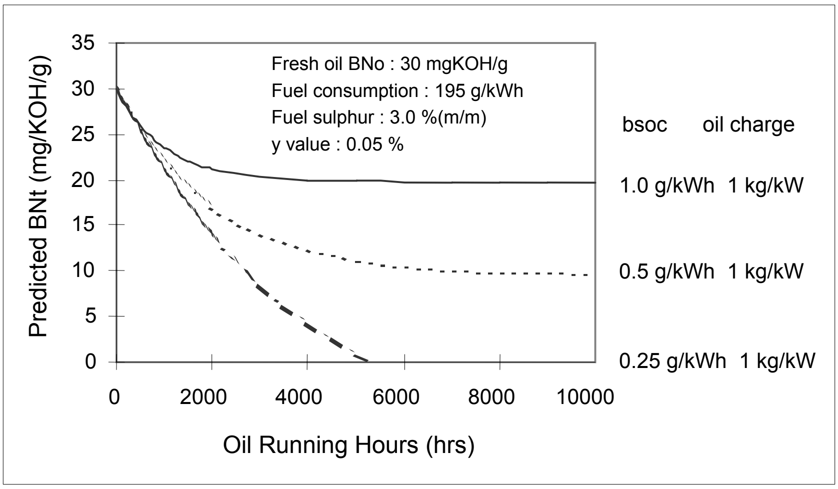


Figure12(b): Effect of SLOC (Fresh Oil : BN 40)

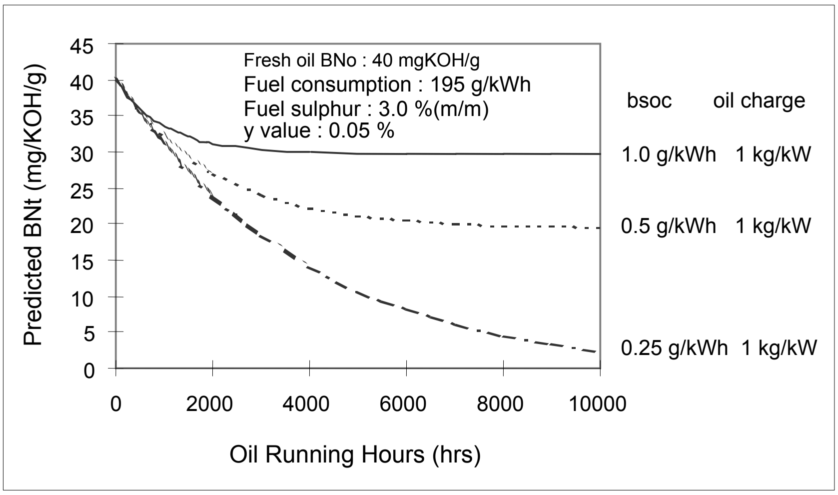


Figure 12(c): Effect of SLOC (Fresh Oil : BN 50)

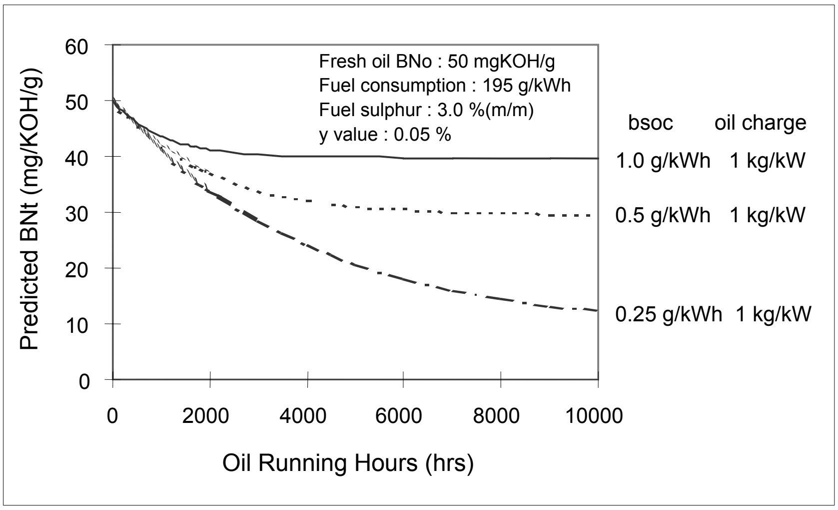


Figure 13: Effect of Oil Charge (Fresh Oil : BN 40)

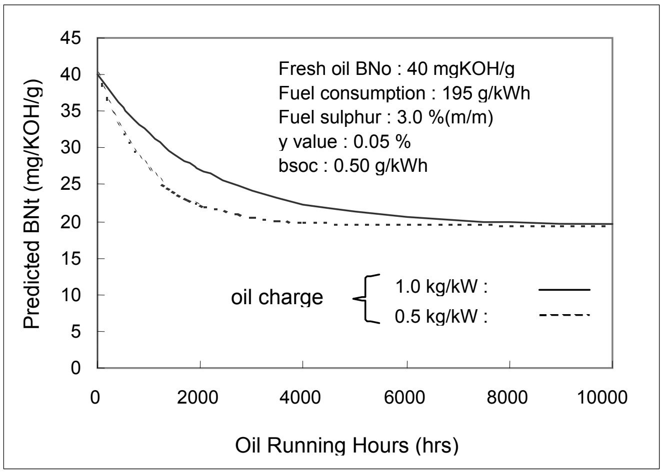


Figure 14: Effect of Fuel Sulphur (Fresh Oil : BN 40)

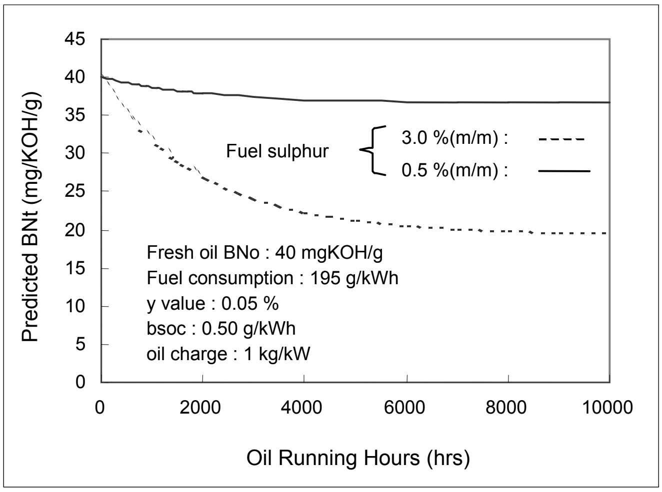
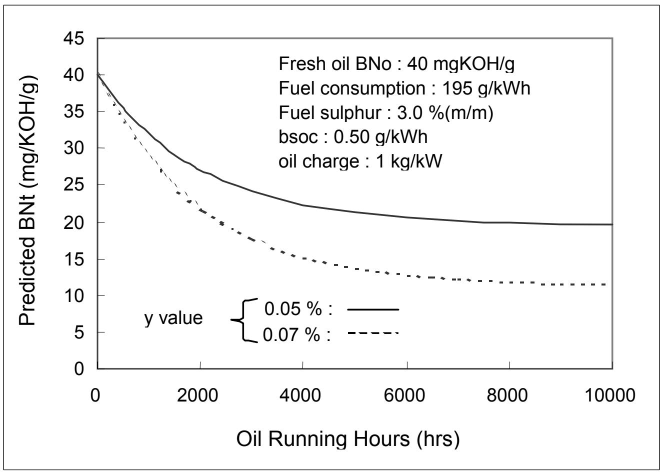


Figure 15: Effect of y value (Fresh Oil : BN 40)



The figures above show that the most economical configuration for a heavy fuel medium speed engine with a y-factor of 0.05% running on 3% sulphur fuel is to have an SLOC of ca. 0.3 g/kWh, so that when a BN 50 lubricant is used, the oil charge never has to be changed because the BN is too low. The equilibrium BN is ca. 20 mgKOH/g, i.e. in the range of typical engine manufacturers minimum recommendation. The y-factor is more often above 0.05% in which case the ideal SLOC under the above conditions is closer to 0.5 g/kWh.

The rate of BN depletion or the time taken to reach the equilibrium BN is determined by the size of the oil charge. Older engines with no anti-polishing ring have significantly higher SLOC's, and a BN 40 lubricant, or less for low sulphur fuels, will be sufficient to keep the BN of the used oil above the minimum limit, so that a full or partial oil change is never required because the BN is too low.

Relatively low equilibrium BN levels are sufficient for most purposes, even with high fuel sulphur levels. On engines with very low SLOC's, more BN is required near the top of the liner, because the oil film near top dead centre which provides neutralisation of corrosive species is refreshed less often, and more alkalinity per volume unit is required to achieve the same protection against corrosion, as compared to high SLOC engines.

BN Test Methods [39]

There is more than one BN test method and the result is different depending on which test method is used. The principle methods for measuring BN in engine oils are ASTM D2896 and ASTM D4739. A comparison of these two methods is given in Table 13 [39].

Anything more basic or alkaline than the acid used in the method will be measured as base. The essential difference between the ASTM D2896 and ASTM D4739 methods is the type of acid which is used: perchloric acid in D2896 is stronger than hydrochloric acid used in D4739. For fresh oils, this difference in acid plays a relatively small role and only small variations are seen, with the D2896 method consistently giving slightly higher values.

For used oils the change in acid between D2896 and D4739 has a major effect (Fig.16). The stronger acid in D2896 measures both lubricant base components and lubricant degradation salts such as metal formates and acetates. In contrast, the D4739 method, with its weaker acid, has little tendency to measure these products, and hence its results are slightly lower than D2896.

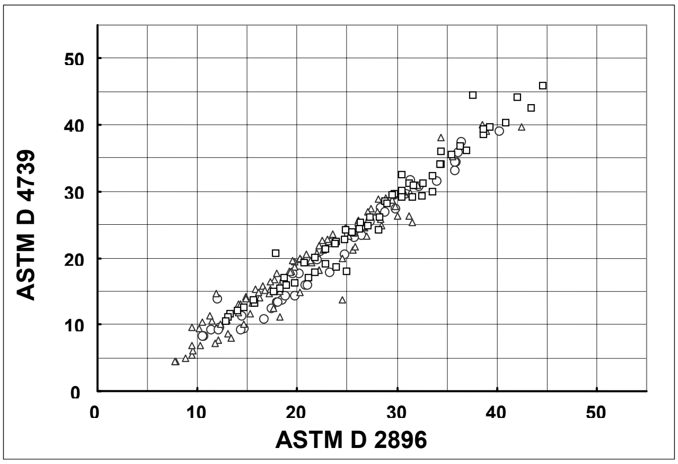
Table 13: ASTM Base Number (BN) Methods : What do they measure? [39]

	ASTM D2896	ASTM D4739	ASTM D664(obsolete)
Acid	Perchloric in glacial acetic acid	Alcoholic hydrochloric Acid	Alcoholic hydrochloric Acid
Solvent	Chlorobenzene / glacial acetic acid	Toluene/IPA/chloroform	Toluene/IPA/water
Measures	- Strong bases - Weak bases	- Strong bases - Only some weak bases	- Strong bases - Only some weak bases
Examples Fresh oil	- All detergent base - All dispersant (amine) base	- All detergent base - Most dispersant base	- All detergent base - Most dispersant base
Examples Used oil	Most Ca, Mg, salts of degradation products	Some Ca, Mg, salts of degradation products	Very few Ca, Mg salts of degradation products

The influence of metal compounds resulting from degradation of oil on the BN determination has been investigated [39] and the results show that predicting which compound is measured by D2896 is not straightforward. Calcium salts of oxidation acids (formic and acetic acids) provide a significant contribution to BN as measured by the D2896 method, but less so for BN D4739. Calcium nitrate is measured by D2896 but not by D4739, and iron (III) nitrate is not measured by either method. Importantly, neither method measures calcium sulphate which is the major salt formed in normal service by neutralisation of sulphuric acid, derived from fuel combustion.

In summary, D2896, to an extent, overmeasures the true base reserve of a used oil. However, a) since the D2896 method has the better precision of the two methods, and b) BN levels of used marine diesel engine lubricants normally remain relatively high in service, D2896 remains as the generally preferred method.

Figure 16: Neutralization (mgKOH/g) by ASTM D2896 & ASTM D4739 Methods Comparison in Wärtsilä 4L20 Laboratory Engine of Three Oil Technologies (20)



The Causes of BN Reduction

- (i) High sulphur content of fuel
- (ii) Very low oil consumption; insufficient fresh oil top-up
- (iii) Very low cylinder liner temperature (low cooling water temperature, high “y” value [see equation 1 and 2 in Section 7.3])
- (iv) Ingress of drain water condensed at air cooler.
- (v) Ingress of splashed sea water due to improper design of intake air vent
- (vi) Other general water contamination (eg from purifiers, oil coolers etc), leading to wash out of additive from poorly formulated oil
- (vii) Low load operation (cold operation)
- (viii) Bad combustion (soot generally contains sulphuric acid)
- (ix) Neglect of fresh oil top-up relative to regular top-up
- (x) Top-up with low BN oil
- (xi) Excess blow-by into crankcase
- (xii) Raw residual fuel contamination / dilution of lubricating oil

The Causes of Increase of BN

- (i) Contamination with cylinder oil of higher BN than the crankcase oil, in for example a four stroke engine with separate cylinder lubrication.
- (ii) Contamination of two-stroke system oil with cylinder drain oil.

7.4. Increase of TAN (Total Acid Number)

What is acid ?

See Appendix 3

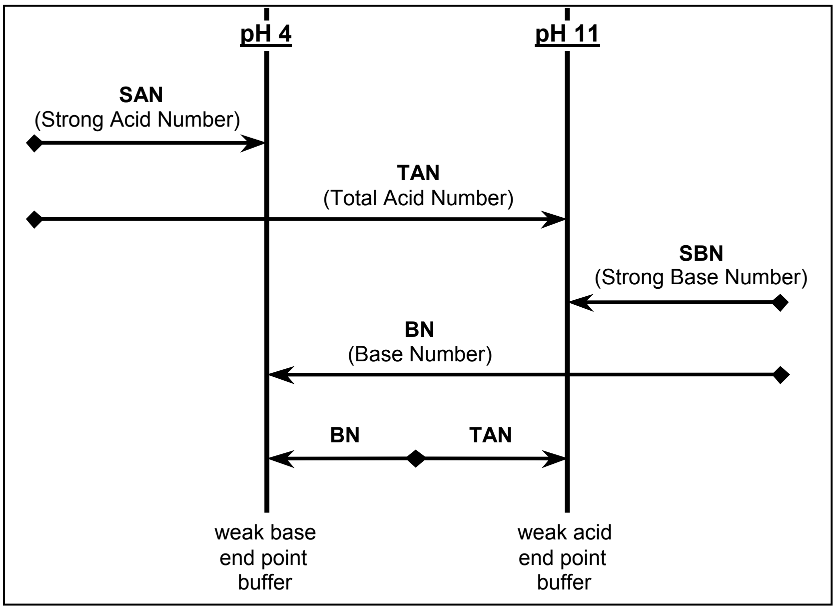
Method of Measurement

The colour indicator method cannot easily be applied to dark-coloured oils. Therefore the electrometric method of titration is used.

ASTM D664 test method defines the total acid number (TAN) of a lubricant as the quantity of base, expressed in milligrams of potassium hydroxide, that is required to react with all of the acidic constituents present in 1 gram of sample.

In this test method the sample is dissolved in a mixture of chloroform and iso-propylalcohol and placed in a potentiometric titration cell. Alcoholic potassium hydroxide is added until the potential difference between the electrodes of the cell becomes constant ; The quantity of potassium hydroxide added determines the total acid number（TAN ）of the used oils. The TAN value comprises both strong and weak acids; because the in-service engine oils are alkaline, it means that their TAN values are generally from weak acids only. Fig.17 illustrates how TAN, SAN, BN, SBN are linked.

Figure 17: TAN, SAN, BN, SBN



Discussion

Oils treated with additive, depending on chemical constitution of the particular additives present, may exhibit an apparent acid and/or alkaline reaction without any free acid or alkali actually present. Fresh diesel engine oils may show TAN of around 1 – 2 mgKOH/g, depending on the brand. It is generally considered that an increase from the initial figure in TAN is either an indication of contamination with acidic combustion products or the result of oil oxidation. In the case of oil oxidation, other evidence is generally available, such as an increase in oil viscosity.

The weak acids formed when oil is oxidised do not attack ferrous metals or white metal but can cause corrosion of copper/lead bearings. These materials are generally oil soluble. The oxidation products formed contain oil-soluble carboxylic acids that are extremely corrosive towards the lead phase of copper/lead bearings. Potential bearing corrosion problems cannot be inferred from the TAN of the used lubricant, since the TAN titrimetric technique cannot distinguish between corrosive and non-corrosive acids. But should the oil show SAN, then there is strong acid and a significant risk of a problem.

7.5. Flash Point Reduction

The purpose of the determination of flash point is to alert against crankcase explosion. A drop in flash point indicates contamination by fuel, though with heavy fuel no significant change may be apparent.

There are two ways of contaminating the used lubricant with fuel components. The one is the direct contamination of the used lubricant with the liquid raw fuel. The other is the indirect contamination of the used lubricant with some evaporated/re-condensed fraction of the fuel.

As a very general guide it is advisable to check for fuel contamination when the flash point drops by 30℃ or more, or the flash point value drops below 180℃ - whether measured by PMCC or COC. An extreme drop in flash point may require replacement of oil charge - see engine builder recommendation or CIMAC 13 and 15. However, note that in event of water contamination, the flash point determination will be affected. If more than a certain amount of water is present in a sample it may not be possible to obtain a flash point. The amount varies, but it may be as high as 0.5 per cent volume.

7.6. Foaming [41]

What is foaming?

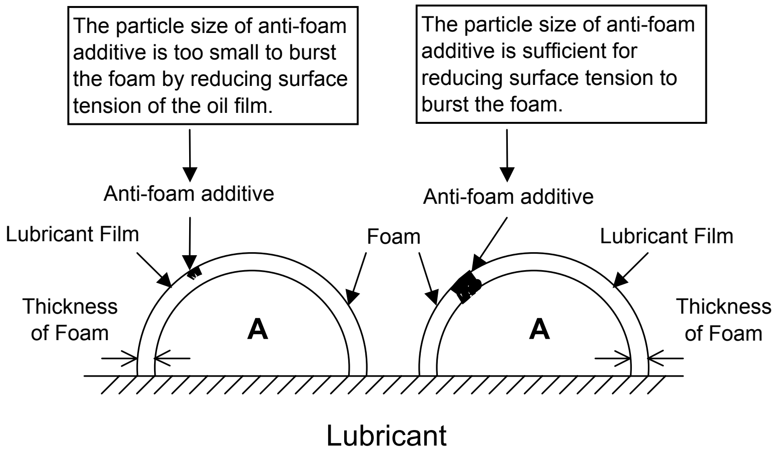
The oil in an engine contains air in entrainment or suspension in the form of bubbles as well as air in solution. There are two different types of air bubbles. The one is that air bubbles are present above lubricant surface. The other is that the air bubbles remain in the body of the lubricants (below lubricant surface).

The definition of “foaming” of the lubricant technology refers to the air bubbles above lubricant surface. Therefore, the air bubbles submerged in the body of the lubricants - air entrainment - are outside scope of this document. The disadvantage of the foaming of the engine oils may be as follows.

(i) Difficulty in measuring oil level.
(ii) Foaming may lead to tank overflow.
(iii) Foaming may lead to mistaken oil level resulting in oil starvation and bearing failure. Similar bad consequence can also happen in case of loose joints at pump suction allowing entrainment of air into the system.
(iv) May promote oxidation due to increase of the surface area of the oil contacting with air.
(v) Foaming (and air entrainment) can lead to bearing cavitational failure.

Diesel engine oils therefore contain “anti-foam” additives to prevent foaming. Anti-foam additives are silicone fluids, which are high molecular weight and are dispersed in oil phase. The size of the anti-foam additives dispersed in the oil may be around 3-5 microns. Anti-foam additives work by disrupting the air bubble film and coalescing air bubbles to collapse the foam and allow air to escape.. See Fig.18)

Figure 18: Illustration of Anti-foam Mechanism.



However, it is generally recognised that anti-foam additive may have a tendency to adversely affect the release of entrained air from the bulk oil.

The anti-foam additive may be removed from the oil by certain depth type filter; and if this happens it could lead to foaming - the phenomenon could be more sensitive in low oil consumption engines with limited oil refreshment (See Table 14(a),(b),(c)).

Test Method for Foaming

Method ASTM D 892

Scope : Determines the foaming characteristics of lubricating oils at specific temperatures; it gives empirical rating of foaming tendencies and stabilities.

Method: Sequence 1: a 190 ml sample, maintained at 24 ℃, is blown with air, via a gas diffuser stone, for 5 minutes and the volume (ml) of foam recorded. The sample is allowed to stand for 10 minutes and the volume (ml) of foam recorded.

Sequence 2: a new sample, 180 ml is run in the same manner as in sequence 1 except that the temperature is 93.5℃

Sequence 3: this is run on the same sample as used for Sequence 2, after collapsing the foam, but using the Sequence 1 conditions.

Results : Data is reported in the following way:

	Foaming tendency, ml(1)	Foaming stability, ml(2)
Sequence 1		
Sequence 2		
Sequence 3		

Note: (1) Foam volume, ml, at end of 5 min. blowing period.

(2) Foam volume, ml, at end of 10 min. settling period.

Discussion :

The foaming characteristics of lubricants are evaluated according to the ASTM D892, with example of typical results shown in Table 14(a). Depletion anti-foam additive by some filter type, will lead to foaming. Therefore, design and selection of oil treatment system is important.

Table 14(a): ASTM D892 Foaming Test Results [41]

		Example Marine Lubricant (Fresh Oil)		Used Lubricant (3) (Anti-foam additive was removed by filter.)
		With Anti-foam Additive	Without Anti-foam Additive	
Sequence 1 (24℃)	Tendency ,ml (1)	Trace	20	40
	Stability, ml(2)	0	Trace	Trace
Sequence 2 (93.5℃)	Tendency ,ml(1)	10	330	380
	Stability, ml(2)	0	0	0
Sequence 3 (94℃→24℃)	Tendency ,ml(1)	Trace	-	50
	Stability, ml(2)	0	-	Trace

Note : (1) Foam volume (ml) at end of 5 min. blowing period.

(2) Foam volume (ml) at end of 10 min. settling period.

(3) Foaming characteristics after several days since the start of the use of the fresh oil.

For information, the foaming characteristics of normal fresh lubricant and that of anti-foam depleted used oil are shown in Table 14 (b) and Table 14 (c) respectively.

Table 14(b): Foaming Test Results [41]
Foaming Tendency at the end of 5 min. blowing period
Fresh Lubricant with Anti-foam additive

Oil Temperature	20℃	40℃	60℃	80℃
At the end of test, ml	10	10	10	10
After 1 min., ml	10	10	10	10
After 3 min., ml	10	10	0	0
After 5 min., ml	Trace	Trace	0	0
After 8 min., ml	Trace	0	0	0
After 10min., ml	Trace	0	0	0

Table 14(c): Foaming Test Results [41]
Foaming Tendency at the end of 5 min. blowing period
Anti-foam depleted Used Lubricant

Oil Temperature	20℃	40℃	60℃	80℃
At the end of test, ml	20	20	70	250
After 1 min., ml	20	20	50	220
After 3 min., ml	20	20	20	40
After 5 min., ml	20	10	0	10
After 8 min., ml	20	10	0	0
After 10min., ml	10	10	0	0

Above figures and matrices are only for information and cannot be taken as reference

7.7. Chemical Changes

Chemical changes, eg formation of organic acids, nitrated hydrocarbons may be indicated by TAN and IR [20].

7.8. Change in Molecular Weight Distributions

For test methods see [16, 17, 18].

7.9 Particle Size Distributions.

For information see [23, 30]. Particle size measuring is typically not common other than sometimes used in newbuild engine flushing procedure - which uses fresh oil and particle monitoring as an indicator of flushing progress.

Particle count of in-service oil. This can be complicated by the colour of the in-service oil, insolubles etc.. When it is carried out, it is typically done after spectrography and ferrography analysis. Those particulates are mainly metal particles or debris from engine wear. Such particle size measurements and trending may be indicative of abnormal wear.

7.10 Oxidation [20] For further details see also Section 13 - Appendix 2.

Another oil parameter affected by stress is oxidation stability. Using differential scanning calorimetry (DSC) the oxidation inhibition of an oil in service may be followed. This research methodology would not be part of routine rapid analysis schemes. Table 15 lists a range of methods to test oxidation stability together with specifications and references. Many of these tests are normally applied for high speed diesel engine oils development.

Table 15: Oxidation Stability Tests used for Engine Oils.
(The Need for better Oxidation / Ageing Tests)

Test Names	Specifications & References	Amount of Sample	Temperature	Duration	Gases	Catalysts	Evaluation Items
Indiana Stirring Oxidation Test (ISOT)	JIS K 2514	250ml	165.5℃	24～96 hrs.	Air(Stirring at 1300 rpm)	Fe & Cu Plate	Viscosity ratio TAN, Lacquer BN, Insoluble
Thin Film Oxygen Uptake Test (TFOUT)	ASTM D 4742	1.5g	160℃	—	O_2 620kPa	Water 2% Fuel 3% Soluble Metal Compound 3%	Induction period (minutes) :Time until decreasing to 175kPa from Max.
Determination of Oxidation Characteristics of Lubricating Oil	IP 48	40ml	200℃	24hrs.	O_2 15 L/h	—	Viscosity ratio BN
Penn State Micro Oxidation Test	SAE Paper 831679 (1983) *1	40μL	200～250℃	—	Air	Fe, Cu Salt of Boron Silicate	Increase trend of molecular weight
High Pressure Differential Scanning Calorimetry	SAE Paper 801383 (1980) *2	1～2g	0 ～500℃	—	Air O_2 N_2 *3	Water Fuel Fuel Soluble Metal Compound (Nitro compound)	Induction period

*1 SAE Paper 831679(1983) : Microoxidation Evaluation of Automotive Crankcase Oil.

*2 SAE Paper 801383(1980) : Characterization of Lubricating Oils by Differential Scanning Calorimetry.

*3 More applicable for studying thermal ageing

The oxidation stability of a lubricant is one of the most relevant criteria.

Field tests under closely monitored conditions, together with used oil analysis, are effective tools for better understanding of oil degradation - but such studies cost money and time. With the aim to save both, a range of bench tests is used, employing full size test engines and laboratory rigs. The relevance of some of the standard test methods to marine application (eg the Motor Service (MS) Sequence tests for automotive engine oils) is questionable. Consequently, improved methods for assessing oil degradation are needed - paying attention to simplicity, suitability for automation, cost efficiency and reproducibility.

7.11. Process of Degradation of Characteristics of Oils in Use and their Control

Oil degradation occurs during service, and this is reflected by changes in oil parameters such as: viscosity, insoluble level, TAN, BN and flash point.

The viscosity of lubricant usually increases in service unless it is contaminated with low viscosity fuel, or there is a breakdown of VI Improver of multigrade engine oils under high shear. In the extreme case, ie with no oil consumption and hence no oil top-up, the viscosity, insolubles and TAN will increase with oil service hours following an approximate straight line with a slope equal to 1/V (Oil charge in g/kW) without arriving at an equilibrium condition. The smaller the oil charge, the steeper the slope. However, where the oil consumption is above a certain level, the increase of viscosity, insolubles and TAN will level out and stabilise to an equilibrium after a certain operating time. The higher the oil consumption, the lower the equilibrium level. The lower the oil consumption is, the higher the equilibrium level is. (See Figs.9(a)(b)(c)– for insolubles trend)

If the oil consumption can be controlled above appropriate level under given operating conditions, the viscosity, insolubles and TAN of used oils can be maintained within their condemning limits. At high oil consumption, the oil parameters (the viscosity, insolubles and TAN) will stabilise quicker the smaller the oil charge. Conversely, the larger the oil charge, the slower the viscosity, insolubles and TAN reach at their equilibrium because of reduced exposure to high temperature piston under-crowns and piston groove areas. The size of oil charge influences the time to reach equilibrium; but it does not affect the equilibrium level (of viscosity, insolubles and TAN). See Figs.9(a)(b)(c)– for insolubles trend.

Some other properties of used oils (e.g. BN and flash points) decrease in service. For these properties, the trends described above apply in the inverse form. See Figs.12(a)(b)(c)– for BN trend.

8. PRACTICAL IMPLICATIONS AND INFERENCES [20]

When a lubricant is stressed, the engine and its lubricant system may be affected in many different ways, for examples:

- deposits in cold areas (e.g. crankcase) or hot areas (e.g. ring belt, piston undercrown, turboblower etc)
- corrosion
- soot induced wear (e.g. depending on minimum oil film thickness of bearings)
- problems in filters and centrifuges

Good monitoring and control of oil condition / quality in service will lessen the impact on the engine.

9. FUTURE TASKS

9.1. Designing More Stress-Resistant Lubricants

In recent years, engine output has been raised dramatically by higher peak pressure, combustion temperature, scavenge air pressure and speed. To cope with this, lubricants have been improved, but more severe requirements are still to come.

In particular, further improvement is needed in thermal and oxidative stability, oil film strength at higher temperatures, spreadability, detergency, dispersancy, heat transfer, and neutralization ability.

There is also room for improvements in the following areas:-

- operation at low oil consumption,
- better separability in purifiers,
- resistance to water, and
- better compatibility with raw fuel

9.2. Environmental Issues

For better environmental protection, the influence of lubricants on exhaust gas emissions and waste oil disposal must be considered.

Improvements are required in engine design, in maintenance and treatment systems of lubricating oils and fuels, and in fuel quality to reflect the rapidly increasing requirements for environment protection. In particular, it is more important than ever to consider the full life cycle of the lubricant - from its manufacture, its application / impact / contribution, and right through to its waste disposal.

10. ANALYTICAL METHODS FOR ASSESSING OIL DEGRADATION

Test methods are discussed in details in [1] and [2].

Test Methods for detecting raw fuel contamination (which may lead to oil degradation) are described in [16, 17, 18].

11. WARNING AND CONDEMNING LIMITS

Oil companies base their recommendations and advice on precautionary and mandatory action limits on their comprehensive data bases. In addition, engine builders and shipping companies have their own controlling limits on correlations of used oil data against wear data of cylinder liners, piston rings and bearings. There can be some differences between the quality limits of oil suppliers, engine manufactures, and users based on differing experiences.

For information, please refer to “Limit for Precautionary and Mandatory Action”, Table 6 (for two-stroke diesels) of page 42, CIMAC Number 15, and Table 7 (for four-stroke diesels) of page 44, CIMAC Number 13, respectively. These limits are set out as guidance, and the quality condition of the oil cannot be fully judged by one single parameter. However, if one of the limits is reached, appropriate remedial action should be considered to correct the situation. Such action can be intensified purification, treating in a settling tank, make-up or partial change of the oil charge. It is recommended the engine builder and the oil supplier be consulted in such a case.

The recommendation and advice of the OEM and the oil supplier take precedence over that of CIMAC.

12. CONCLUSIONS

It is obvious that oil degradation is indeed a very wide subject covering many parameters for the many engine applications and designs. No single document can capture the complete subject. This document attempts to collate inputs from various industry experts. Many of the concepts and principles are still evolving and no doubt various sections of this document will similarly evolve. The value of this document is that it captures a very wide and complex subject in a single document, and provides information in a user-friendly language with numerous references for those who are interested in more detail.

13. APPENDICES

Appendix 1. A Mathematical Model simulating Insolubles Build-Up in used Engine Oils [26]

Trunk piston diesel engines burning residual fuel are usually operated with separators in a bypass configuration. These have to remove water, soot and other contaminants from the oil. The oil acts as transport medium for insolubles produced in the engine and carries the insolubles to the separator for removal. The degree of engine fouling is determined by the concentration of insolubles and by the oil's tendency to form deposits. In consequence it is assumed that the effectiveness of the separator has an influence on engine cleanliness. In the Model, the lubricant is considered as a fluid circulating from the sump to the engine, from the engine to the separator and back again into the sump. Hence the amount of soot is influenced by :

(i) The production rate of insolubles.
(ii) The share of these insolubles deposited on engine surfaces, particularly on the cylinder liner surface.
(iii) The share of these insolubles removed by filters and centrifuges
(iv) The loss of oil (and contaminants) by combustion and in the separator.
(v) The lubricant quality

In analogy to [32], the amount of solids, N(g), formed per time unit, t(h), can be calculated as follows:

$$dN/dt = m - (a.Q + D + U)\,N/V \tag{1}$$

where m (g h^{-1}) is the insolubles production rate in the oil and V (g) the oil volume. U (gh^{-1}) is the oil consumption. Since V is taken as constant, the consumption must be exactly matched by top-up with fresh oil. D (gh^{-1}) reflects the tendency of solids to adhere to metal surfaces. aQ indicates the effectiveness of the separator, comprising two terms : Q (gh^{-1}), the oil throughput through the centrifuge and a, the specific efficiency, i.e., the percentage of particles removed from the oil passing through the separator. The theoretical maximum value for the efficiency is a = 1. At much lower values a is influenced by the oil residence time in the cleaning unit t_r, and in the case of gravity separation, the sedimentation time of solids, t_s.

$$a = 1 - \exp(-t_r/t_s) \qquad \text{ie } \{\text{for } t_r/t_s << 1\} \tag{2}$$

$$t_r/t_s = (\Delta p^* d^2 / 18\,\eta)\,(\omega^2 * V_c / kQ) \tag{3}$$

where Δp (kgm^{-3}) is the difference between particle and oil density, d (m) is the average particle size, η (Pas) is the oil viscosity, ω (rad s^{-1}) the angular speed of the centrifuge rotor, V_c (m^3) a size factor of the centrifuge. Equation (3) assumes spherical particles and Stokes' sedimentation. The factor $k = 2.8 \times 10^{-7}$ converts the volume flow Q from (gh^{-1}) into (m^3s^{-1}). The integration of equation (1) yields the insolubles concentration:

$$C = \{m / (a.Q + D + U)\} \times \{1 - \exp[-\{(a.Q + D + U) / V\} \times t]\} \tag{4}$$

For the cumulative sludge yield in the separator, S (g), one finds after rearranging and integration of equation (4):

$$S = \{a.Q.m / (a.Q + D + U)\} \times \{t_e - C_e V / m\} \tag{5}$$

where C_e is the insolubles content (gg^{-1}) at the end of the test and t_e. the time at the end of the test.

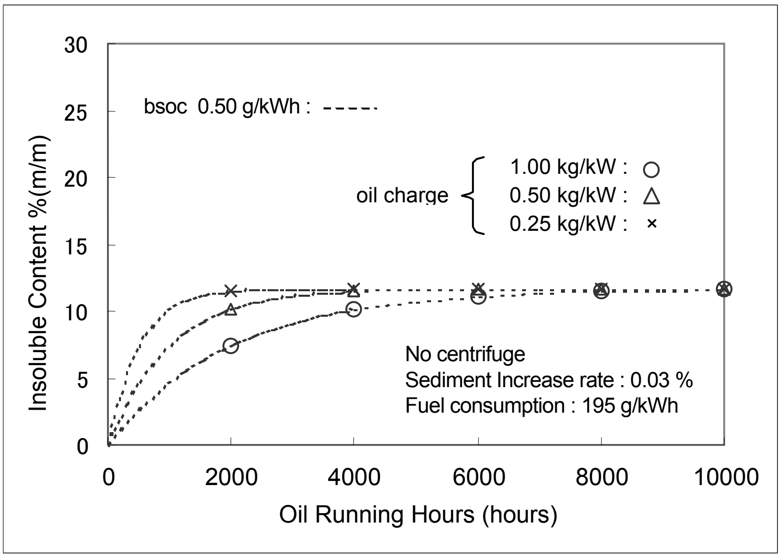
Equation (1) describes the case where oil composition still changes while approaching its equilibrium value. In the equilibrium situation the left-hand side value of (1) becomes zero. This reduces the complexity of above equations significantly and, in consequence, the equilibrium value for insolubles (C_{eq}) can be found from (4a).

$$C_{eq} = m / (aQ + D + U) \qquad \textbf{(4a)}$$

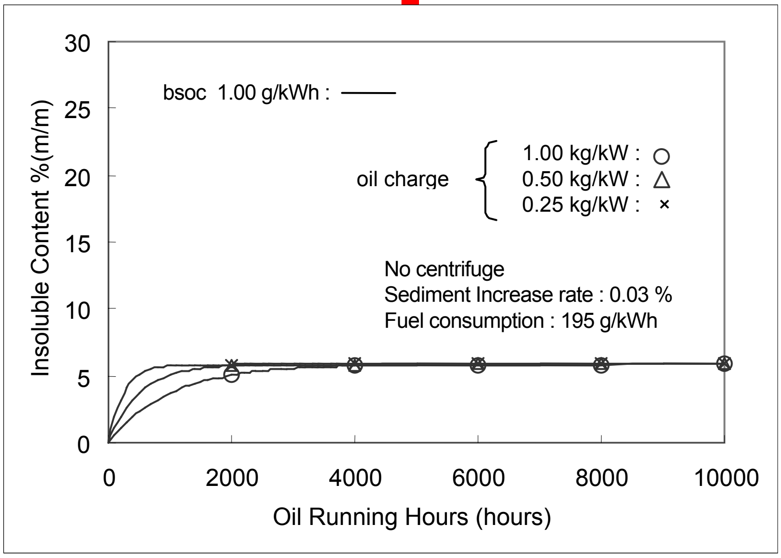
The effect of soot-flocculation must be considered as well. This means that instead of treating the system as a uniform dispersion, certain ranges of particle sizes must be taken into account. As a consequence, it can be seen that the relative predominance of the processes governing oil contamination, as mentioned before, may change, depending on the influence of particle size.

Tendencies of the insolubles build-up computed using above equations are shown in Figs.9(a)(b)(c) for reference, where the influence of oil consumption and oil volume in circulation (oil charge) are shown on insolubles levels. These figures show that where no centrifugal separator or oil filtration is present, very high insolubles levels will occur and will equilibrate from around 7% (for high oil consumption rates) to 23% (for low oil consumption rates).

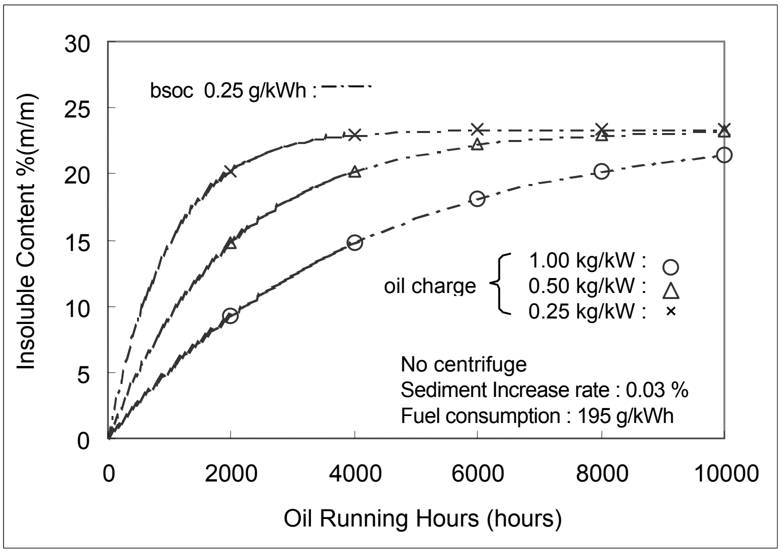
Repeat of Figure 9(a): Factors influencing the rate of insolubles build-up.



Repeat of Figure 9(b): Factors influencing the rate of insolubles build-up .



Repeat of Figure 9(c): Factors influencing the rate of insolubles build-up.



As mentioned before in Section 7.2, after inorganic calcium salts, soot is the second largest share of contaminants found in diesel engine oils during service. Therefore, the current understanding of soot formation is discussed in detail. . Although the mechanism is still not fully understood, it is generally accepted that soot particles may promote engine wear, thereby reducing the useful engine component life, fuel efficiency and performance. This problem will be further exacerbated with more and more diesel engines of increased mean effective pressure coming into service, in particular those with drastically reduced lubricating oil consumption.

Soot formation is an inevitable part of the normal combustion process in a diesel engine [33] and soot particles may get into the lubricating oil in two different ways [30]:

- Firstly, during the combustion process, around 0.1% of the exhaust gas (known as blow-by) will force its way into the crankcase by passing the clearances between piston rings and cylinder walls.

- Secondly, soot particles can also deposit on the oil film coating the cylinder walls [34]. This mixture is then wiped by the piston rings into the oil sump during the next intake stroke of the piston.

It was found that most of the soot particles mix with the lubricating oil by the second mechanism [34]. The amount of soot entrained in blow-by gas contributes to a minor part (few %) of the total soot mass in the lubricating oil. In [34, 35] the principal mechanism of soot deposition on the cylinder walls during the combustion process was identified as thermophoresis.

Soot acts as an oil thickener, producing an increase in viscosity and, in some cases, even gelling of the oil [36, 37]. This may lead to poor oil circulation during the cold start of small high speed marine diesel engines, to an inadequate lubrication of the engine's moving parts and to an increase in wear. Wear debris, unless filtered out, can promote more wear thus generating more debris. Like a chain reaction, this cycle can propagate excessive levels of contamination and high rates of wear [38].

In view of the serious impact of high levels of soot and wear debris on engine condition and the very high insolubles levels that are possible in an uncontrolled situation (Figs.9(a),(b),(c)) it is essential that such material is removed as effectively as possible. Correct operation of centrifuge and filters is vital to ensure that insolubles levels are kept below acceptable maximum levels (i.e. below condemning limits specified by the engine manufacturer). One aspect of efficient centrifuge operation is centrifuge capacity which is referred to in Section 7.1: "Countermeasures against Premature Viscosity Increase of the Oil in Use".

Appendix 2. Oxidation Processes [42]

In a Diesel engine, great volumes of hot combustion gases come in contact with pistons, piston rings, cylinder liners and other engine parts. These gases contain oxygen. In consequence, there will always be an oxidative attack on the lubricant. The degree of oxidation will depend on the thermal load, on the resistance of the oil against oxidation, on time, and a number of other factors.

In trunk piston engines, oil deterioration by oxidation affects the entire lubricant system content, because the oil is used for the lubrication of all engine parts, not only the cylinder / piston area where most oxidation takes place.

The deterioration of a lubricant by oxidation becomes apparent by phenomena like viscosity increase, TAN increase, discoloration, and the increase of oxidized hydrocarbon molecules. Oxidation, when severe, results in the formation of sludge, varnish and even coke.

The oxidation process becomes even more complex in view of the chemical reactions between oxidized lubricants and to an extent fuel hydrocarbons together with catalytic effects initiated by the presence of wear particles, dust, water and contact with metal surfaces etc. The rate of oxidation, furthermore, is influenced by the contact area between air and lubricant and also by the level of temperature and residence time.

Hydrocarbon oxidation occurs via a well documented free radical process [47].

Equation (1) shows the start of hydrocarbon (RH) oxidation with the formation of the radical $\mathrm{R}\bullet$:

$$\mathrm{R\,H} + \mathrm{O_2} \rightarrow \mathrm{R}\bullet + \mathrm{HO2}\bullet \qquad \text{(spontaneous initiation)} \qquad \textbf{(1)}$$

This process is realtively slow and happens at relatively weak carbon-hydrogen bonds in the hydrocarbon structure.

$\mathrm{R}\bullet$, once formed, rapidly reacts with oxygen:

$$\mathrm{R}\bullet + \mathrm{O_2} \rightarrow \mathrm{ROO}\bullet \qquad \text{(propagation, fast)} \qquad \textbf{(2)}$$

$\mathrm{ROO}\bullet$ in turn reacts with another hydrocarbon molecule to form a hydroperoxide (ROOH) plus an $\mathrm{R}\bullet$ radical as shown in equation [3] :

$$\mathrm{ROO}\bullet + \mathrm{R\,H} \rightarrow \mathrm{ROOH} + \mathrm{R}\bullet \qquad \text{(propagation)} \qquad \textbf{(3)}$$

The production of $\mathrm{R}\bullet$ free radicals which then rapidly react, as in equations (2) and (3), give rise to a radical chain reaction.

In practice the initiation of oxidation via equation (1) is not particularly easy. The more likely process, particularly at elevated temperatures, is via decomposition of peroxide. This process and the reaction that follows is shown in equations (4) and (5):

$$\mathrm{ROOH} \rightarrow \mathrm{RO}\bullet + \mathrm{OH}\bullet \qquad \text{(decomposition)} \qquad \textbf{(4)}$$

$$\mathrm{RO}\bullet + \mathrm{RH} \rightarrow \mathrm{ROH} + \mathrm{R}\bullet \qquad \text{(autocatalysis, fast)} \qquad \textbf{(5)}$$

R • will then react with oxygen as per equation (2) and each chain propagation reaction yields another hydroperoxide molecule. If each of these decomposes as per equation (4) there is a rapid increase in the rate of oxidation.

A radical chain reaction can be terminated either by co-reaction of two peroxyl radicals (ROO•) giving a non-radical product or, as in a formulated lubricant, by the action of anti-oxidants. There are two main types of anti-oxidants:

a) a primary (chain breaking) anti-oxidant which inhibits the formation of free radicals R •, see equations (6) and (7) in comparison to equation (3)

$$ROO\bullet + AH \rightarrow ROOH + A\bullet \quad \text{(primary inhibition, AH is the inhibitor)} \qquad \textbf{(6)}$$

$$A + ROO\bullet \rightarrow RO_2A \quad \text{(fast, primary inhibition)} \qquad \textbf{(7)}$$

Typical primary inhibitors are hindered phenols like 2.6-ditertiarybutylphenol and amine type oxidation inhibitors like phenyl-α-napthylamines.

b) a secondary anti-oxidant which again inhibits the formation of free radicals R • but this time by hydroperoxide decomposition (secondary inhibition) properties:

$$ROOH + B \rightarrow \text{non-radical products (secondary inhibition, B is the inhibitor)} \qquad \textbf{(8)}$$

Typical secondary anti-oxidants are sulfur-phosphorus compounds e.g zinc dialkyldithiophosphates.

At higher temperatures (above 200 degC) the primary and secondary antioxidants behave synergistically. This explains why most formulated lubricants have both types of inhibitor present.

The RO• formed in equation (4) are decomposed and / or oxidized to form the final products of oxidation such as aldehydes, ketones, alcohols, ethers, etc.

Due to the variety of combustion products present - NOx, sulfur dioxide, carbon soot, water, unburnt fuel, wear particles, dust, etc, the actual reactions are extremely complicated. The end result is that insolubles like varnish and sludge are formed in the oil from further (non-radical) chemical reactions [43, 44, 45, 46, 47].

Finally, metal de-activators can have an effect as oxidation inhibitors. This is because the metallic surfaces of gliding engine components as well as wear particles and metal salts present in oil can act as catalysts in the oxidation process [43, 44, 45, 46, 47].

Appendix 3. What is Acid ?

In order to understand acidity, it is firstly necessary to consider what happens in water. Pure water dissociates to a small extent into equal numbers of hydrogen and hydroxyl ions, reaching an equilibrium according to the equation (1):

$$H_2O \Leftrightarrow H^+ + OH^- \qquad \textbf{(1)}$$

The product of the concentration of H^+ ions and the concentration of OH^- ions is always constant. This is expressed in the form:

$$[H^+][OH^-] = K \qquad \textbf{(2)}$$

Since the value of K is 10^{-14} and in pure (natural) water $[H^+] = [OH^-]$, it follows that both $[H^+]$ and $[OH^-] = 10^{-7}$. An acid is a substance which, when dissolved in water, dissociates into positively charged hydrogen ions H^+ and negatively charged ions. Thus, for hydrochloric acid:

$$HCl \Rightarrow H^+ + Cl^- \qquad \textbf{(3)}$$

and for acetic acid :

$$CH_3COOH \Rightarrow H^+ + CH_3COO^- \qquad \textbf{(4)}$$

This dissociation of acids therefore increases the concentration of H^+ ions in the water but, since $[H^+][OH^-]$ is always constant, some of the hydrogen ions will combine with an equal number of OH^- ions to form water until equilibrium is established. In an acid solution the concentration of H^+ ions will therefore be greater than 10^{-7}**.** The strength of acid is determined by the concentration of H^+ ions in its solution, that is to say, by its degree of ionisation. A strong acid is almost completely ionised, whilst a weak acid is only slightly ionised. Thus in normal solutions (that is, containing the equivalent weights in grams per litre) the strong hydrochloric acid is 78.4 per cent ionised whereas the weak acetic acid is only 0.4 per cent ionised. Fundamentally, the difference between acidic and basic solutions lies in the hydrogen ion concentration.

What is pH value ?

A convenient scale for expressing hydrogen ion concentration is the pH value which is defined in equation (5):

$$\text{pH value} = \log_{10}(1 / [H^+]) \qquad \textbf{(5)}$$

where $[H^+]$ is the concentration of hydrogen ions as gram ions / litre (dm^3). In pure neutral water, the pH value is therefore

$$\log_{10}(1 / 10^{-7}) = 7 \qquad \textbf{(6)}$$

In other words, in a solution of pH 7 there will be one gram of H^+ ions in 10^7 litres (dm^3). Acid solutions will have pH value less than 7, and solutions of bases greater than 7. Thus, in an acid solution of pH 4, there will be one gram of H^+ ions in 10^4 litres (dm^3) of solution, while in an alkaline solution of pH 10 there will be only one gram of H^+ ions in 10^{10} litres (dm^3) of solution.

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15. GLOSSARIES

Absorption	Variation of peaks at specific wave lengths in FTIR (DIR), indicating deterioration, oxidation, nitration, reduction in additive concentration. See also "DIR" and "FTIR".
Abrasive Wear	Wear caused by abrasive particles
ACEA	Association des Constructeurs Europeens de l'Automobile (Association of European Automotive manufacturers)
Acid	Any substance containing hydrogen in combination with a non-metallic element(s) and capable of producing hydrogen ions in solution. An acid is capable of neutralising or being neutralised by a base.
Acidity	In lubricants, acidity denotes the presence of acidic constituents whose concentration is usually defined in terms of an acid number. The number denotes mg KOH consumed when 100g of the oil sample is titrated under the condition of the test method.
Additives	A chemical compound or compounds added to a lubricating oil for the purpose of imparting new properties or enhancing existing properties.
Adhesive Wear	Wear caused by metal to metal contact due to oil film break down eg scuffing
Air/Fuel ratio	Ratio of air mass to fuel mass present in cylinder at start of combustion.
AN	Acid Number, has replaced TAN (Total Acid Number)
Aniline Point	The lowest temperature at which a hydrocarbon fluid is completely miscible with an equal quantity of aniline. The higher the reading, the lower the aromatic content, and hence the smaller the effect on rubber.
Antifoam Agent	An additive used to suppress the foaming tendency of petroleum products in service. May be a silicone oil to break up surface bubbles or a polymer to decrease the number of small entrained bubbles.
Antiwear Agent	Additives or their reaction products which form thin, tenacious films on highly loaded parts to prevent metal-to-metal contact.
API	American Petroleum Institute
API Gravity	An arbitrary scale adopted by the American petroleum Institute for expressing the relative density of an oil. Degrees API = $\left(\frac{141.5}{\text{rel. density @ 60 F}} \right) - 131.5$
Aromatics	Hydrocarbons of ring structure having the smallest hydrogen to carbon ratio.
Ash	Inorganic, non combustible solid residue remaining after ignition. Some additives, particularly conventional detergent additives, leave behind a powdery residue after combustion. Excess ash can cause engine malfunction if allowed to build up in the combustion chamber, cylinder liner ports and turbochargers.
Ash (Sulphated)	The ash content of an oil, determined by burning the oil and complexing the metals in the residue with sulphuric acid. Expressed as % by mass.
Asphaltenes	Components of asphalt which are insoluble in petroleum naphtha but are soluble in aromatic solvents. They are made up largely of high molecular weight polynuclear hydrocarbon derivatives containing carbon, hydrogen, sulphur, nitrogen, oxygen and usually nickel, iron and vanadium.
ASTM :	American Society for Testing Materials
Bactericide	A biocide specifically formulated to kill bacteria.
Barrel	A unit of volume measurement used for petroleum and petroleum products. a barrel = 42 US Gallons, $\simeq$ 35 Imperial Gallons or $\simeq$ 159 litres.
Base	A compound which reacts with an acid to produce a salt plus water.
Base Number	A measure of the acid-neutralising power in a lubricating oil, also known as Total Base Number.
Base Stock(Base Oil)	Refined petroleum oil used in the production of lubricants and other products. The base stock may be used alone or blended with other base stocks and/or additives, to manufacture a finished lubricant.
Beta Value	Defined as the number of particles bigger than the specified size after filter. See ISO 4572.
BFOC	See "SFOC" - the preferred term.
Biogas	Gases derived from microbial or biochemical decomposition processes. Main components : methane, carbon dioxide, often H_2S.
Bitumen	A viscous liquid or solid consisting of hydrocarbons and their derivatives which is soluble in an aromatic solvent such as benzene. It is non volatile and softens when heated. Bitumen may be black or brown in colour and possesses waterproofing and adhesive properties. It is obtained from refinery processes but is also found as a natural deposit.

Black Oils	Asphaltic materials are added to lubricants used for open gears and steel cables to impart extra adhesiveness, giving them the characteristic black colour.
Blending	The intimate mixing of various components, including base oils and additives, in the preparation of a product of specified properties.
Blow-by	Passage of combustion gases past the piston rings of internal combustion engines, resulting in contamination of the crankcase oil.
Boundary Lubrication	Lubrication between two rubbing surfaces without the development of a full fluid lubricating film. It occurs under high loads and requires the use of antiwear or EP additives to prevent metal-to-metal contact.
BSOC	See “SLOC” - the preferred term.
Bulk Modulus	The reciprocal of the compressibility of an oil. The higher the Bulk Modulus of a fluid, the greater its incompressibility.
Cams	Eccentric lobes attached to a camshaft and driven by a crankshaft which are used in most internal combustion engines to open and close valves and sometimes operate fuel pumps.
CARB	California Air Resources Board.
Carbon Residue	Coked material remaining after an oil has been exposed to high temperatures (without oxygen) under controlled test conditions. Carbon residue is thus an indicator of the coke forming tendencies of an oil. It can be expressed as Conradson (CCR), Ramsbottom (RCR) or Micro-Carbon Residue (MCR).
Catalyst Fines	Small (typically less than 50 micron) particles of aluminium silicate used as a catalyst in catalytic cracking (cat cracker) refineries. They are sometimes carried over in the refinery process and can be found in residual fuels. They are very abrasive and can cause excessive wear in engine parts - particularly fuel pumps, injectors, cylinder liners and piston rings.
Centipoise (cP)	See Poise
Centistoke (cSt)	See Stoke
Cetane Index	A measure of the ignition quality of a distillate fuel, that is the relative ease with which the fuel will ignite when injected into a compression - ignition engine. Cetane Index is calculated from the API gravity and the mid boiling point of the fuel. High Cetane Indices indicate shorter ignition delays and are associated with better combustion performances.
Cetane Number	Similar to Cetane Index but is derived from a standard engine test rather than by calculation.
Chemisorption	Many gases react with surfaces by chemically bonding. In contrast to physisorption, chemical adsorption (chemisorption) involves the formation of strong chemical bonds between adsorbate molecules and specific surface locations known as chemically active sites. Chemisorption is thus used primarily to count the number of surface active sites which are likely to promote chemical and catalytic reactions.
CHP	Combined Heat & Power. Term for all engines generating heat and power (co-generation)
Cloud Point	The temperature at which a cloud or haze begins to appear when an oil, which has been previously dried, is cooled under prescribed conditions. Such a cloud or haze is usually due to the separation of wax from the oil.
COC	Flash point measured by Cleveland Open-cup
Cold Filter Plugging Point(CFPP)	A measure of the ability of diesel fuels to flow at low temperature. A fuel with a low CFPP is capable of being used satisfactorily at low ambient temperatures and not cause blockages in fuel systems through the precipitation of wax particles.
Copper Strip Corrosion	A qualitative measure of the tendency of a petroleum product to corrode pure copper.
Corrosion Inhibitor	A substance added to a lubricant to protect against metal corrosion.
Crosshead Diesel Engine	Slow-speed marine diesel engine with separate lubrication systems for cylinders and crankcase. Invariably operating on the 2-stroke cycle these engines derive their name from the crosshead bearing which couples the piston rod and the connecting rod.
Crown	The top of the piston of an internal combustion engine above the firing ring which is exposed to direct flame impingement.
CSR	Continuous Service Rating – typically 80-90% MCR
Cylinder Oil	Lubricating oil having a high BN for the lubrication of the cylinders of crosshead marine diesel engines and some types of trunk piston engines.
Demulsibility	The ability of lubricant to withstand the formation of an emulsion with water. This property is measured by a test which times the separation of a well-mixed sample of oil and water, and gives a 'demulsification Number' or 'Value'.
Density	Mass per unit volume.
Detergent	A substance added to a lubricant to keep engine parts clean. In engine oil formulations, the detergents most commonly used are metallic soaps with a reserve of basicity to neutralise acids formed during combustion.

Detonation	Uncontrolled ignition/combustion with very high flame speed. Severe pressure waves with hard noise known as knocking. High risk of mechanical/thermal damage.
Dew Point	The temperature at which water vapour in the air starts to condense to liquid.
Differential Infrared Spectroscopy (DIR)	Method to compare fresh and used oils by showing different peaks at different wavelengths. Used to determine deterioration of engine oils with reference to oxidation, and nitration. See FTIR.
Differential Infrared Spectroscopy (DIR)	Method comparing fresh and used oil by showing different peaks at specific wave lengths. Method widely used to assess deterioration of gas engine oils with reference to oxidation and nitration.
Digester Gas	See "Sewage Gas".
Dilution of Engine Oil	Contamination of crankcase oil by unburnt fuel leading to reduced viscosity and flash point.
Dispersant	An additive designed to disperse oil insoluble sludge in suspension, thus preventing harmful deposition in oilways.
Distillate	An product obtained by condensing the vapours distilled from petroleum or its products.
Distillation Range	The range of temperatures, usually determined at atmospheric pressure by standard apparatus, over which boiling, or distillation, of a liquid proceeds. Only a pure substance has one definite boiling point at a particular pressure. Petroleum have a range of boiling points because of their varying complex range of hydrocarbon compounds.
Drop Point	The temperature at which a grease passes from a semi-solid to a liquid under specified test conditions.
Dry Gas	Natural gas containing no hydrocarbons heavier than butane and pentane. Can contain up to 99 % methane.
Dry Sump	Engine lube oil system with an external tank reservoir.
Dual Fuel	Term used for gas engines running on combustible gas ignited by controlled "pilot" injection of 1 – 10 % fuel with adequate ignition quality, i.e., gas oil or heavy fuel oil.
Dumb bell Blend	A blend of (usually two) components with an extreme of a particular blend parameter, such as viscosity, density, distillation curve.
Emulsibility	The ease in ability of fluids to form emulsion (see emulsion)
Emulsifier	A type of surfactant effective at producing stable emulsions.
Emulsion	An intimate mixture of fluids which are non soluble in each other. An emulsion is said to "break" when the fluids separate.
End Point (final Boiling Point)	The highest temperature indicated on the distillation thermometer when a light distillate is subjected to one of the standard laboratory methods of distillation.
Engine Deposits	Accumulations of sludge, varnish and carbonaceous residues on engine components.
Engine Test	Use of an internal combustion engine to evaluate lubricants. Parameters such as piston ring groove fill (by deposits), piston varnish, component wear, oil viscosity etc. are measured - to apply a performance rating.
Esters	Compounds of alcohols and fatty acids which form the major constituent of many synthetic lubricating oils.
Eutectic	A mixture of compounds (eg vanadium and sodium) resulting in a low melting point
Extreme Pressure (EP) Lubricants	EP oils and greases contain additives which, under the effects of high temperature and pressure, form a protective film on metallic surfaces, preventing metal-to-metal contact if the normal hydrodynamic film breaks down under high pressure.
FCC Fine	See catalyst fines
Ferrography	Ferrographic Analysis. A method for detecting wear metal particles “graded” by a magnetic field for further study using photo sensor or a microscope.
Fire Point	The lowest temperature at which an oil vaporises rapidly enough to burn for at least five seconds after ignition under standard conditions.
Flash Point	The lowest temperature to which a combustible liquid must be heated to give off sufficient vapour to form a momentarily flammable mixture with air when ignited under specified conditions.
Floc Point	A measure of the tendency of an oil to flocculate - or precipitate wax - under prescribed conditions. It is mainly applicable to refrigeration oils.
Four Ball EP Test	Method for determining extreme pressure (EP) properties of fluids. One steel ball under load rotates against three stationary balls in the form of a cradle. Heated test fluid is subjected to a series of timed tests at increasing loads until welding occurs. Wear is described by scar diameter plus load to weld in kg.
Friction	The resisting force encountered at the common boundary between two bodies when, under the action of an external force, one body moves, or tends to move, relative to the other.
FTIR	Fourier Transformation of InfraRed spectroscopy. Digital generation of spectral information. See DIR.
FTIR	Fourier Transformation Infrared Spectroscopy

FZG Gear Test Rig	A method for determining the load carrying ability of lubricants. Calibrated spur gears are operated at fixed speed and controlled initial oil temperatures for 15 minute stages. The load on the gear teeth is increased after each stage. Performance is judged by the number of stages run up to a defined weight loss of the test gears or visual assessment of damage to the tooth flanks. Maximum number of stages is 12. Normal reporting format is to quote the failed stage.
Gas Oil	A petroleum distillate having a viscosity and distillation range between those of kerosene and light lubricating oil. The distillation range of gas oils usually extends from 200°C to 380°C. Gas oil is used as a fuel in medium and high speed diesel engines and as a burner fuel in heating installations.
GPC	Gel Permeation Chromatography
Grease	A lubricant composed of an oil, or oils, thickened with a soap or other thickener, to a semi-solid or to a solid consistency.
H_2S	Hydrogen Sulphide, acidic, poisonous, flammable gas found in bio and natural gases. Disagreeable odour. Robust alkalinity of gas engine lubricant required when present.
Hot Corrosion	Corrosion phenomena of hot components (piston crown, exhaust valve etc) by the combination of vanadium and sodium compounds at critical ratios and high temperature.
Hydrocarbons	Chemical compounds which consist entirely of carbon and hydrogen. They form the basic composition of all fuels and lubricants derived from petroleum.
ICP (or PES)	Inductively Coupled Plasma Emission Spectrochemical Analysis. A method for detecting elements (mainly metals) in oil at ppm level by using plasma emissions
Immiscible	Liquids incapable of forming homogeneous mixture, eg. oil plus water.
Inhibitor	A substance which is added in a small proportion to a lubricant to prevent or retard undesirable changes in the quality of the lubricant, or in the condition of the equipment in which the lubricant is used.
Insolubles	Contaminants found in used oils due to dust, dirt, wear particles, oxidation products, combustion product etc often measured as pentane/heptane or toluene insolubles to reflect insoluble character.
IP :	Institute of Petroleum
JIS :	Japanese Industrial Standard
Kinematic Viscosity	Measure of a fluid's resistance to flow under gravity at a specific temperature (usually 40°C or 100°C)
Knocking	Hard metallic noise heard when engine fires in uncontrolled mode. See "Detonation".
Lambda Value	Ratio of combustion air actually charged to combustion air theoretically required. LV = 1 is defined as "stoichiometric condition". Lean burn engines run at LV > 1.
Landfill gas	Produced by anaerobic decomposition of household and industrial waste. Generally contains 40 – 60 % methane, 40 – 50 % CO_2, and 10 % N_2. May also contain H_2S, chlorinated hydrocarbons and silicon compounds.
Lands	The vertical surfaces of the piston crown and the areas between the piston rings.
Lean Burn Engine	Gas engines running on air excess, except in pre-chambers where gas is ignited. See also "Lambda Value" and "Stoichiometric Condition".
Liner Lacquers	Hard resin like coatings formed on the surface of liners filling the honing grooves. Such lacquers may lead to increased oil consumption.
LPG	Liquefied Petroleum Gas. Consists mainly of propane or butane or mixtures thereof. Liquid at ambient temperature when kept under pressure.
Lubricant	Any substance reducing friction between moving surfaces.
MCR	Maximum continuous rating (of an engine). The rating at which the manufacturer sets for operation at 100% loading
Methane No. (MN)	Figure rating the anti-knock performance of a gaseous fuel. Pure methane was given the methane number 100, hydrogen has 0. Other gases may have higher or lower MNs. Gas mixtures may have wide ranges due to changes in composition.
MIL-	US Military specifications
Mineral Oil	Oil derived from mineral sources, notably petroleum.
Miscible	Opposite of Immiscible. See “Immiscible”.
Multigrade	'Multigrade' is a term used to describe an oil with low temperature and high temperature viscosities that fall within the limits of two different SAE numbers.
Naphthenic Base Stock	A type of base stock prepared from Naphthenic crudes (crudes containing a high percentage of ring type aliphatic hydrocarbons). They are characterised by high specific gravity plus low viscosity index.
Natural Gas	Gas from gas or oil fields. Mixture of gases, mainly methane, varying amounts of propane, butane, CO_2, N_2, occasionally H_2S. Transport normally by pipeline, occasionally liquefied by cooling to - 165 °C max (LNG = Liquefied Natural Gas).
NCR	See “CSR” - the preferred term.
Neutralisation Number	A measure of the acidity or alkalinity of an oil. The number is the mass in milligrams of the amount of

	acid (HCl) or base (KOH) required to neutralise one gram of oil.
NG 1, 2, 3	Gas engine oil classification system proposed by SAE/ASTM. Categories are : NG1 – stoichiometric engines, NG2 – lean burn engines, NG3 – automotive gas engines.
Nitration	Process in which nitrogen oxides formed during combustion attack the lubricant, resulting in additive depletion, viscosity increase and deposit formation.
NLGI Number	A numerical scale devised by the U.S. National Lubricating Grease Institute for classifying the consistency range of lubricating greases. The higher the number, the 'stiffer' or less viscous the grease and vice versa.
Non-Newtonian Behaviour	Behaviour of a fluid (eg lube oil) with viscosity characteristic Behaviour of lube oils demonstrating viscosity depending from shear rate at low temperatures.
OEM	Original equipment manufacturer, eg engine designer
OSF	Oil Stress Factor
Oxidation	Process in which oxygen reacts with hydrocarbon molecules, forming insoluble carbonaceous residues and resins. This results in viscosity increase and deposit formation
Oxidation Catalyst	Used in very lean burn engines, operating at 250 – 500 °C, able to reduce hydrocarbons and carbon monoxide. Sensitive to some additive components, in particular phosphorus. A limit of 300 ppm max in the oil, therefore, is often placed.
Oxidation Inhibitor	An additive which reduces oxidation e.g that of the oil.
Oxidation Stability	A measure of resistance of a product to oxidation mechanism.
Paraffinic Base Stock	A type of base stock prepared from Paraffinic crudes (crudes containing a high percentage of open-chain aliphatic hydrocarbons). They are characterised by low specific gravity and high viscosity index.
Penetration	Measure of consistency (hardness) of a grease. All penetration measurements are in inverse scale of consistency - that is, the softer the consistency, the higher the penetration number.
Petrolatum	Also referred to as "mineral Jelly" or "petroleum jelly", petrolatum is a salve like mixture of oil and microcrystalline wax obtained from petroleum.
Petter WI	Single cylinder gasoline engine. Evaluates oil oxidation by viscosity increases and copper/lead bearing weight loss. Duration is 36 hours at 1500 rpm with sump oil temperature at 137°C.
PH	A measure of acidity or alkalinity in terms of the logarithm of the hydrogen ion concentration with the sign reversed. pH 0 = extreme of acidity pH 7 = neutral pH 14 = extreme of alkalinity
Physisorption	Absorption with no chemical bonding
Pilot Fuel	Small quantity of liquid fuel injected into combustion chamber of dual fuel engine to effect ignition of a gas with poor ignition quality. Pilot fuel is normally gas oil but occasionally heavy fuel oil.
PMCC	Flash point measured by Pensky-Martens Closed-cup
Poise (P)	The standard unit of dynamic viscosity, usually quoted as centipoise (cP).
Polishing (Bore)	Excessive smoothing out of the surface finish of the engine cylinder liner to a mirror-like appearance, resulting in poor retention of oil and poor ring sealing, potentially leading to high oil consumption and scuffing.
Polyalphaolefin	A synthetic lubricant produced by polymerisation of unsaturated hydrocarbons.
Pour Point	The lowest temperature at which a lubricant will pour or flow under specified conditions. Gives an indication of the lowest operating temperature for which an oil is suitable.
Pour Point Depressant	An additive used in a small proportion to lower the pour point of a lubricant by modifying the formation of wax crystals so that they do not agglomerate.
Precipitation	Dropping out of solids from solution
Pumpability	The characteristics of an oil that permit satisfactory flow to and from the engine oil pump and subsequent lubrication of moving components.
Refining	Series of processes for converting crude oil and its fractions to finished petroleum products, including thermal cracking, catalytic cracking, polymerisation, alkylation, reforming, hydrocracking, hydroforming, hydrogenation, hydrogen treating, solvent extraction, dewaxing, deoiling, acid treating, clay filtration and de-asphalting.
Residual Fuel Oil	Heavy fuel oils produced from the residue of the fractional distillation process rather than from the distilled fractions.
Ring Sticking	Resistance to free ring movement due to deposits.
Rings	The circular metallic elements that ride in the grooves of a piston and provide compression sealing during combustion. Also used to spread oil for lubrication of the cylinder liners.
Rust Preventive / Rust Inhibitor	Additive for coating metal surfaces with a film that protects against rust.

S.I.P.W.A	Sulzer Integrated Piston Ring Wear-detecting Arrangement. This equipment monitors the rate at which piston rings wear in crosshead engines.
SAE :	Society of Automotive Engineers
Sampling cock/tap	Cock/tap at a suitable, representative point of a lube or fuel system for taking representative samples.
Scuffing	Abnormal wear occurring in engines due to localised metal to metal contact. It can be prevented through the use of antiwear, extreme pressure and friction modifier additives.
Selective Catalytic Reduction (SCR)	Exhaust gas treatment system with urea or ammonia injected into exhaust gas to reduce NO_x. Catalyst poisoned by sulphur.
Semi-synthetic	Blend of mineral and synthetic base oils
Sewage gas	Particular form of biogas generated by bacterial decomposition of sludges from sewage. Generally contains 50 – 70 % methane, 20 – 30 % CO_2 and often H_2S.
SFOC	Specific fuel oil consumption, based on g/kWh or g/bhph
Shear Stability	The property of resisting physical change under high rates of shear when applied to a Viscosity Index Improver. It is the ability of the VI improver molecules to withstand breakdown into smaller molecules.
Silica	Abrasive contaminant eg catayltic fines, dust particles (e.g from landfill gas). Very abrasive, resulting in excessive wear.
SLOC	Specific lube oil consumption, based on g/kWh or g/bhph
Sludge	Oil insoluble products formed from lubricants and/or fuels used in internal combustion engines, and deposited on engine parts other than those in contact with the combustion space.
Solvent Extraction	Refining process used to separate reactive components (unsaturated hydrocarbons) from lube distillates in order to improve the oils oxidation stability, viscosity index and response to additives.
Sour gas	Natural gas that contains a significant amount of H_2S (up to 5 %).
Spark Ignited	Term used for gas engines in which the air/ fuel charge is ignited by spark plugs.
Stoichiometric Condition	The theoretically exact amount of air needed for complete combustion of the fuel.
Stoke (St)	The unit of kinematic viscosity, ie, the measurement of a fluid's resistance to flow defined by the ratio of the fluid's dynamic viscosity to its density; usually quoted as centistokes (cSt).
Straight Run	Fuels produced by distillation without cracking or alteration to the structure of the constituent hydrocarbons.
Sulphur Conversion Ratio	See [Rec 13, p.37]. The ratio of : sulphur which condensed as sulphuric acid the total sulfur ingested with the fuel
Surfactant	A compound able to reduce surface tension and commonly used to achieve emulsification, wetting or detergency.
Sweet gas	Natural gas containing less than 10 ppm H_2S.
Thermal Cracking (Visbreaking)	An oil refinery process in which the reaction is produced by the action of heat and pressure.
Thermophoresis	Describes the interaction of heat and particles of various sizes.
Three Way Catalyst	Generally used in stoichiometric engines to convert harmful combustion components to H_2O, CO_2 and N_2.
Timken OK load	Measure of the EP properties of a lubricant. Lubricated by the product under investigation, a standard steel roller rotates against a block. Timken OK load is the heaviest load that can be carried without scoring.
Tribology	The science of lubrication, friction and wear.
Trunk Piston Diesel Engine	Medium-Speed, or High-speed engine generally using the same oil for both cylinder and crankcase lubrication, and utilising connecting rods to transmit piston power directly to the crankshaft rather than through a crosshead.
Turbine	A piece of equipment in which a shaft is steadily rotated by the impact of a current of steam, air, water, or other fluid directed from jets or nozzles upon blades of a wheel or series of wheels.
Turbocharger	Compressor driven by exhaust gas driven turbine supplying air at higher pressure to the engine to increase power.
Valve Guttering and Torching	Damage to exhaust valves due to high temperature corrosion and erosion.
Valve Recession	Excessive wear of valve seat and face caused by combined effects of metal abrasion, high temperature corrosion, functional sliding and adhesion.
Viscosity	That property of a liquid by virtue of which it offers resistance to motion or flow. It is commonly regarded as the 'thickness' of the liquid. Viscosity decreases with increasing temperature.
Viscosity Index (VI)	A value indicating a fluid's change of viscosity with temperature.
Viscosity Index Improver	An additive employed to raise the VI of a mineral oil and other products.
Volatility	Amount distils off or vaporises with temperature - highly volatile means large amount
Wet Gas	Natural Gas containing heavier hydrocarbons like ethane, propane, butane plus small quantities of hydrocarbons liquid at ambient temperatures.

Wet Sump	Engine lube oil system in which the crankcase serves as the oil tank; a system without an external tank reservoir; common in smaller 4-stroke engines.
Wobbe Index	Ratio of a gas's calorific value to the square root of it's specific gravity. Indicates thermal input provided by gas at given temperature.
Zeppelin	Big gas container carrying militant non-smokers.
Zinc (ZDDP/ZDTP)	Commonly used name for zinc phosphorous compound used as anti-wear and anit-oxidation inhibitor.

16. ACKNOWLEDGEMENT

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