INTERNATIONAL COUNCIL ON COMBUSTION ENGINES

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CIMAC Guideline

On the Lubrication of Reciprocating Gas Engines

CIMAC Working Group 8 – Marine Lubricants

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1. INTRODUCTION

This document brings together insights into and current practices for the lubrication of gas burning engines, excluding rotary, automotive and railroad applications. Its objective is to contribute to the efficient and reliable operation of such machinery.

Combustion processes in gas engines are different from those in internal combustion engines burning liquid fuels. Therefore, their lubrication requires solutions that are different from those typically used in Diesel and spark ignited combustion engines for liquid petroleum fuels.

This document compiles insights into the lubrication of gas engines, generated by the Working Group's members who represent users, engine and equipment manufacturers, institutions as well as additive and lubricant suppliers.

Engine scope for this recommendation:
- Marine & stationary:
- High speed (Four-stroke)
- Medium speed (Four-stroke)
- Low speed engines (Two-stroke) *

** Excluding old two-stroke gas field compression engines.*

Audience:
- End-users
- Shipyards & ship designers
- Engine manufacturers
- Lubricant industry
- Engine designers
- Schools / courses

2. DESCRIPTION AND APPLICATION OF GAS ENGINES

Gas engines are internal combustion engines fuelled by a variety of combustible gases such as but not limited to methane, natural gas, LPG, LEG etc.

Typically, a gas engine needs a primary ignition source to ignite the fuel at the correct crank angle in the combustion chamber.

The mechanical design of large bore gas engines is often derived from existing Diesel engine constructions. Therefore, two-stroke crosshead designs are found as well as trunk piston four-stroke models. Over the years, both electrical efficiency and power of gas engines have improved. See Figure 1 for an example from four stroke engine development over the years.

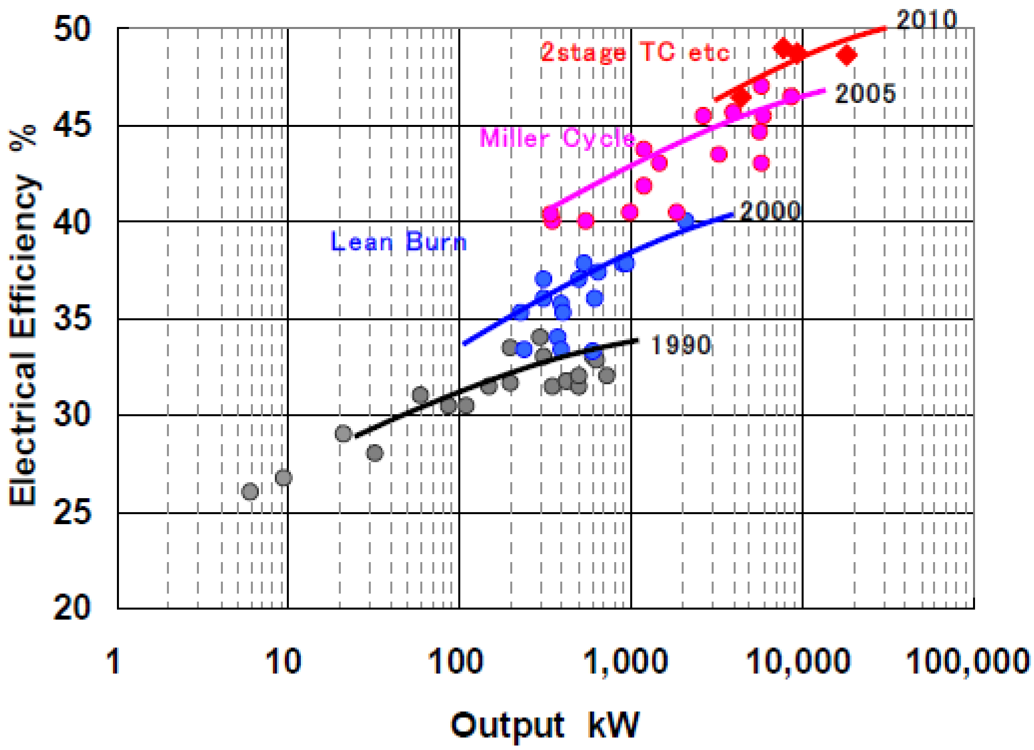


Figure 1 Chart showing development of 4-stroke gas engines. Courtesy: ASME ICES 2012 81042

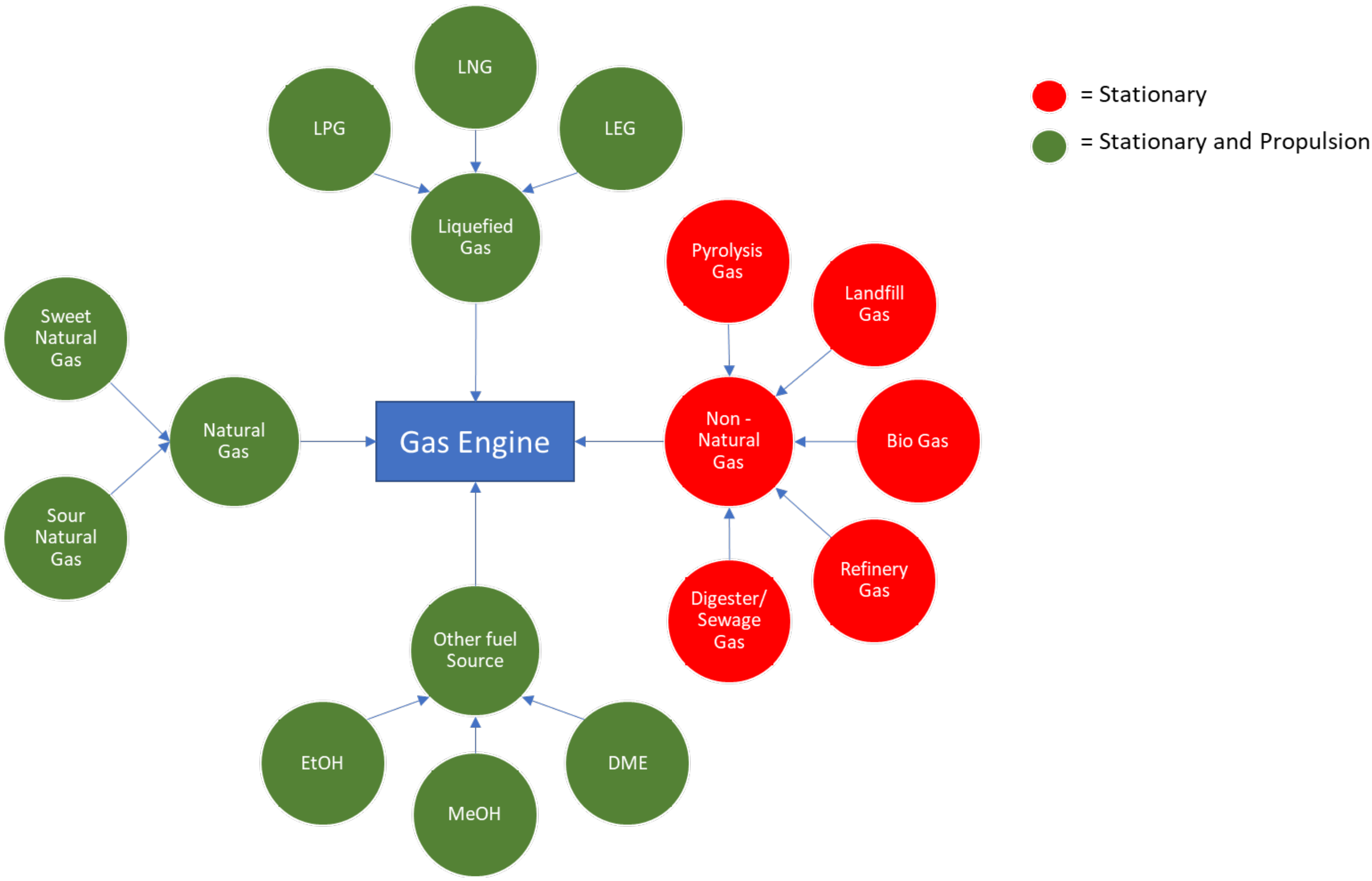
2.1 Applications

Gas engines are used in a wide variety of areas including both industrial and marine applications. In the industrial sector gas engines are used for producing electricity at base load and peak-shaving plants as well as for producing both electricity and heat at CHP plants.

Additionally, smaller size gas engines are used at landfills, sewage plants and mining installations for CHP.

In marine applications gas engines are used in container ships, LNG carriers, product tankers, ferries, coast guard vessels and harbour tugs. Further, in oil & gas field applications gas engines are common on production platforms, floating, production and offloading (FPSO) vessels and supply vessels.

Gas engines are effective power units with high efficiency offering a solution that can, depending on design principle, significantly reduce CO_2, NO_x, SO_x and PM emissions when compared to engines running on liquid fuels. Depending on their design, gas engines may utilize gaseous fuel types other than natural gas, like ethane (LEG), propane (LPG), sewage gas, landfill gas, sweet and sour gases from oil fields and refineries and gases produced from biomass and CBM from mining. The engine designer should be consulted before using any other gas type, in order to ensure the suitability of the fuel to the engine and application. Popularity of gas engines is expected to increase in the future as new gas pipelines and LNG terminals are constructed.



Picture 1 Representation of different fuel types for gas engines

More detailed descriptions of the various fuel types can be found in appendix 6.

3. LUBRICATION OF FOUR STROKE ENGINES

3.1 Selection Criteria

This section deals with selection criteria for lubricating oil quality which are particularly valid to gas engines and their fuels. For general lubricating oil quality criteria, the corresponding section 2.3 of the "Guidelines for the Lubrication of Medium-speed Diesel Engines" [1] can be consulted.

Engine and operational features to be considered include engine design, air-to-fuel ratio, thermal stress, running conditions, wear problems, knock sensitivity, lubricant treatment systems, exhaust gas treatment including Selective Catalyst Reduction (SCR), oxidation catalyst, Particulate Filters and exhaust gas heat recovery systems, etc.

Important fuel properties to be considered are: energy content, acidic and corrosive properties, ignition quality, presence of contaminants and variation in fuel hydrocarbon composition, for example the concentration of methane, ethane, propane, i-butane, n-butane, etc. as well as e.g. nitrogen and carbon dioxide contents. Though the quality of natural gas can vary depending on geographical area, landfill gas in particular, is subject to wide variations in composition and quality, necessitating on-site monitoring to allow adjustments to engine operation.

It is important to realize that many of the design, operational and fuel aspects can conflict with each other and the user must choose the most appropriate lubricant. A compilation of the most relevant parameters to be considered when selecting a gas engine lubricant is shown in Table 1. Also refer to the lubricant supplier regarding product suitability and availability.

In spark ignited gas engines lubricating oil selection is relatively simple and typically a low ash gas engine oil is a recommended alternative for operation natural gas, ethane (LEG) and propane / butane (LPG). In cases where more aggressive gas qualities are used, use of medium-ash gas engine oil will be a more optimum alternative.

If dual fuel engines are operated continuously on gas, the same lubricating oil qualities as for spark ignited gas engines can be used. Lubrication of dual fuel engines is more challenging in case when several fuel qualities, i.e. gas, distillate fuel or even residual fuel are used periodically. In alternate operation on several fuel qualities one has to make a decision by considering that 1) alkali reserve (BN level) will be high enough in order to avoid corrosion and deposit formation related to lubricating oil detergency and that 2) lubricating oil ash content (BN level) is not too high in order avoid presence of excessive amount of lubricating oil originating ash in combustion chamber and to avoid deposit formation on engine component surfaces, which can result in e.g. burning of exhaust valves as well as knocking and preignition. In general, it can be mentioned that in alternate operation on gas and distillate fuel BN 10 – 15 trunk piston engine oils are typically suitable and if only a small part of total service hours is operated on distillate fuel, even the use of low ash gas engine oils can be allowed. In case distillate fuel sulfur content is high and / or a major part is operated on it, use of a BN 20 oil can be considered as well. When also residual fuel is used as a fuel, then BN 30 – 40 trunk piston engine oils are recommended but in case only a small part of operation takes place on residual fuel, also the use of BN 20 oils can be considered.

When possible, impurities have been removed from natural gas and the gas is filtered according to OEM instructions the question is about a clean fuel quality. Before treatment natural gas can contain some dust and particles and, in some cases, also minor amounts of non-combustible compounds. However, lubricating oil contamination with insoluble material originating from fuel is less critical in gas engines compared to diesel engines burning liquid fuels. Although lubricating oil treatment needs certain attention, the sensitivity of the lubrication system towards fouling by insoluble material is lower. Consequently, the size of lubricating oil purifiers could be smaller in case those are used. A viable approach is many times the use of an effective fine filter together with a centrifugal filter.

Engine type							
1) Engine type description							
	Spark ignited gas engine (SG/SI)	Spark ignited gas engine (SG/SI)	Dual fuel engine (DF)	Dual fuel engine (DF)	Dual fuel engine (DF)	Gas diesel engine (GD)	Gas diesel engine (GD)
2) Typical Fuels							
2.1) Typical Quality Liquid Fuel							
Pilot fuel quality	-	-	Distillate fuel	Distillate fuel	Distillate fuel	Distillate fuel	Distillate fuel and / or residual fuel
Back-up fuel quality	-	-	Distillate fuel	Distillate fuel	Distillate fuel and / or residual fuel 1)	Distillate fuel	Distillate fuel and / or residual fuel 1)
2.2) Typical Quality Gaseous Fuel							
Natural Gas / Natural Gas & Hydrogen blends	✓	✓ 3)	✓ 2)	✓ 2)	✓	✓	✓
Liquid Ethane Gas / Liquid Petroleum Gas	✓		✓ 2)	✓ 2)			
Digester Gas / Landfill Gas / Bio Gas / Sour Gas	✓ 3)	✓					
3) Lubricating oil quality							
Lubricating oil quality	Low ash gas engine oil	Medium ash gas engine oil	Low ash gas engine oil 2)	TPEO with BN of 10 - 20 2)	TPEO with BN of 30 - 40	TPEO with BN of 10 - 20	TPEO with BN of 30 - 55
Lubricating oil ash content [% m/m]	~ 0,40 - 0,60	~ 0,6 - 1,0	~ 0,40 - 0,60	~ 1,3 - 2,5	~ 3,5 - 5	~ 1,3 - 2,5	~ 3,5 - 7
4) Basic requirements							
Detergency	xx	x	x	xx	xxx	xx	xxx
Dispersancy	xxx	xx	xx	x	x	x	x
Extreme pressure	xx	xx	xx	xx	xx	xx	xx
Antiwear	xx	xx	xx	xx	xx	xx	xx
Oxidation control	xxx	xxx	xxx	xx	x	xx	x
Nitration control	xx	xx	xx	x	x	x	x
Additional alkalinity	-	-	-	x	xx	x	xx
Symbols used:							
xxx	high importance						
xx	moderate importance						
x	low importance						
✓	suitable						
Blank	technology doesn't exist at this stage						
Note 1) When using ULSFO RM (max. 0,10 % m/m sulphur) or VLSFO RM (max. 0,50 % m/m sulphur) fuels, depending on OEM requirements the recommended lubricating oil BN level can also be lower than mentioned in the table.							
Note 2) Selection between Low ash gas engine oil vs. BN 10 - 20 TPEO depends on whether natural gas or distillate fuel is used as a main fuel and what are the lengths of operation periods on each fuel quality. Further, the OEM instructions shall be taken into account.							
Note 3) Selection between Low ash gas engine oil vs. Medium ash gas engine oil depends on engine design features, expected lubricating oil drain intervals and the use of aftertreatment equipment (e.g. SCR, DPF). Further, the OEM instructions shall be taken into account.							

Table 1 Selection Criteria for Gas Engine Lubricants

3.2 Monitoring of lubricating oil condition

The basic principles of used lubricating oil condition monitoring are compiled in section No. 5 of the "Guidelines for the Lubrication of Medium-speed Diesel Engines" [1]. However, the following additional important quality criteria are important to assess the fitness for purpose of a gas engine lubricant in use.

- Oxidation
- Nitration
- Acidity: Total acid number (TAN) and Strong acid number (SAN)
- Basicity: Total Base number
- Initial pH

Though both in stoichiometric (air-to-fuel ratio 1) and lean-burn gas engines higher combustion temperatures could be seen compared to equivalent diesel engines, it is important to notice that temperatures of engine components in contact with lubricating oil are still many times lower. High combustion temperatures as well as high component temperatures will increase the risk of:

- Formation of organic acids that contribute to the Total Acid Number (TAN)
- Viscosity increase
- Increased oxidation
- Increased nitration (a reaction between oil components and oxides of nitrogen (NOx) formed during the combustion process)

Therefore, some additional procedures are included in the analytical monitoring of the oil in service.

3.3 Fourier Transform Infra-Red Spectroscopy

Levels of both oxidation and nitration can be detected using modern Infra-Red (Fourier Transform Infra-Red - FTIR) spectroscopy techniques. Typically, OEM guidelines refer to differential FTIR (occasionally DIR) data measured in units of A/cm (absorption based on 1 cm oil layer thickness) at a wave frequency of 1713 and 1631 cm^{-1}, for oxidation and nitration, respectively. The determination of values from IR-Spectra requires a valid reference spectrum and even then the oxidation value might be influenced by several factors. Hence the oxidation value should not be used as a single criterion for an oil change. It is recommended to consider increased viscosity and TAN as well as degradation of BN and i-pH value as supportive indicators for oxidation.

3.4 Base Number

The Base Number (BN) indicates amount the alkaline reserve of a lubricant being available for the neutralization of acids which are produced during combustion process. The change in BN compared to fresh oil value and monitoring the BN trend gives a key indication regarding the combustion process and gas quality. Land based experience shows that BN depletion is one of the common factors leading to an oil change in the gas engines.

3.5 Total Acid Number, Strong Acid Number and i-pH Value

As both oxidation inhibition and BN level are depleted, weak organic acids may build up in the oil. Such might subsequently lead to corrosion of copper / lead bearing overlays. Organic acids are detected by the ASTM D 664 Total Acid Number (TAN) method.

By comparison with the fresh oil values, the TAN allows conclusions to be drawn regarding the oxidation of the oil and the breakdown of oil additives. It provides essential information for the evaluation of oil change necessity.

The Strong Acid Number (SAN) is included for completeness. A detectable value indicates the presence of mineral acids that cause severe corrosion. This makes the lubricant unfit for further use. SAN [mg KOH/g] is only recorded in TAN titration when the oil contains strong, aggressive acids, such as those used in gas engines with changing gas quality.

As BN and TAN do not provide information on the neutralisation capacity of an oil for all kinds of acids which may enter the oil during operation of gas engines, the i-pH value can additionally be reported. The i-pH value is a measure of the hydrogen ion (H^+) concentration in oil. The lower the pH value the more acidic is the sample. Only values greater than 4.5 may be considered acceptable.

3.6 Viscosity

To measure the viscosity of lubricating oil is a standard test and possible to do also at site conditions with a Test Kit.

Viscosity trend of a gas engine oil gives valuable information about lubricating oil performance and engine behaviour / condition. A rise in viscosity does not consequently have to be a sign of oxidation. It might be caused as well by water or glycol contamination or increased soot (not to be expected for gas engines). To derive the reason for viscosity changes additional tests like FTIR and elemental analysis are recommended.

3.7 Water

Water contamination can originate both from engine coolant and from external source, like sea water. Water intake may induce corrosion and cavitation as known for diesel engines, but it might also accelerate the oxidation process even in smaller concentrations.

It is recommended to check the water content by the Karl Fischer test method in case water leakage is suspected. Additionally, analysis of sodium, chloride and glycol may inform the source of contamination.

3.8 Quality Limits for the Oil in Use

In practice the engine builders are giving instructions for the recommended oil drain interval or what level of deterioration a lubricant can tolerate during service to ensure safe and trouble-free operation. Compliance with these limits appears to be mandatory.
For general guidance a table of oil criteria was compiled together with limits for precautionary and mandatory actions that the CIMAC Working Group "Lubricants" considers as safe for the operation of a gas engine. These are shown in Table 2.

Physical Quantity	Unit	Method		Limit	
		ISO / DIN / IP	ASTM	Precautionary action	Mandatory action
Viscosity - at 100 °C - at 40 °C	mm²/s (cSt)	ISO 3104	ASTM D7279 ASTM D2270	 +/- 15% +/- 25%	 +/- 25% +/- 35%
BN *) depletion	mg KOH/g	ISO 3771, DIN 51639-1	ASTM D2896	< 60% of new oil	< 50% of new oil, TAN > BN
TAN	mg KOH/g		ASTM D664	+ 1,5 increase	+ 2,5 increase
i-pH value	-		ASTM D7946	< 4,5	< 4,0
SAN	mg KOH/g		ASTM D664	> 0	> 0
Water	% v/v	DIN 51777-2	ASTM D6304 ASTM E2412	> 0,15	> 0,30
Oxidation	abs/cm	DIN 51453	ASTM E2412 ASTM D7414	> 15	> 25
Nitration	abs/cm	DIN 51453	ASTM E2412 ASTM D7624	> 15	> 25
Wear metals	mg/kg	DIN 51399-1	ASTM D5185	**)	**)
Flash point (Closed Cup) Flash point (Open Cup)	°C °C	DIN EN ISO 2719, DIN EN ISO 3679 ISO 2592	ASTM D93, ASTM D7236 ASTM D92	< 190 < 210	< 170 < 190
Total insolubles	% m/m	IP 316	ASTM D4055	> 0,5	> 1,0 ***)

Table 2 Limits for precautionary and mandatory actions

*) Previously called "TBN"

**) Due to varieties in engine design and materials used in engine components no general limits can be specified. Engine manufacturers and oil suppliers can advise. Further, pay attention to chlorine and silicon contents in landfill gas engine installations.

***) For Dual fuel gas engines burning residual fuel limits of the CIMAC Guidelines No. 13 apply.

3.9 Challenges and solutions

One challenge in gas engine development is related to ongoing tightening of emission regulations. In gas engines lubricating oil consumption is contributing to particulate matter (PM) emissions and thus there is a pressure to decrease lubricating oil consumption. Lower lubricating oil consumption means higher stress for lubricating oil and for this purpose development of new additives and the use of higher quality, e.g. API Group II or even API Group III or IV base oils in gas engine lubricants is needed.

However, it has to be taken into account that the Kinematic Viscosity of API Group III base oils is low relative to group I or group II and that thickening is needed in order to achieve a commonly required SAE 40 viscosity grade. It is due to this reason plus global availability and the increased cost of synthetic base oils relative to mineral base oil that such base oils are not selected for the majority of products. Artificial sweetening can also be an alternative to increase lubricating oil consumption instead of changing the whole oil batch at once.

A number of gas engines are installed and utilised in combined heat and power (CHP) plants. In such applications it is important that also auxiliary equipment, like e.g. exhaust gas boiler has a high availability during the winter period. Experience indicates that the use of higher quality (API Group II or IV) base oils in gas engine oils results in better cleanliness of exhaust boiler and makes the deposits softer and easier to remove.

In gas engine development work one continuous trend is to increase the engine output and efficiency. This action is also increasing thermal stress of lubricating oil which can be seen in increased oxidation rate and sometimes also in increased nitration rate.

Lubricating oil oxidation increases its acidity. Above 150°C oxidation becomes more prominent. Nitration of lubricating oil can be divided to the formation of organic nitrates and other nitro compounds. Both these reaction products will lead to increased sludge formation at the stage when lubricating oil additives can no longer prevent the increase of nitration. Organic nitrates normally decompose at temperatures above 150°C. The use of better quality base oils as already described above has proven to decrease oxidation and formation of organic nitrates.

One additional challenge in lubricating oil and additive development work are the increasing legal regulations like REACH which makes it more difficult or even prevents the use of certain chemical compounds and substances. As an example, paradodecylphenol (Tetra Propenylphenol), which has been used in the manufacture of additive components and packages for many years and in many gas engine oils has to be identified in the safety data sheet and using special pictograms placed on the on the package in case a specified concentration is exceeded. As a result of this, lubricating oil manufacturers may have to adjust the chemical composition to remove the compound or reduce the concentration below threshold limit values or remove their products from the market. Even if they have a proven track record. New chemical regulations may result in new lubricating oil formulations being introduced to the market. The new formulations must first be validated by engine manufacturers to ensure their suitability, performance and durability.

3.10 Field Experience

During the recent years the number of 4-stroke spark ignited and dual fuel engines have increased significantly and several OEMs are offering engines both for marine and industrial applications. Thus, there start to be also more field experience available from natural gas operation compared to year 2000 when the CIMAC Recommendations 19 “Recommendations for the lubrication of gas engines” was first published. In addition to natural gas also other gas qualities like liquefied ethane gas (LEG) and liquefied petroleum gas (LPG) have started to be more commonplace, but existing field experience from those gas qualities is still limited.

Mostly the field experience about 4-stroke gas engines is positive and one of the obvious reasons for this is in the fuel quality, i.e. natural gas both as liquefied natural gas (LNG) and pipeline gas are considered to contain low concentrations of impurities such as S and ash which results in cleaner combustion.

Gas engines experience some combustion phenomena that are not typically found in the 4-stroke diesel engine.

Pre-ignition, knocking and misfiring are phenomena which have been identified in the field installations both in the spark ignited and dual fuel engines.

Calcium is the major ash constituent in gas engine lubricating oils. Both the calcium content as well as lubricating oil consumption have an influence on the presence of ash particles in the combustion chamber. The negative consequences of particulate matter in the combustion chamber can be deposit formation on the surfaces of engine components, like piston top, exhaust valves, flame plate and turbocharger as well as the risk for pre-ignition due to the presence of hot ash and/or lubricant derived particles which further can result in knocking.

In Dual fuel engines the selection of lubricating oil quality in terms of Base number level is an important criterion to ensure trouble free operation. The selection is however a compromise since operation on gas vs. residual fuel require conflicting properties from the lubricating oil. An example of the conflicting requirements can influence the exhaust valve and seat condition. Too low ash content will prevent formation of the proper tribolayer on the exhaust valve sealing surface which can lead to excessive valve wear. Too high ash content can lead to the formation of dents on the exhaust valve sealing surface causing in the worst-case blow-by and burning of valves.

In gas engines, the lubricating oil lifetime depends mainly on lubricating oil volume and lubricating oil consumption. In medium-speed gas engines, oil change intervals of > 20000 oil service hours can be achieved (A much longer period when compared to the same size diesel engine, depending on engine model and operation). The individual lubricating oil property which will hit the condemning limit first and lead to an oil batch change also varies. Lubricating oil can oxidize leading to viscosity increase, Base number can decrease and Acid number increase due to chemical reactions taking place during service. Since the combustion of gas is very clean, insoluble material level in used lubricating oil remains typically low and specific sludge formation or varnishing issues are not commonly observed even if lubricating oil consumption is at low level. However, in modern highly rated gas engines engine component temperatures can be higher than in older engines and also hot spots can form to combustion chamber components like cylinder head flame plate. Lubricating oil related ash particles can first attach to surface hot spots where they may agglomerate to form bigger particles. The agglomeration may from time to time release larger particles which will then circulate in the lubricant, this may then cause deposits or detrimental harm to other engine components.

Cleaner burning fuels are beneficial for the lubricating oil which retain acceptable condition for longer periods of time. In spark ignited medium speed gas engines, centrifugal separators are not required. However, for dual fuel engines that use distillate as pilot fuel and back-up fuel centrifugal separators may be considered as an option. For dual fuel engines that may switch to residual fuel operation, centrifugal separators are a must have.

Cleaner burning fuels decrease wear rates of many engine components including e.g. cylinder liners, pistons and piston tops.

Instead of centrifugal separators, automatic filters, paper filters and centrifugal filters can be used for lubricating oil cleaning. The filter fineness (μm) is normally similar to those used for medium-speed diesel engines. There is no evidence that filtration of lubricating oil in gas engines using filter fineness of > 5 μm will lead to removal of additives.

Chapter 3.11 of this document includes a list of lubricating oil and engine related factors which offer more information of experiences from field installations. However, it should be noted that field experience data may vary depending on engine design, engine condition, operating conditions, lubricating oil quality, lubricating oil volume, lubricating oil consumption, etc.

3.11 Possible challenges encountered during operation

Issues with the lubrication of gas engines may occur due to lubricating oil and/or engine related factors. Table 3 shows the possible factors in both categories, their possible causes and options for undertaking rectification.

Problem	Possible reason	Lubricating oil solution	Engine solution	Remarks
		Oil related		
1. Rapid oil thickening	Oxidation, nitration, evaporation, presence of insoluble material	Better thermal & oxidative stability, improved dispersancy, less volatile base oils, improved treatment	Lower engine component temperatures, higher oil consumption (sweetening), bigger oil volume, condition of cylinder liners, pistons and piston rings	
2. Severe oxidation	High thermal & oxidative stress	Better quality base oil, improved performance of oxidation inhibitors	Lower engine component and oil temperature, bigger oil volume	
3. Nitration	High combustion temperature and NO_x level in exhaust gas, too rich air-to-fuel ratio	Better quality base oil, improved performance of nitration inhibitors	Optimum injection timing and leaner air-to-fuel ratio	
4. BN depletion	Presence of sulfur / other acid compounds in gas	Higher BN level, better quality BN utilization	Shorter lubricating oil change interval, de sulfurization of gas, bigger oil volume	Higher BN level increases deposit formation and preignition risk
5. Carbon type deposit formation	Oil degradation, high oil consumption, high engine component temperatures, poor engine maintenance	Improved additive technology	Ensure that engine is maintained in a proper way	
6. Lacquer / varnish type deposit formation	Oil degradation, oxidation, nitration, presence of insoluble material	Improved additive technology	Oil treatment, shorter oil change intervals,	
		Engine related		
7. Knocking	Too low MN, presence of ash deposits in combustion chamber	Lower ash content, Better quality base oil,	Lower oil consumption, use of knock sensors	Check gas composition and its MN
8. Spark plug failures	Erosion of contact pad material, peeling of noble metal material	Lower ash content (Ca, Mg, Zn, P contents)	Ensure that a right type of spark plug is used, optimize energy content of spark, lower oil consumption	
9. Valve seat wear	Lack of tribofilm on valve and valve seat sealing surface	Higher ash content of oil	Optimized oil flow through valve stem	Higher ash content increases deposit formation risk on combustion chamber component surfaces

Table 3: Possible challenges related to gas engine oils and engine behaviour

4. LUBRICATION OF TWO STROKE ENGINES

4.1 The Role of the Lubricant

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

To achieve this, the cylinder lubricant is required to:

- Spread uniformly over the cylinder liner surface (enabled by the lubrication system)
- Form a stable oil film to provide lubrication and a gas seal between the liner and the piston rings
- Neutralise acids formed from the products of the combustion
- Minimise deposit formation on piston surfaces and ring grooves
  - Deposits on piston surfaces may disrupt the oil film
  - Deposits in the piston ring grooves may lead to ring sticking or breakage
- Flush away particles formed during combustion from the combustion chamber as well as wear particles
- Prevent corrosion of the cylinder liner and other combustion chamber components while the engine is stopped

Traditionally cylinder lubricants have been designed for heavy fuel oil (HFO) operation but now other fuels such as distillate and gaseous fuels are becoming more widely used. As engine development and efficiency increases and engine designs are required to cope with a wider range of fuels, the temperature and pressure conditions to be endured by lubricant and engine components will inevitably become more severe and varied. Cylinder lubricants are required to perform under these varying conditions.

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

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

A general recommendation for selection of cylinder lube oil feed rate depending on deposit formation is shown in Figure 2 below. A minimum feed rate must be provided to guarantee a lubricating oil film and to keep the components clean. Gaseous fuels (LNG & LPG) do not normally contain sulfur, so the neutralisation of sulfuric or other acids is no longer the main challenge when the engine is operated on gas mode. Engine cleanliness is now the main challenge for the cylinder lubrication. Gas engines are generally lubricated close to the engine specific minimum cylinder oil feed rate. The cylinder oil feed rate can be increased if there are issues with cleanliness.

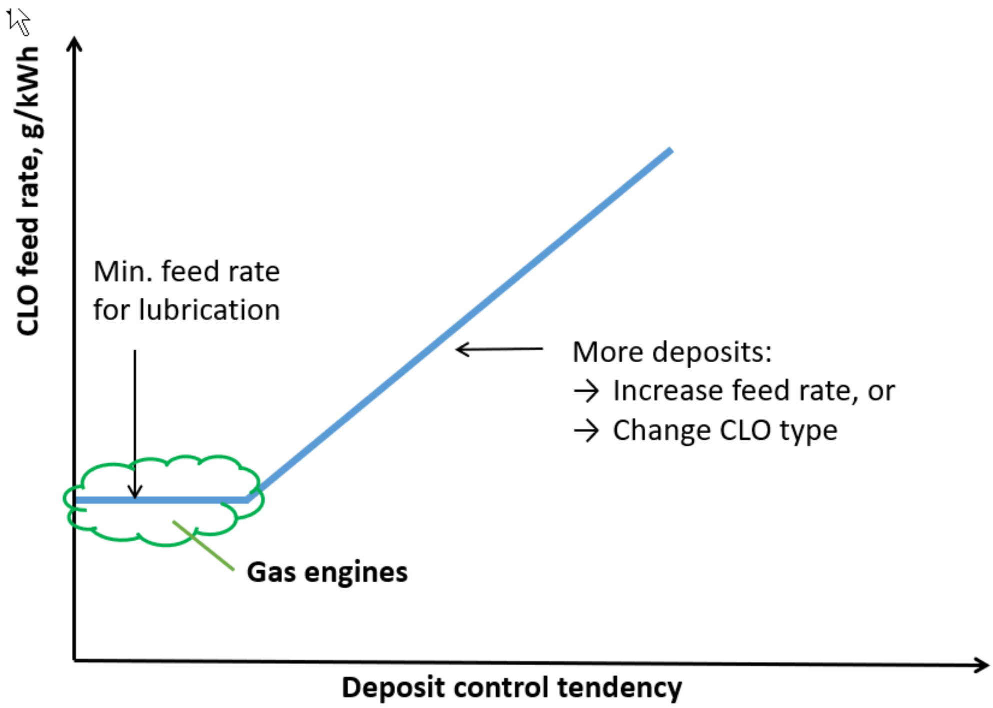


Figure 2: General recommendation for cylinder lube oil (CLO) feed rate adjustment depending on deposit control tendency.

4.2 Lubricating oil selection criteria

This paragraph deals with selection criteria for cylinder lube oil quality and provides operational guidelines on how to lubricate low speed engines operated on natural gas. At the time of writing of this document, design of the engines and applied lubrication solutions are still evolving.

In order to control deposits in the combustion chamber and after treatment systems, it is preferred to lubricate with a lower BN cylinder oil. However, since all engine designs on the market today use sulfur containing liquid pilot fuel (to a greater or lesser extent) to provide a fuel ignition source, the cylinder oils selected will also require some sulfuric acid neutralization properties to protect the engine against corrosion. Typically, a low BN cylinder oil is selected.

High BN oils cylinder oils have inherently higher deposit control properties. To manage deposit tendencies some OEM's recommend the use of higher BN cylinder oils for a limited period to promote piston cleanliness.

Continuous use of high BN oils may have a detrimental effect on particle emissions and fouling of the exhaust system post combustion chamber and exhaust gas after-treatment equipment, it is recommended to start with a lower BN cylinder oil and only utilize a higher BN cylinder oil option when excessive deposits in the piston ring land area are observed via port inspections.

In all cases, OEM recommendations should be followed. The OEM and/or lubricant company should be consulted if further guidance is needed. The graph in Figure 3 below shows an example of the recommended steps to be followed.

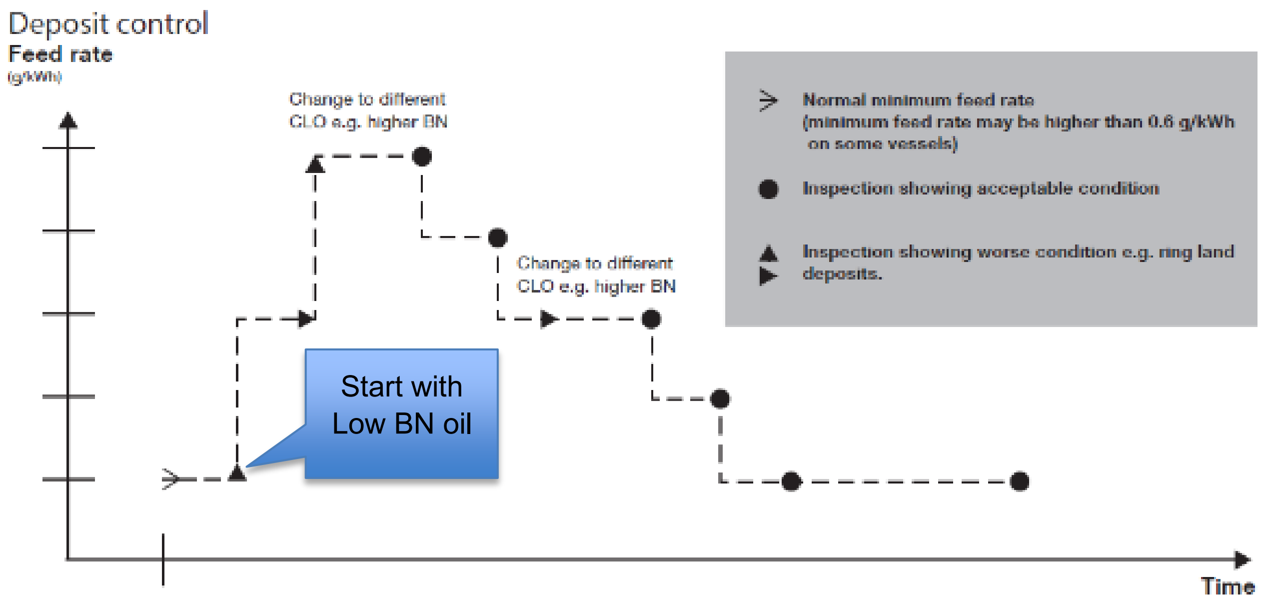


Figure 3: Example of feed rate optimisation.

Lubrication is started with a low BN oil, if deposit build up is observed at an inspection point after a couple of hundred hours of operation with the low BN oil, feed rate can be increased stepwise to improve condition. If no improvement is achieved, the operator can switch to an oil with higher cleaning ability (detergency) to clean up the engine, e.g. higher BN oil (following specific OEM recommendations). After an improvement in condition is observed, feed rate can be optimised gradually towards the minimum feed rate if an acceptable cleanliness level is maintained.

4.2.1 General guidelines

OEM guidelines provide up to date recommendations to maintain optimum engine operation. Please refer to OEM guidelines for specific details.

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

General cylinder lube oil BN guide

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

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

Today, cylinder lube oils can be acquired with different levels of BN. At time of publishing the range is: 15-145 BN.

When the engines are operated on gas, the resulting fuel mix (Gas and pilot fuel) is generally equivalent to an ultra-low-sulfur fuel as the gas contains very little, if any, sulfur, and the amount of pilot fuel is small. When the engine switches over to liquid fuel operation, the engine acts like a diesel engine, and it may be subject to cold corrosion. For more information on cold corrosion, please refer to CIMAC guideline [2].

All engines are different and must be treated individually. However, some general advice can be given for operation on gas:

- Use cylinder oils with good deposit control to avoid deposit build up.
- Cylinder oil feed rates should be kept as low as possible.
- Lubricant oil quills or injectors must be kept in good working order to maintain correct oil dosing and distribution.
- Drains (scavenge air, water mist catcher, receiver, and piston underside) must be kept clean and fully operational.
- Cylinder condition should be monitored, and action should be taken based on observations. As wear is generally low, actions to address deposit build-up should be the priority.

Different recommendations might apply. Please refer to OEM guidelines.

4.2.2 Challenges/Practical Aspects

In terms of lubricant selection, maintaining a good level of cleanliness on the piston assembly (as described in section 4.1) is the most relevant aspect of lubrication to guarantee reliable piston running conditions for 2-stroke engines operating on gas or low sulfur fuels.

4.2.2.1 Deposit Build-up due to thermal stress of the cylinder oil

Experience has shown that lubricating with low-BN cylinder oils can prevent excessive build-up of lubricant ash ($CaCO_3$) deposits. Nevertheless, there have been numerous observations suggesting that some engine designs might suffer from deposit build-up related to the thermo-oxidative strength of these oils. Generally, low-BN oils contain a higher proportion of base oil and less additives compared to high-BN oils. Lubricant additives, in particular some detergent additives, are more thermally stable than the base oils typically used in marine lubricants. Therefore, to address deposit control due to thermal exposure of low-BN cylinder oils, some engine manufacturers consider for certain engines the use of an oil with higher deposit control as an option to lubricate gas operated 2-stroke engines.

This means that some ships may have to carry two separate cylinder oils to address lubricating needs of the main engine – a low-BN cylinder oil for gas operation and a higher-BN oil for either fuel oil operation or as alternative to clean up/control deposit formation in the piston assembly. The BN level of the alternative cylinder oil to be used as well as the extent of the lubricating period is subject to the specific engine and operating conditions following specific OEM advice.

4.2.2.2 Deposit Build-up due to excessive ash content of the cylinder oil

Experience from the past with older engine designs using high-BN cylinder oils at relatively high feed rates, in combination with low sulfur fuels, showed in some instances the formation of excessive ash deposits on the piston assembly that lead to bore polishing and consequent scuffing incidences. This experience has not been widely observed in recent years in modern 2-stroke engines because of introduction of piston cleaning rings. Engine manufacturers have further addressed this concern by recommending low-BN cylinder oils or intermittent use of high-BN oils. Continuous operation on high-BN oils when the alkalinity in the cylinder oil is not required is generally not recommended, and when applied, continuous cylinder condition monitoring is strictly advised, including but not limited to regular cylinder port inspections.

Challenges with lubricant ash deposits when running on high BN oils, have been observed in engine equipment downstream of the combustion chamber such as exhaust valves, duct, turbochargers, boilers and exhaust gas aftertreatment (e.g. SCR & EGR installation). Increased cleaning and maintenance of this equipment might be necessary depending on the ash throughput and accumulation rate which depend on both BN and feed rate of the cylinder oil in use. For specific guidance, please consult OEM or oil supplier.

4.3 Monitoring

Please also refer to the "CIMAC Recommendation for the Lubrication of Two-Stroke Crosshead Diesel Engines" [1].

Successful optimisation of the lubrication and improvement of the cylinder condition depend on close monitoring of the condition and resultant actions being taken according to OEM guidelines.

Modern engine designs and variable operating patterns with a variety of fuel sulfur levels make low speed two-stroke diesel engine monitoring a necessity. Without regular port inspections and piston underside drain oil analysis, using both on-board and laboratory methods, the operator is often unaware of the effectiveness of the applied cylinder lubrication settings and oil selection. For instance, if too little oil and/or too low a base number are used, cold corrosion may result when the engine is operated with sulfur containing fuel, similarly engine cleanliness can be severely impacted if inadequate feed rate or lube oil is applied.

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

- Scavenge port inspections
- wear measurements
- drain oil analysis.

An overview of general advice for monitoring the engines can be seen in Figure 4.

General advice for monitoring of gas engines are:

- Undertake scavenge port inspections every 14 days on a new engine or after changing operating parameters. It is recommended to perform inspections at least monthly or every 250-500 h running hours.
    - Check especially for deposit built up and micro seizures.
    - Ring groove clearances by feeler gauges
    - Engines should be clean and no micro seizures visible.
    - Act on results
- Measure the wear:
    - Piston rings: check piston ring coating thickness at regular intervals
    - Liner: once a year
    - Wear rates should be low
    - Act on results
- Make drain oil analysis:
    - Interval:
        - 500-1000 running hours for lab testing,
        - Every 200-300h by using on-board equipment and after operating parameter change.

      More frequent if wear or cleanliness issues are detected
    - Total Iron (Fe) content should be low
    - Residual BN should not be below 25% of the new value
    - Act on results

Figure 4: General advice for monitoring two stroke gas engines

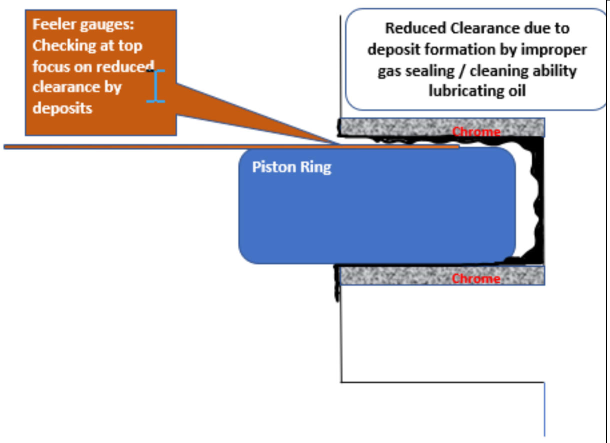
4.3.1 Inspections

Scavenge port inspections

Visual inspections through the scavenge ports provide useful information about the condition of cylinders, pistons and piston rings. Visual port inspections by qualified and experienced personnel should be carried out following OEM guidelines. Regular inspections can detect changes in the cylinder condition.

When operating on gas, special attention should be paid to the cleanliness of the engine, as well as signs of adhesive wear on the piston rings, which are the first indications of insufficient lubrication and possibly bore-polished liner surfaces. Keeping the piston rings moving freely requires the right attention. When piston ring groove clearances are reducing, close monitoring is required, and action should be taken to tackle the root cause. (Fig. 5 left).

Checking clearances for deposits



Checking clearances for wear

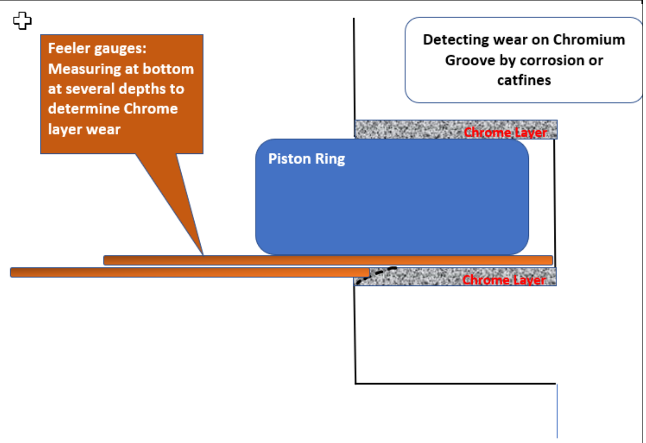


Figure 5. Checking of ring groove condition. Also refer to OEM guidelines.

It is recommended to make port inspections every 250-500 running hours. If the condition is good and the engine is clean, the intervals can be increased. If the condition is not satisfactory, actions should be taken. See figure 6.

Observed condition	**Example 1:**	**Example 2:**	**Action**
Clean condition			*No action required*
Medium deposits on ring land(s)			*Increase feed rate or change oil type* *Close monitoring*
High deposits on ring lands(s) *Reducing clearances / ring movement*			*Increase feed rate and if condition not improving;* *Move to higher BN oi or oil with better cleaning ability*

Figure 6: Condition by port inspection

4.3.2 Wear measurements

As part of regular engine inspections, the engine crew should measure the liner, piston ring coating and piston ring groove wear. The wear measurements should be stored in the vessel maintenance system. It is recommended to analyse the wear in order to assess whether the lubrication and fuel management is adequate. Furthermore, component lifetime can be assessed based on a number of measurements and preventative maintenance can be planned.

Experience so far shows that piston ring and liner wear is very low when operating on gas.

4.3.3 Drain Oil Analysis

On 2-stroke engines, during normal operation, fresh cylinder lube oil is injected into the cylinder and the used oil is drained from the bottom of the cylinder liner and discharged (once-through principle). See figure 7.

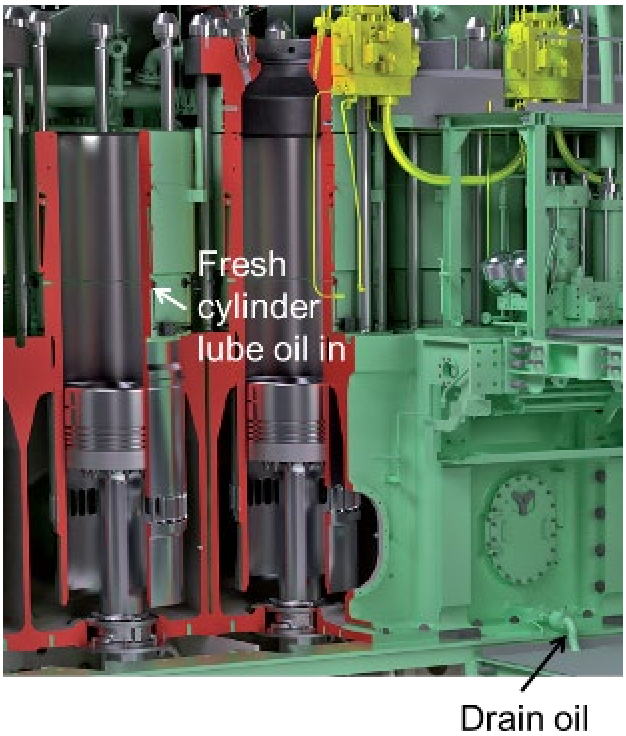


Figure 7: Fresh cylinder lube oil is injected and scavenge drain oil comes out

The used cylinder lube oil (also called "scavenging" drain oil, piston underside drain oil, drip oil or scrape down oil) can be sampled from the engine through the scavenge bottom drain. Analysis of the drain oil can show whether the cylinder condition is within the normal range or whether action must be taken. Such actions could be adjusting the cylinder lube oil feed rate or changing cylinder oil type.

The analysis of the drain oil is indicative of the cylinder condition mainly through the BN-value and the iron-content (Fe). The evaluation should be based on the combination of both BN and Fe in order to determine proper actions. However, in a gas engine there is little BN depletion and Fe is more important. Once readings have been obtained, the engine manufacturers lubrication guidelines should be consulted to ensure the engine is operating in the recommended range or if any feed rate or change of cylinder oil type is required.

Figure 8 below was developed for engines operated on high-sulfur fuel and provides good guidance on actions depending on the results of the drain oil analysis. It is recommended to optimise the cylinder lube oil feed rate to secure that the drain oil analysis results remain in the safe area. The results, which are expected for gas engines, are shown in the full-coloured blue cloud: Low Fe and BN depending on the original cylinder oil BN.

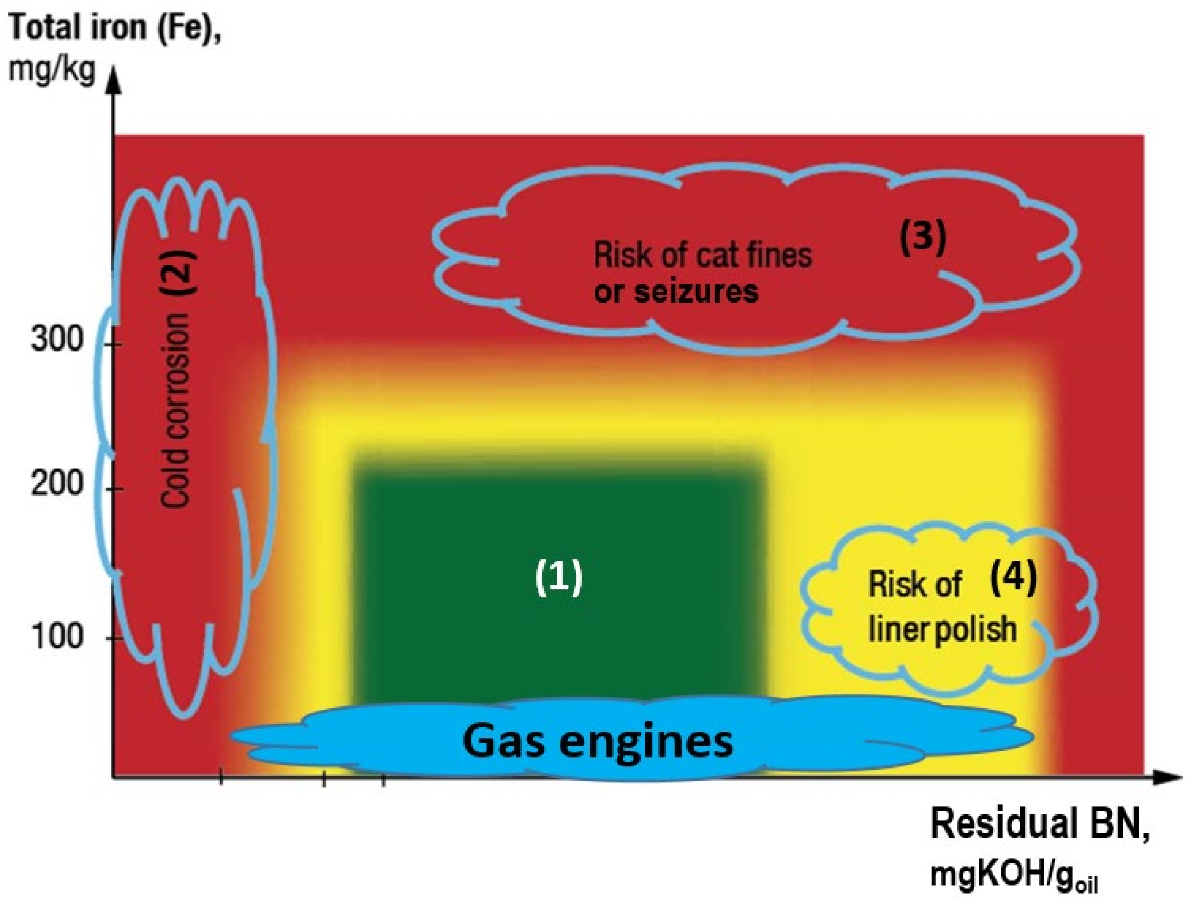


Figure 8*: Scavenge Drain Oil analysis interpretation for operation on:*

- *Gas: blue area: Fe should be low, and BN depend on original cylinder oil BN.*
- *HS HFO fuel / VLSFO: (1) green area: keep current operation procedures; (2) "Cold Corrosion": increase cylinder oil feed rate and/or switch to a higher BN cylinder oil; (3) "Risk of Cat fines or seizures": Cat fines check fuel centrifuge operation and cleanliness of the fuel, seizures check piston ring running surface; (4) "Risk of liner polish": consider to reduce cylinder lube feed rate or switch to a lower BN cylinder oil*

4.3.4 Guidance for drain oil analysis interpretation for gas operation

Continuous evaluation of drain oil samples is recommended. The feed rate must be adjusted so that the total iron (Fe) content does not exceed 100 ppm. Normal values for total iron in the drain oil are in the range of 10-20 ppm. Residual BN may vary depending on engine and oil type. Normal values for residual BN are in the range of 0-10 BN below the original cylinder oil BN.

Generally, the residual BN should not be lower than 25% of the original cylinder oil as the oil would otherwise be exhausted. It is important to consider the effect of system oil contamination into the drain oil sample from leaking stuffing boxes or piston cooling oil, as the lower BN value of the system oil can influence the result. Most on shore laboratories provide this service. Samples should be taken at regular intervals, and more frequently if issues are suspected, as shown in the overview in Figure 9.

General guidance regarding drain oil for continuous operation on gas:

- Sample intervals:
  - 500-1000 running hours for lab testing
  - 200-300 running hours on board testing
  - More frequent, if suspicion on issues or changes in operation (E.g running in, etc, …),
- Results:
  - Fe:
    - Normal level: 10-20 ppm
    - Sudden increase should be investigated and action to be taken
  - Residual BN:
    - Normal level: 0-10 BN below original cylinder oil
    - Generally, the remaining BN should not be lower than 25-% of original cylinder oil
  - Act on results

Figure 9: Drain Oil guidance for two stroke operation on gas

On-board equipment

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

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

Evaluation of the corrosive level

The residual BN of the drain oil should be close to the original BN value. If the residual BN is too low, then increase the feed rate and investigate the cause.

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

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

Different analysis methods detect different wear types (Table 4). Some measure total iron while others measure the iron formed by adhesive or abrasive wear. This could be wear derived from “normal wear” mechanisms, from cat fines in the fuel, from micro-seizures and/or scuffing. These iron wear-particles are magnetic therefore measured by devices using the magnetic flux technique.

Wear particles from cold corrosion are iron oxides which are non-magnetic. On-board detection methods for corrosive wear-forms are based on chemical reactions. Results from both the ferro-magnetic iron and the corroded iron should be combined to provide the total iron reading.

Wear types	**Wear mechanism**	**Measuring method**		
		Magnetic iron	**Corrosive iron products**	**Total Iron**
Normal wear Cat fines Micro-seizures Scuffing	Abrasive or adhesive wear	X		X+Y
Cold corrosion	Corrosive wear		Y	

Table 4 : Correlation between wear type and mechanism and different iron measuring methods.

On shore laboratories typically use ICP-AES and MS techniques to determine the total iron. These methods look at smaller particles, however, it is able to measure both corrosive and adhesive / abrasive iron particles depending on the technique and sample preparation method used. OEM recommendations are based on these methods.

X-ray can be measured on board and in the lab and allow larger particles to be measured. However, proper homogenizing of the sample is important. Looking at ferrous magnetic particles is important for gas engines since corrosion is less of an issue and engine magnetic wear particles are a sign of (micro) seizures.

The chart displays the three Fe detection methods relative efficiency (vertical axis), and size of particles best measured with the corresponding Fe detection method.

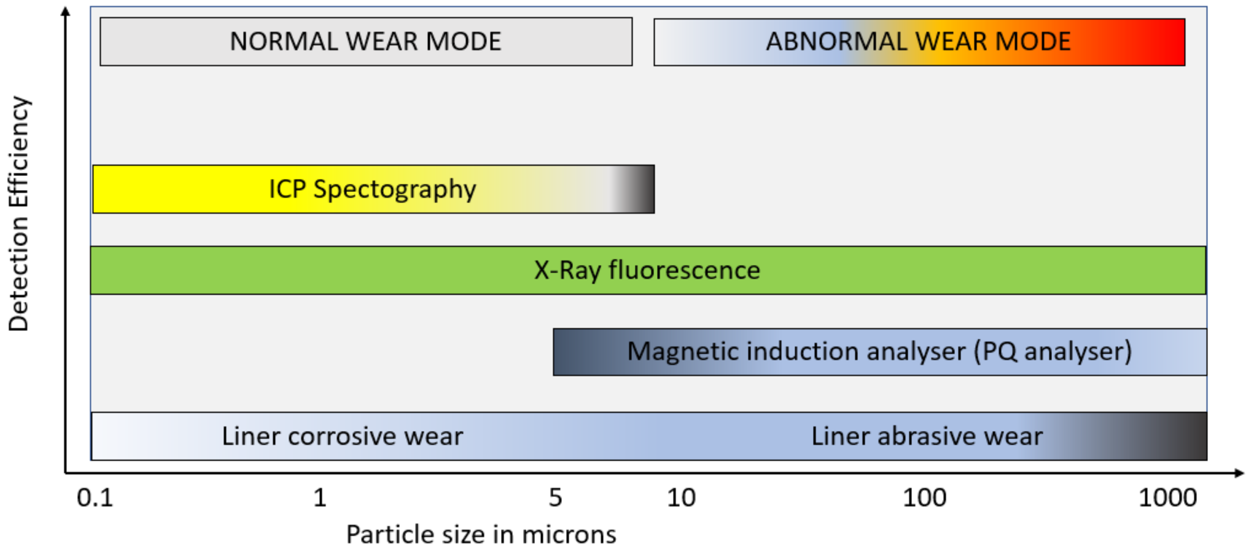


Figure 10: Different iron detection methods have different measurement performance.

Depending on the measuring method, different values may be obtained, and care must be taken to evaluate these values as different actions may be recommended as a result:

- If the magnetic iron method shows high iron, it must be complimented by results of the residual BN to evaluate whether the wear type is due to cold corrosion or e.g. normal low wear.
- If the residual BN is too low, it could be cold corrosion, and the action should be to increase the cylinder lube oil feed rate or change to a higher BN oil.
- If the residual BN is in the safe area, it indicates a satisfactory condition and no further action should be taken.
- If the residual BN is high, the engine might suffer from increased deposits and the response action should be to lower the cylinder lube oil feed rate or change to a lower BN oil.

Lab testing

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

Examples of standard test methods for:

- Total iron (Fe): ASTM D5185-09 (ICP)
- BN: ISO 3771:2011 (E)

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

4.4 Service Experience

Field experience from two-stroke gas engines is generally very good. Measured wear rates of piston rings and liners are on a very low level. The gas engines require cylinder lube oils with high cleaning ability (detergency) to keep piston and ring grooves clean. First experience shows that lube oil dependent deposit build up on piston and ring grooves is an issue if cylinder oils with lower deposit control are used.

4.4.1 Wear

Due to the negligible sulfur present in gas operation, the combustion chamber component corrosive wear rates are very low, usually lower compared to components in high sulfur HFO operated engines.

Even with very low wear rates, it may occur that the pistons require early or unscheduled overhauls because some piston rings are found stuck in the piston ring groove because of deposits build up. Such situations increase the risk for piston ring / liner damage or even breakage of piston rings.

Piston rings with hard coating are standard for gas engines to increase the margin against scuffing and to secure extended periods between overhaul.

There are two methods in use to apply the hard coating on the piston ring substrate. Thermal spraying and galvanic methods. Today, typically these two types are applied:

- Thermal sprayed Cermet-coating which is a composite: part-ceramic, part-metallic material
- Galvanically applied chrome ceramic coating: chromium coating with aluminium oxide (Al_20_3).

Both coatings have a good wear and temperature resistance. (Fig 11 and 12)

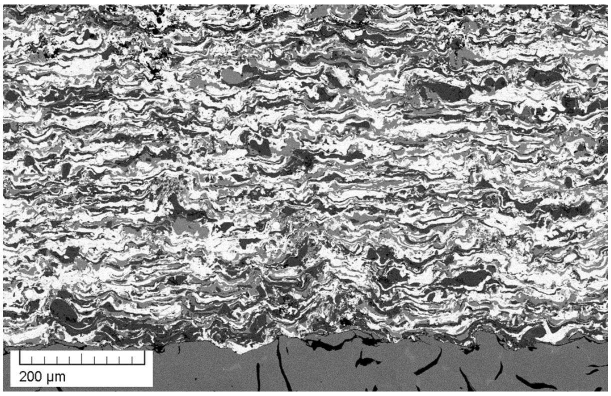


Figure 11: Cross-section of plasma-sprayed Cermet coating. SEM micrograph.

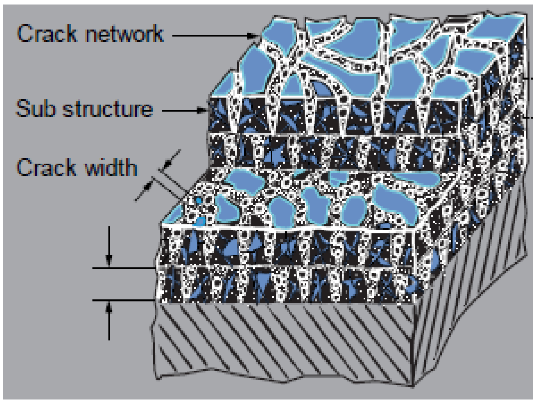


Figure 12: Cross section of a chrome ceramic layer. Chromium coating with aluminum oxide (Al_20_3).

In the event of limited lubrication, the very hard and thermally stable coatings and the differences in metallurgy between the two moving surfaces (piston ring and liner) should prevent adhesive wear.

4.4.2 Piston Assembly Cleanliness (Deposits)

When operating on gas, low-BN cylinder oils have been recommended for lubrication. In several cases it has been observed that engines experienced deposit built-up on the piston crown land, ring lands, behind the rings and in the ring grooves. In some cases, excessive deposits behind the rings and in the ring groove will hinder the free movement of the rings. This situation can lead to uncontrolled blow by, unwanted ring deformation, excessive abrasive or adhesive wear, or ring breakage.

The cylinder lube oil should have enough thermo-oxidative stability to survive in the harshest conditions of the cylinder liner close to the combustion chamber. This will help to minimise deposit formation on the piston top land and in the piston ring pack.

The formation of H_2SO_4 is lower in VLSFO and ULSFO fuelled engines relative to higher S containing fuels as the fuels contain less Sulphur. The primary source of acid neutralisation capacity of a cylinder oil comes from the $CaCO_3$ contained within the detergent core. If the $CaCO_3$ is not converted to $CaSO_4$ through neutralisation of the acid, then it is possible for the $CaCO_3$ to contribute to deposits on the piston. Therefore, it is preferable to reduce the amount of $CaCO_3$ contained in the lubricant by lowering the overall BN. This then reduces the impact of deposits caused by unreacted $CaCO_3$.

However, recent experience is indicating that cylinder oils formulated with lower BN and ash content are not always able to prevent deposit accumulation when subject to more severe gas application running conditions. Therefore, there is a greater demand for increased performance from the lubricant to work under these conditions to keep the piston and liner clean.

The deposit formation occurs on the piston top land, between the piston rings (ring land) and in the piston ring groove on top and behind the piston rings (Fig. 13).

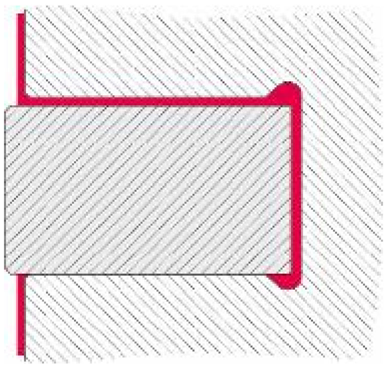


Figure 13: Schematic of deposit (red) build-up behind piston rings.

Deposits on the piston crown land, in the piston ring grooves and on the ring lands, may lead to bore polishing giving the liner surface a mirror like appearance and interfere with the cylinder lube oil film formation. This bore polishing could also lead to increased abrasive and adhesive wear.

Deposits found in the combustion chambers of engines operating on high sulfur fuels, consist primarily of calcium sulfate ($CaSO_4$), which is the reaction product formed in the neutralisation of sulfuric acid. For engines operating on low sulfur containing fuels, the deposits found consist of both $CaCO_3$ and $CaSO_4$.

Figure 14: Figures 14.1, 14.2, 14.3, 14.4 and 14.5 show examples of cylinder condition from service. Figures 14.1, 14.3, 14.4 and 14.5 show condition when the engine is operating on a cylinder oil with too low cleaning ability, while Figure 14.2 shows an engine that has operated on cylinder oils with sufficiently high cleaning ability.

Figure 14.1: Continuous operation on gas and low-BN cylinder oil leads to ring land deposits and deposits behind the piston rings.

Figure 14.2: Continuous operation on gas and 100 BN cylinder oil keep the engine clean in the ring belt and might contribute to adverse build-up of exhaust system deposits.

Figure 14.3: Operation on gas and low-BN leads to ring land deposits.

Figure 14.4: Deposits on top ring backside.

Figure 14.5: Deposits on top ring groove.

4.4.3 Drain Oil results

Drain oil results generally show very low Iron (Fe) results, and a low consumption of BN. This is fully in line with the very low wear and the low content of sulfur in the fuel. Results from an engine operating on less than 0.10% S fuel and gas using a 25 BN oil can be seen on Fig. 15.

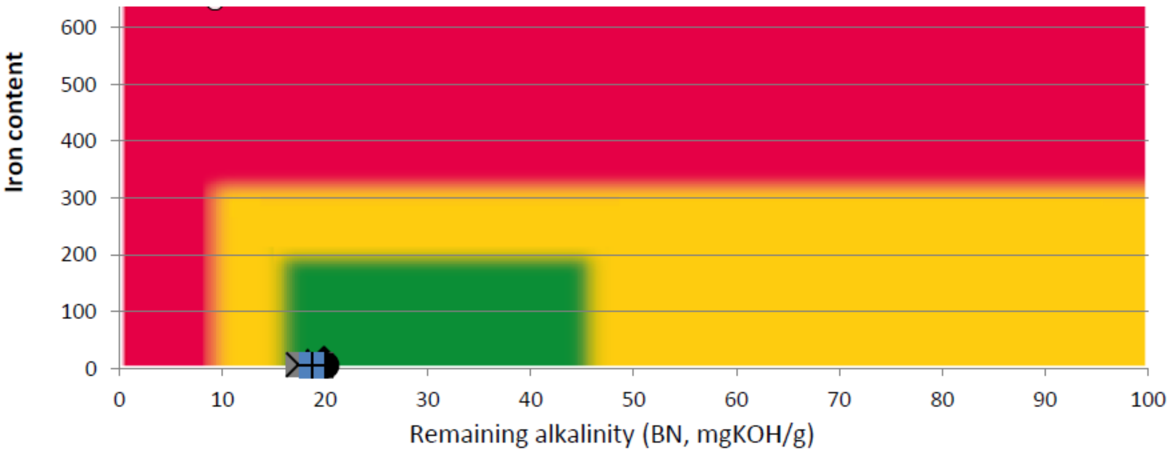


Figure 15: Drain oil results from operation on less than 0.10% S fuel and gas using 25 BN oil. Note the very low amount of Fe, and BN consumption of 5-10 BN.

5. Appendix 1

5.1 Gas Engine types and combustion challenges

Driven by more stringent environmental legislations and better, widespread, availability, the use of gas engines has found their way into new markets including the marine and power generation sectors. Today, gaseous fuels are used in various types of engines including the very large medium and low speed engine applications covered in this document. The main principles applied are typically quite similar and can be divided into three main categories depending on how the gas is introduced to and ignited in the cylinder. The categories are termed:

- Spark ignited (with prechamber for large medium engines)
- Direct Gas Injection
- Dual Fuel engine

5.2 Spark Ignited (SI)

The Spark Ignited (SI) gas engine is essentially an Otto type engine, similar to a gasoline engine. It has a spark plug fitted in the combustion chamber that ignites the premixed air/gas mixture. The gas is mixed with the intake air, usually in the intake manifold outside of the cylinder prior to the compression stroke. The advantages of this system are that only one fuel system is needed (no pilot fuel). The challenge for gas engines is the sensitivity to early self-ignition and/or knocking. This is controlled by limiting the compression ratio of the engine and control of ignition point. Thus, the thermal efficiency of the SI engine may be lower than in similar diesel engines. This knocking behaviour can further be affected by the presence of excessive amounts of oil carry over or ash in the combustion chamber, as they can act as unwanted ignition source. It should be noted that spark ignited gas engines could be used in marine applications with certain limitations however this is not a typical approach.

Spark ignited gas engines can be divided into two modes of operation, Lean Burn and Stoichiometric (Rich) burn engines. Table 5 below shows how different engine fuel:air ratios affect performance and Figure 16 represents these comments pictorially.

Lean burn advantages	Rich burn advantages
NOx level as low as 0.5 g/bhp-hr without after treatment (then SCR)	Lowest practical overall emissions
Suitable for Biofuels if not catalytic aftertreatment is needed	Lowest formaldehyde/HAPs emission level
Lower Carbon footprint (CO_{2e}) at NOx over ~1.0 g/bhp-hr	Lower Carbon footprint (CO_{2e}) at NOx under ~1.0 g/bhp-hr
Efficiency (Fuel consumption) Advantage at NOx over ~0.5 g/bhp-hr	Efficiency (fuel consumption) advantage at NOx under ~0.5 g/bhp-hr
Higher power density	Very low NO_2:NOx ratio
	Lower Demands on air and ignition systems
	Greater fuel flexibility without ‘knock’

Table 5 Comparison of Lean burn versus Rich burn 4 stroke gas engines (Source: INNIO)

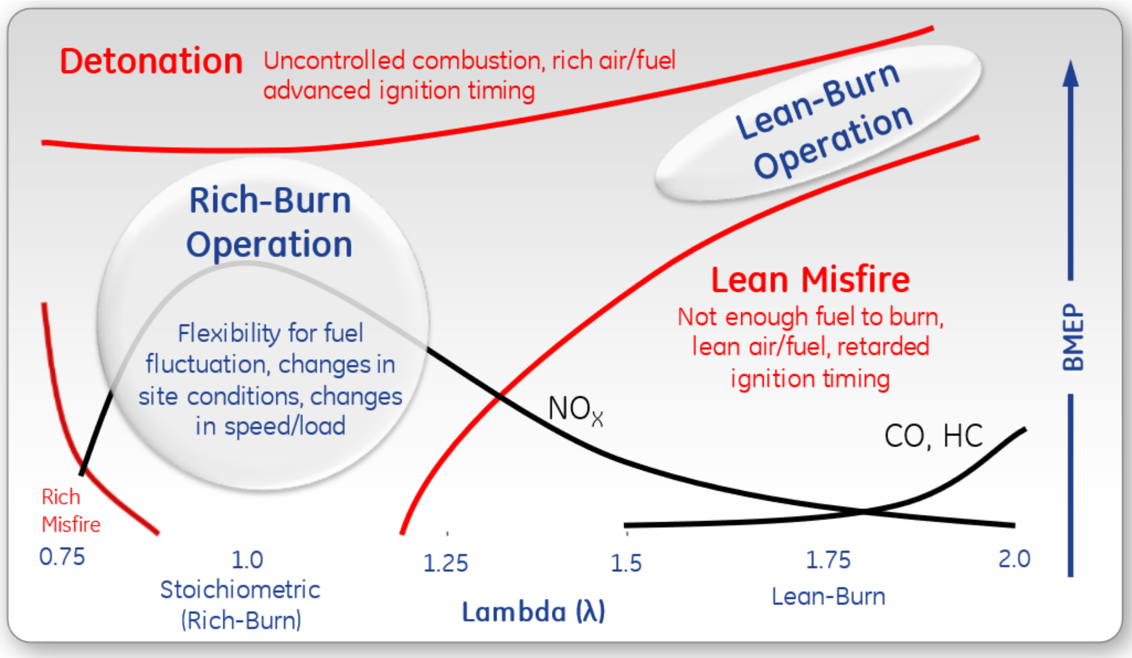


Figure 16 Gas engine operational influences on combustion phenomena (Source: INNIO)

5.2.1 SI gas engine aftertreatment devices

To achieve low NOx emissions lean burn engine operation can be combined with EGR or SCR while stoichiometric engines are combined with a three-way catalyst.

Further, compared to other gas engine concepts, SI engines show a certain risk of methane slip as the gas is premixed with the air. For stoichiometric SI engines the use of a three-way catalyst is possible to reduce methane emissions

5.3 Direct Gas Injection (GI)

The Direct Gas injection (GI) engine uses a pilot flame to ignite a direct injection of gas. The pilot injection is usually timed prior to the gas injection in order to set up the right conditions that can ignite the gas injection. This mode of operation is thus very similar to a common diesel engine, with the difference that two fuel systems are used. This system is not sensitive for pre-ignition, or knocking, as there is no premixing of the gas and air charge. This also implies that under normal operation there is very limited methane slip. Having two separate direct injection systems in principal allows for operation at any ratio of liquid fuel (HFO/distillate) and gas. The NOx levels are similar to those from a regular direct injection engine, or diesel engine. Exhaust Gas Recirculation (EGR) or Selective Catalytic Reduction (SCR) can be used for engines in need of complying with IMO Tier III NOx regulations.

5.4 Dual Fuel (DF)

Dual Fuel (DF) engines uses premixed gas/air mixture, like the SI engine, and a diesel pilot flame is used to ignite the mixture, like a gas injection engine. The engine is thus an Otto engine when burning gas. However, the mode of operation can be shifted to pure compression ignition, diesel engine, if the gas is turned off and only fuel oil is used. The engine power is typically limited compared to a traditional diesel engine of similar bore due to the risk of knocking or pre-ignition of the premixed gas/air charge. The emission of unburnt fuel (methane slip) is higher than from the high-pressure direct injection. This makes it important to control methane slip in a way to ensure compliance with possible legislations. The low-pressure gas injection system, similar to that for the SI engine, simplifies the engine relative to the gas injection engine.

Further, the premixed operation gives lower NOx emissions which simplifies after treatment. These factors have made the DF engine the most applied multi fuel solution on the market for medium speed engines and is also available for large low speed crosshead engines. Economic, technical & safety considerations require the engine to run at high compression ratios and with a lean gas/air mixture. With varying gas quality (expressed in the Methane Number, MN) the knock behaviour for the engine may change considerably - giving abnormal combustion and knocking. To avoid this, modern engines therefore employ knock sensors / data analysis and feedback which can then adjust the ignition timing and air/fuel ratio of the engine.

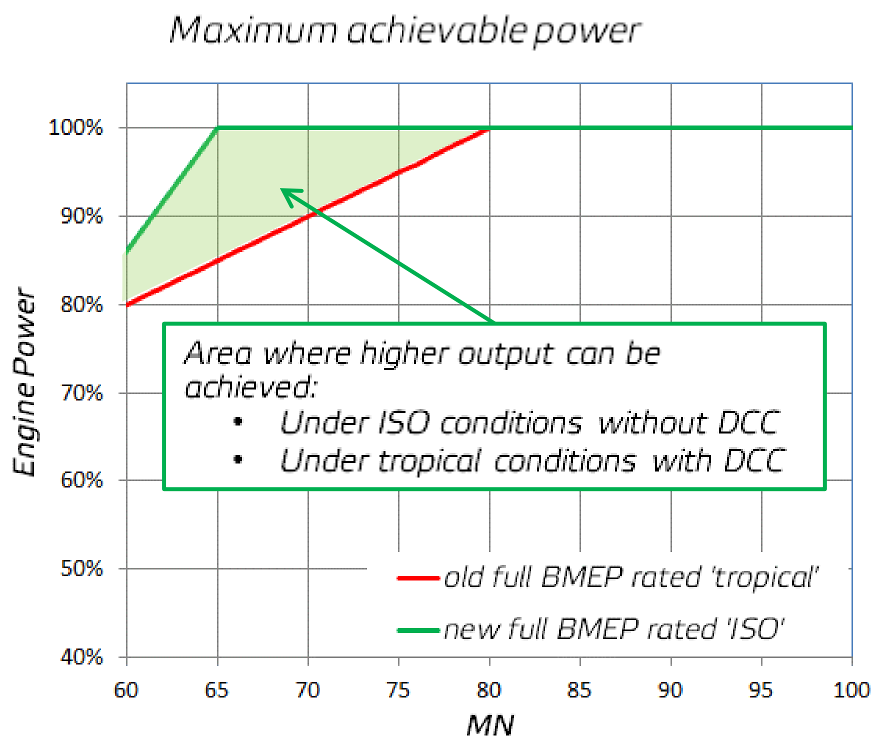


Figure 17: relationship between 2 stroke engine power and MN
Source WinGD / DCC = Dynamic Combustion Controlled

5.1 Overview of gas engine types

Table 6 and 7 below summarizes the described gas engine principles for, currently, available four and two stroke engines, respectively.

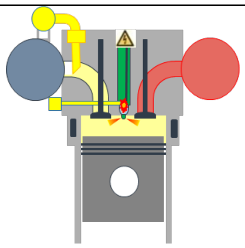
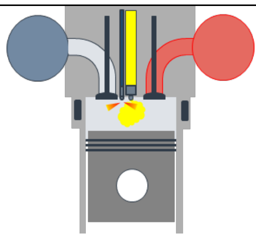
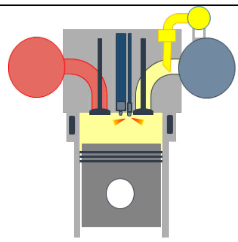
Four-stroke engines			
	Spark Ignition gas engine	**Gas Diesel engine** **(Direct Gas Injection)**	**Dual Fuel Engine**
Principle of operation	 Spark ignition (possibly in a Pre-chamber) Pre-mixed gas/air charge	 Pilot fuel ignition Direct gas injection at TDC Possibility for regular fuel, diesel, mode and mix modes.	 Pilot fuel ignition Pre-mixed gas/air charge Possibility for regular fuel, diesel mode
Fuel mixtures	100% gas (only)	Any gas – liquid fuel mixture possible from 100% diesel/HFO down to the minimum pilot amount (typically 3-5% pilot needed)	Gas mode (typically 1-3% pilot diesel/HFO needed) Gas/Liquid Fuel mixing possible Possible by single injector for pilot and regular fuel
Gas pressure	Low (<10bar)	High (>200bar)	Low (<10bar)
Advantages	100% gas mode Lower NOx Only one fuel system required Gas Fuel flexibility	No pre-ignition or knocking risk (No gas pre-mixing) Full power for any fuel mixture Low/v. low methane slip 3 fuel flexibility (Gas/Diesel/HFO)	3 fuel flexibility (Gas/Diesel/HFO) Lower NOx in gas mode
Disadvantages	Sensitive to pre-ignition No liquid fuel option Short exchange intervals of spark plugs Methane slip	Cannot run on gas alone High pressure gas system required Higher NOx than other gas engine types	Cannot run on gas alone Sensitive to pre-ignition Possible reduction of maximum power in gas mode Methane slip

Table 6 Gas engine principles for four stroke engines

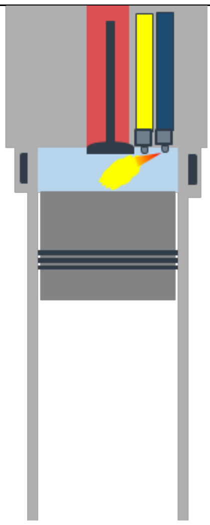
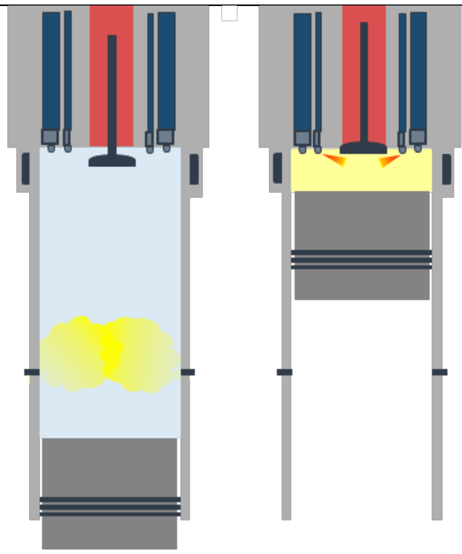
Two-stroke engines		
	Gas Diesel engine	**Dual Fuel engines**
Principle of operation	 Pilot fuel ignition Direct gas injection at TDC Possibility for regular fuel, diesel, mode and mix modes.	 Pilot fuel ignition Pre-mixed gas/air charge Possibility for regular fuel, diesel mode
Fuel mixtures	Any gas – liquid fuel mixture possible from 100% diesel/HFO down to the minimum pilot amount (typically 3-5% pilot needed)	Gas mode (typically 1% pilot diesel/HFO needed) Fuel Sharing (any mixture of gas and liquid fuel)
Gas pressure	High (>100bar)	Low (<16bar)
Advantages	No pre-ignition or knocking risk (No gas pre mixing) Full power for any fuel mixture Very low methane slip 3 fuel flexibility (Gas/Diesel/HFO) Lower Methane slip	3 fuel flexibility (Gas/Diesel/HFO) Lower NOx in gas mode, meeting IMO Tier 3 (without any additional measures) Low pressure gas system
Disadvantages	High pressure gas system Higher NOx, requiring after treatment system for IMO Tier III compliance	Sensitive to pre ignition Reduction of maximum power compared to a diesel engine to avoid knocking Higher Methane slip

Table 7 Gas engine principles for two stroke engines

5.2 Combustion Challenges

Spark Ignited (SI) and Dual Fuel (DF) combustion principles may face some combustion challenges based on fuel quality, ambient conditions, engine operation (dynamic) and engine configuration. The challenges can be divided in three different situations:

- Pre-ignition
- Misfiring
- Knocking

5.2.1 Pre-ignition

Pre-ignition needs an ignition source because the temperature in the combustion chamber before the combustion is too low to lead to any auto ignition of the gas-air mixture. The likelihood of preignition increases if the engine is operating close to the knocking limit. Several sources of ignition have been identified: the auto ignited lube oil; the hot particles originated from lube oil deposit; the local hot surface of the combustion chamber such as the electrode of spark plug. Pre-ignition generates a peak pressure antagonistic to the desired timing in the stroke and leads to engine failure when events accumulates or happen too frequently.

5.2.2 Misfiring

Misfiring means unstable or irregular combustion which can take place when approaching too lean combustion causing variation in the start of the combustion from cycle to cycle. See Figure 18. Misfiring leads to lack of power output from the cylinder. The reasons can be no fuel, no ignition, wrong fuel air mixing (too lean or too rich especially in the prechamber) or too low temperature. The consequence is variation in load or speed. Cause could also be weak ignition source, e.g. spark plug, retarded ignition, etc. Additionally, engine start at very cold ambient conditions may also cause misfiring.

5.2.3 Knocking

Knocking results from the auto ignition of the remaining unburned gas (the end gas) at the periphery of the cylinder. It is the consequence of the auto ignition of the mixture itself and does not require any ignition source. It happens because of the very high temperature of the end gas resulting of heat transfer from the burning gas nearby the cylinder wall. The knocking generates multiple post combustion peak pressure that can lead to engine failure.

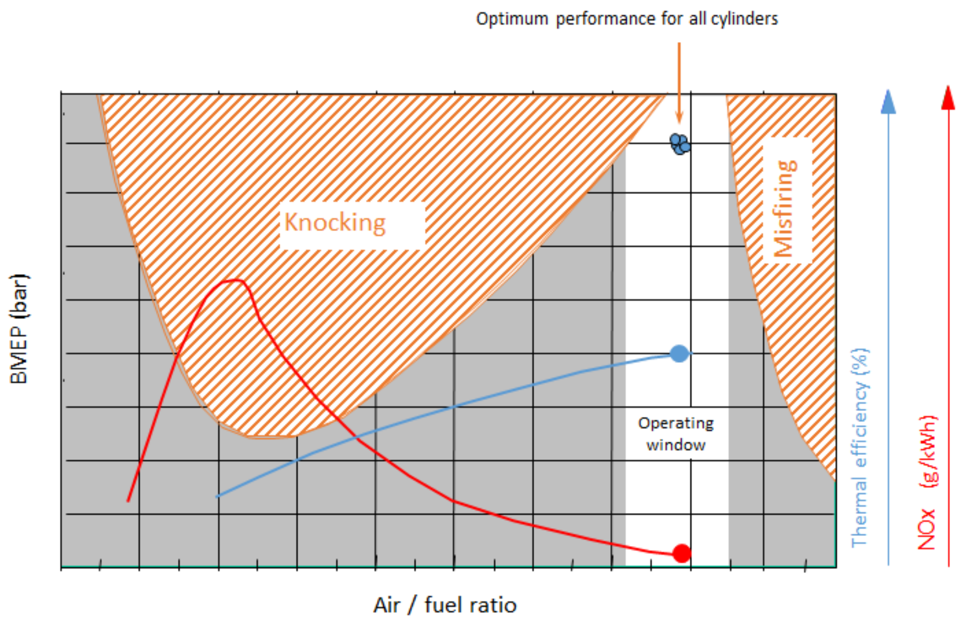


Figure 18 Schematic showing combustion challenges in Spark Ignited (SI) and Dual Fuel (DF) engines. Courtesy: Wärtsilä

5.2.4 Controlling Strategy

An example of a controlling strategy to the combustion challenges knocking is shown in Figure 19. As the Dual Fuel (DF) engine may suffer from knocking or mis-firing, if the MN (Methane Number) is too low for the desired operation. In this case the pressure in the combustion chamber and therefore the engine power must be reduced. The decision to de-rate is a balance between engine power density, efficiency, ambient conditions and MN.

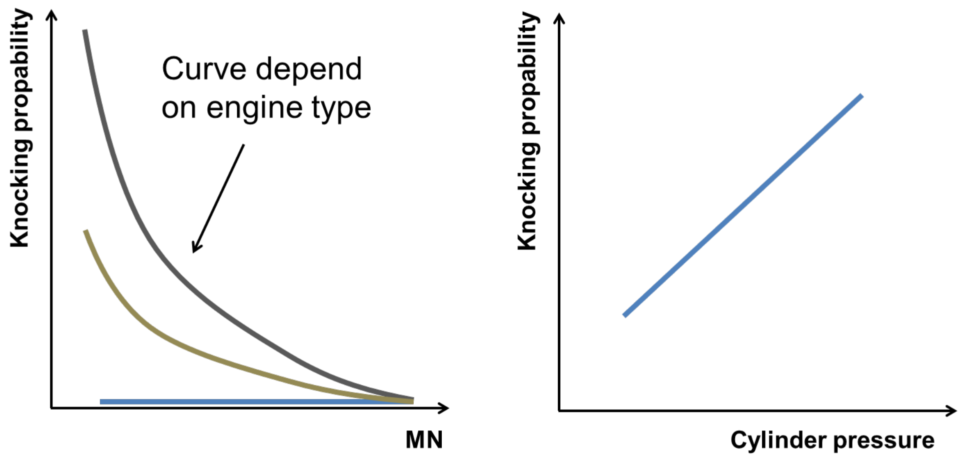


Figure 19 Relationship of cylinder pressure and Methane Number against knocking probability

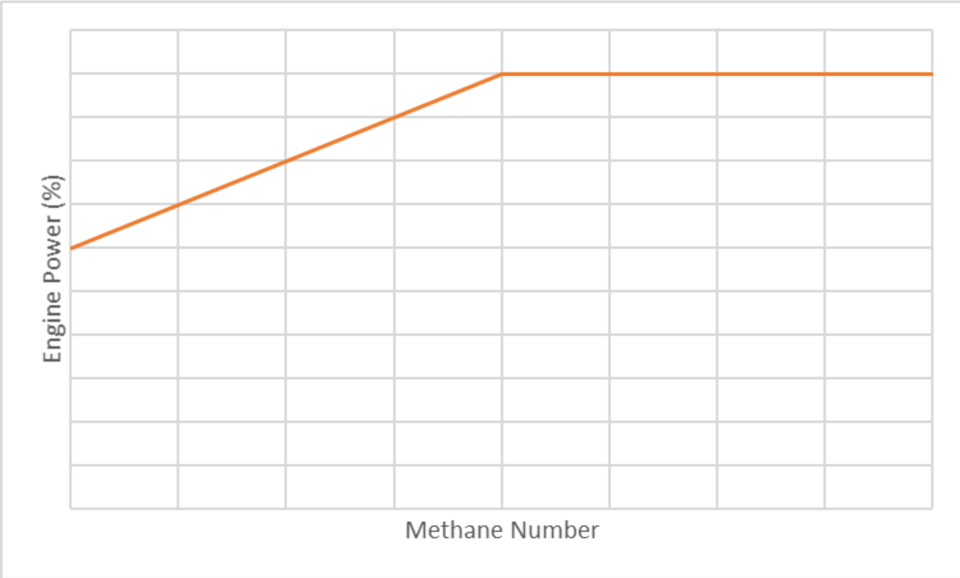


Figure 20: Relationship of engine output/de-rate against Methane Number

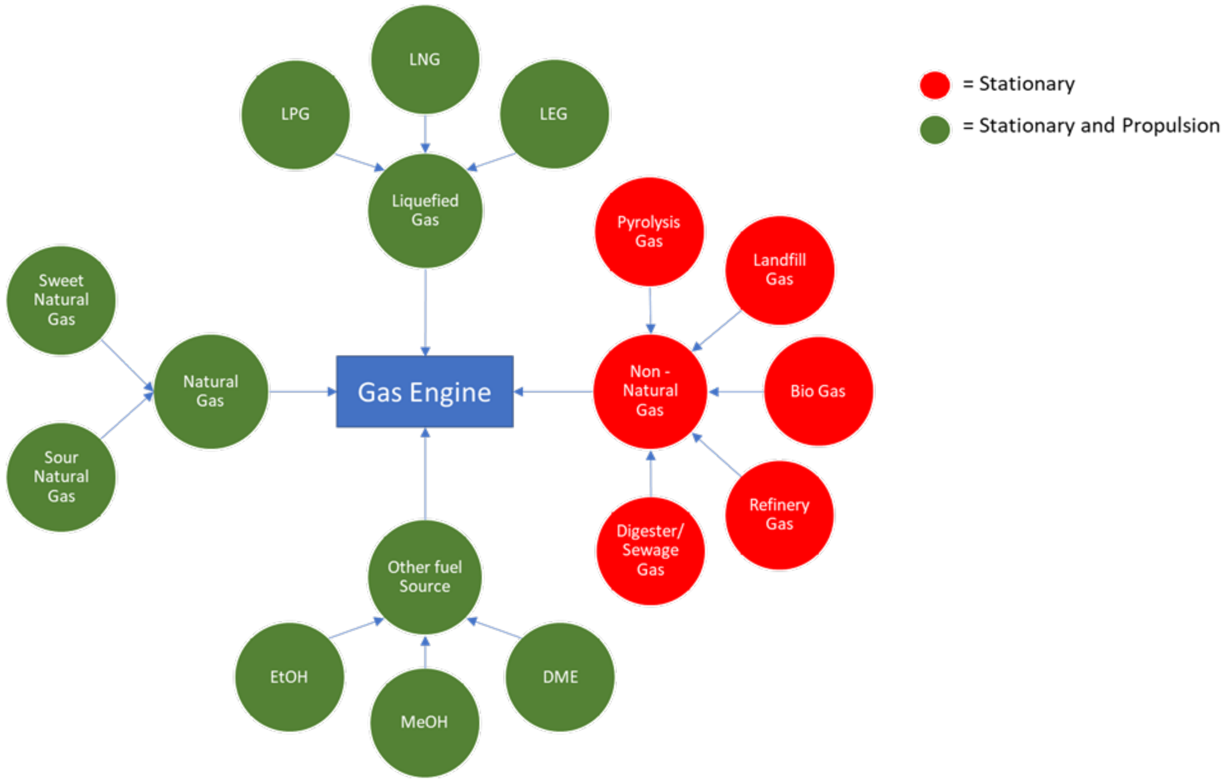
6. Appendix 2

6.1 Fuels for Gas Engines

6.1.1 Types of fuel

Fuels suitable for gas engines can be sourced from natural or non-natural gas and feedstocks.

Picture 2 gives an example of the variety of potential fuel types available and their use according to stationary and propulsion or just stationary power alone.



Picture 2: Fuel sources suitable for general use in gas engines

6.2 Natural Gas

6.2.1 Sweet and Sour Natural Gas

Oil field gases are produced by the same geological process as fossil fuel: anaerobic decay of organic matter deep under the Earth's surface. Deposits rich in oil are usually known as oil fields, and deposits rich in natural gas are usually called natural gas fields.

Sour gas is natural gas or any other gas containing significant amounts of hydrogen sulfide (H_2S). Natural gas is usually considered sour if there are more than 5.7 mg of H_2S per m^3 of natural gas, which is equivalent to approximately 4 ppm by volume [2], under standard temperature and pressure. Within oil refineries or natural gas processing plants, the removal of organosulfur compounds and hydrogen sulfide is referred to as "sweetening". The sweetened products lack the sour, foul odours of mercaptans and hydrogen sulfide.

6.3 Liquefied Gas

6.3.1 Liquid Natural Gas, LNG

LNG is liquefied natural gas, a clear, colourless, non-toxic liquid that forms when natural gas is cooled to -162ºC (-260ºF).

This shrinks the volume of the gas 600 times which results in an efficient mode of storage and transportation of natural gas.”

LNG contains mainly methane (CH_4), and in lesser amounts ethane (C_2H_6), heavier hydrocarbons and nitrogen. The composition of the LNG varies due to origin (e.g. Qatar, Australia), processing (e.g. different plants refines depending on equipment and market situation). Data on LNG compositions (Table 8) is published by the International Group of LNG Importers (GIIGNL) and The Society of International Gas Tanker and Terminal Operators (SIGTTO) among others.

LNG has low amounts of contaminants. It is in the nature of the liquification that the gas is cleaned since the different compounds in the gas are liquefying at different temperatures.

However, it does not mandate that liquid gas is completely clean, since it depends on the source of the gas and also the quality of the processing / liquification plant.

LNG Industry 2016 GIIGNL[1]	Unit	Average	Min	Max
Lower calorific value (LCV)	MJ/kg	49.4	48.7	49.8
Methane Number (MN)[2]	-	77	66	99
Methane (CH_4)	mol %	91.8	82.6	99.7
Ethane (C_2H_6)	mol %	6.0	0.1	12.6
Propane (C_3H_8)	mol %	1.5	0.0	3.6
Butane + (C_4H_{10} and higher)	mol %	0.5	0.0	1.5
Nitrogen (N_2)	mol %	0.2	0.0	0.7

Table 8 Variations in LNG composition.

The LNG Industry, GIIGNL annual report 2016 ed. MN calc. EN 16726-2015

6.3.2 Liquefied Petroleum Gas (LPG)

Liquefied petroleum gas or liquid petroleum gas (LPG or LP gas), also referred to as simply propane or butane, are flammable mixtures of hydrocarbon gases used as fuel. LPG is prepared by refining petroleum or "wet" natural gas, and is almost entirely derived from fossil fuel sources, being manufactured during the refining of petroleum (crude oil) or extracted from petroleum or natural gas streams as they emerge from the ground.

6.3.3 Liquefied Ethane gas (LEG)

Ethane is an organic chemical compound with chemical formula C_2H_6. At standard temperature and pressure, ethane is a colourless, odourless gas. Like many hydrocarbons, ethane is isolated on an industrial scale from natural gas and as a petrochemical by product of petroleum refining.

Ethane liquifies at a relatively low pressure. By storing the ethane fuel as a liquid under pressure, many more BTU's of fuel can be stored in the same volume of cylinder compared with CNG. Compared with LNG there is much less logistical and infrastructure complexity in the supply chain to get the liquid ethane fuel on-board a vessel.

Ethane has a higher volume-based energy density than methane. It is also clean burning and low in sulfur like methane.

Low speed engines operated on Ethane apply the same combustion principle as LNG operated engines.

6.3.4 Compressed natural gas (CNG)

CNG (Methane stored at high pressure) can be used in gas engines or dual fuel engines, like above mentioned LNG applications.

CNG is made by compressing natural gas (which is mainly composed of methane, CH_4), to less than 1 percent of the volume it occupies at standard atmospheric pressure. It is stored and distributed in hard containers at a pressure of 20–25 MPa (2,900–3,600 psi), usually in cylindrical or spherical shapes.

CNG could be compressed out of natural gas sources, from gas collected from landfills or wastewater treatment plants where it is known as biogas.

6.4 Non-Natural Gas

6.4.1 Refinery Gas

Refinery gas is a mixture of gases generated during refinery processes which are used to process crude oil into various petroleum products which can be traded or sold. The composition of this gas varies, depending on the composition of the crude it originates from and the processes it has been subjected to. Common components include butanes, butylenes, methane, ethane, and ethylene.

6.4.2 Digester / Sewer Gas

Digester / Sewer gas is a complex mixture of toxic and nontoxic gases produced and collected in sewage systems by the decomposition of organic household or industrial wastes, typical components of sewage. Sewer gas can be used as a power source, thus reducing the consumption of fossil fuels. The gas is pumped into a cleaning system and then used as a fuel to power a generator or combined heat and power (CHP) plant. Sewer gases may include hydrogen sulfide, ammonia, methane, carbon monoxide, sulfur dioxide, nitrogen oxides and siloxanes.

6.4.3 Landfill Gas

Landfill gas is a complex mixture of different gases, created during the anaerobic decomposition of organic substances in municipal solid waste (MSW) and commercial and industrial (C&I) wastes by the action of microorganisms, therefore potentially containing contaminants at higher levels. Hence this type of gas needs careful quality assessment before introduced into the engine for combustion."

A very special challenge is the formation of 'sand' in the combustion process if the gas contains silicates. This is typical for municipal landfills

6.4.4 Pyrolysis gas

The use of pyrolysis gas as fuel is considered as a renewable fuel. The underlying principle is the thermal and anaerobic decomposition of biomass from various sources (*e.g.* agricultural wastes, wood residues and municipal waste) into liquids, solids and gases. The composition of the produced syngas is highly dependent on the used biomass source. One common issue of this type of gas is the higher number of contaminants, such as hydrogen, tars and a high level of moisture, which require technical modifications of the engine and result in a reduced output.

6.4.5 Biogas

Biogas typically refers to a mixture of different gases produced by the breakdown of organic matter in the absence of oxygen. Biogas can be produced from raw materials such as agricultural waste, manure, municipal waste, plant material, sewage, green waste or food waste (anaerobic digestion with anaerobic bacteria, which digest material inside a closed system, or fermentation of biodegradable materials). It is a renewable energy source and, in many cases, exerts a very small carbon footprint.

Biogas consists primarily of methane (CH_4) and carbon dioxide (CO_2) and may have small amounts of hydrogen sulfide (H_2S), moisture and siloxanes. The gases methane, hydrogen, and carbon monoxide (CO) can be combusted or oxidized with oxygen.

Biogas requires dual-fuel technology for the marine engine and extra storage facilities, either as pressure tanks or cryogenic tanks for LBG. Biogas is usually produced from inland biowaste and thus presents challenges in terms of costs to transport LBG to marine vessels.

6.5 Potential fuels and admixtures

6.5.1 DME

Dimethyl ether (typically abbreviated as DME), also known as methoxymethane, wood ether, dimethyl oxide or methyl ether, is the simplest ether. It is a colourless, slightly narcotic, non-toxic, highly flammable gas at ambient conditions, but can be handled as a liquid when lightly pressurized. Dimethyl ether (DME) can be produced by catalytic dehydration of methanol, or from syngas. The properties of DME are similar to those of Liquefied Petroleum Gas (LPG). Above -25°C or below 5 bar, DME is a gas. Hence its use as a transport fuel is similar to that of LPG. DME is degradable in the atmosphere. [8]

6.5.2 Natural gas Hydrogen mixtures

The admixing of hydrogen to natural gas pipeline networks is considered as a sustainable and cost-effective method for future application in e.g. power generation in order to meet global environmental legislations. It is currently widely investigated and commonly accepted that up to 10 - 25 mol% of hydrogen can be applied without issues (such as an increase of carbon monoxide emission, decreasing the flame stability and cold ignition problems). If the concentration of the hydrogen gas is higher it could impact safety and affect the integrity of the piping material durability. Because of the involved risks in hydrogen bunkering and storage onboard, application of hydrogen admixtures in the shipping industry is under investigation.

7. Appendix 3

7.1 Gas Quality

Gas quality has an impact on the performance of gas engines. The composition is mainly determined by the origin of the source and refining process. The variation in components has an impact on the suitability and quality of the specific gas as fuel for combustion engines. In general, these fuels are composed of short hydrocarbons (methane, ethane, propane, butane) carbon mono- and dioxide, hydrogen, hydrogen sulfide, nitrogen and oxygen.

7.2 Causes for variations in gas compositions for LNG tanks

Another important difference in LNG quality is caused by the type of extraction. The natural boil-off gas type has a high methane content and is obtained by taking off the gas on top of the liquid. Alternatively, the forced boil-off gas is extracted from the bottom part of the tank and evaporated separately. Generally, this gas contains a higher concentration of heavy hydrocarbons, thereby lowering the potential knocking resistance. (ref: CIMAC position paper, December 2008, Information about the use of LNG as Engine fuel). This is only relevant for engine designs with knocking challenges (see section 3.11 and 5.8).

Gas engines on many LNG-carriers can be supplied with gas either as vaporised LNG or as BOG from the cargo tanks, or in a combination of the two. The composition of these two is not necessarily the same and therefore the composition of the gas delivered to the engine can change rapidly. The reasons why the compositions of the LNG and the gas are changing are given below:

LNG contains mainly methane (CH_4), and in lesser amounts ethane (C_2H_6), heavier hydrocarbons and nitrogen. The composition of the LNG varies due to origin, processing and terminals.

Ageing and BOG: LNG in the ships' tanks will change composition and properties over time. This is due to the unavoidable heat-influx from the surroundings, which will cause vaporisation of lighter compounds. Nitrogen has the lowest boiling point and will evaporate first, followed by methane and then the heavier hydrocarbons. This process is called ageing and the gas produced is referred to as boil-off gas (BOG).

BOG contains a higher amount of nitrogen compared to the LNG in the tank. The heating value of BOG containing a lot of nitrogen will be significantly lower than for methane.

The remaining LNG in the tank will have an increased percentage of ethane and heavier hydrocarbons.

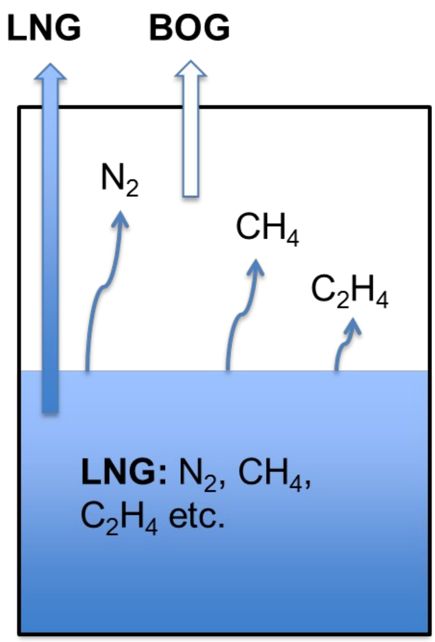


Figure 21 Schematic of extraction of LNG vs BOG (Boil Off Gas). The gas composition and thereby the gas quality of the two methods will be different.

Spraying LNG inside the tanks in order to keep these cooled during ballast voyage will force heavier hydrocarbons to evaporate more than if evaporating naturally. The composition of the BOG is then changed.

Stratification: LNG of different densities can form separate layers within the storage tanks. The heavier LNG containing higher hydrocarbons is in the bottom of the tank and the lighter on top. This layering is referred to as stratification. Pumping LNG from the bottom of the tanks results in higher concentration of heavier hydrocarbons being discharged.

7.3 Contamination and emissions

Contaminations in the gas have a direct influence on the performance of the engine. Low quality gas can result in sub-optimal performance, higher emissions or even engine damage. They can affect engine wear, oil degradation, and increased emissions or fuel consumption.

Contamination of the fuel gas with sulfuric or halogenated compounds in the presence of water can result in the formation of corrosive components, such as hydrogen sulfide (H_2S), hydrochloric acid (HCl) and hydro fluoric acid (HF) and is dependent on the source of the gas. These products can give corrosive wear on piston rings and cylinder liners, reduce lubricant lifetime and after-treatment components (*e.g.* exhaust oxygen sensors, catalytic converters and heat recovery systems). In addition, ammonia found in sewer gas can lead to nitrogen oxide (NOx) emissions, whereas the presence of sulfur in gas results in the emission of sulfur dioxide. Sulfur can be found in some natural gases or its admixtures (such as hydrogen and biomethane) as a natural component, but also may be added as odorant for safety reasons. (ref: SEPA, Environment Agency, Guidance on gas treatment technologies for landfill gas engines).

The analytical determination of the natural gas composition is most frequently obtained by gas chromatography. The physical properties that are used as gas quality parameters (*e.g.* heating value, Wobbe Index, relative density etc.) can be further calculated using the outcome of these analyses. The general compositions of the fuels mentioned above are shown in Table 9. Various techniques have been developed for determining other parameters but there is no clear single practice, thereby further hampering European standardization. (ref: CEN/TC 234/WG 11).

Composition (%)										
Fuel	Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Methane (CH_4)	Ethane (C_2H_6)	Propane (C_3-H_8)	Butane (C_4H_{10})	Hydrogen (H_2)	Hydrogen Sulfide (H_2S)	Oxygen (O_2)	Nitrogen (N_2)
Digester Gas	30		64				0.7	0.8		2.0
Landfill Gas	47	0.1	47				0.1	0.01	0.8	3.7
Natural Gas*/LNG	0 - 0.8	0 - 0.45	82 - 93	0 - 15.8			0-1.8	0 - 0.18	0 - 0.35	0.5 - 8.4
Ethane	0 – 4.4		<2	94 – 98	<2					<0.1
Propane				2.0 - 2.2	73 - 97	0.5 - 0.8				

Table 9: compiles the most important gases used in gas engines together with typical data relevant for the application of gas engine lubricants.

*Hydrogen gas can be added as admixture to natural gas

7.4 Heating Value and Wobbe Index

The most important parameters for gas quality are the heating value and the Wobbe Index. The heating value tells how much energy is stored in the gas. More specific, it can be differentiated in the higher (upper or gross) and lower (net) heating value (HHV and LHV, resp.) and is expressed in mega joules per kg (MJ kg^{-1}) or kilojoules per mole(kJ mol^{-1}) . The higher heating value is the amount of heat produced by the complete combustion of a unit quantity of fuel. Subtraction of the amount of heat produced by water vaporization during combustion gives the lower heating value (LHV).

7.4.1 Wobbe Index

The Wobbe Index (WI) is like the heating value a measure of the energy storage in the gas. In contrast to the heating value, the Wobbe Index is corrected with the square root of the specific gravity of the gas to give the heating value at the orifice where the gas is burned and expressed in mega joules per standard cubic meter (MJ m^{-3}). The Wobbe Index gives an indication of the interchangeability of different gases. A combination of these two parameters gives a good indication of the gas quality.

7.4.2 Methane Number

Another important method to determine the gas quality is the Methane Number (MN). This calculated number gives an indication of the knocking tendency of a fuel. Please note, that Methane Number (MN) is not the same as methane content (mol%, vol% or mass%) of a gas. The MN of LNG varies and as per 2016 data, 62% of the LNG exports exhibited MN of less than 75 (for example as calculated by MWM method).

Higher MN allows higher compression ratios thus engines with optimized efficiency. A lower MN indicates a higher risk of knocking for some engine types. In this case, fuel self-ignites in the cylinder before it is ignited by the flame, which can result in engine damage. To avoid knocking, engine operation has to be adjusted to lower efficiency and performance levels in dual fuel engines (not applicable for engines using gas diesel principle). (Ref: CIMAC position paper, July 2015, Impact of Gas quality on gas engine performance).

Country	LNG Export (MTPA)	Market share (%)	CH_4 (mol%)	LCV (MJ/kg)	MN (-)
Qatar	77.8	31.8	90.9	49.3	74
Australia	29.4	12.0	87.5	49.3	68-71
Malaysia	25	10.2	91.7	49.3	73
Nigeria	20.4	8.3	91.7	49.5	75

Table 10: LNG Exports and market share by country in million ton per annum (MTPA). Ref.:The LNG Industry, GIIGNL annual report 2016 ed and IGU World Gas LNG Report – 2016 Edition

7.4.3 Calculation of Methane number

With varying gas quality (expressed in the Methane Number, MN) the knock behaviour for the engine may change considerably - giving abnormal combustion and knocking. To avoid this, modern engines therefore employ knock sensors that adjust the ignition timing and air/fuel ratio.

The actual – at the time of writing this CIMAC recommendation - agreed international standard to calculate methane number is EN 16726. This method is referred to as the “MWM - method”.

However, development is ongoing, ASTM has for example modified the algorithm to satisfy their needs. ISO/TC 193/WG 8 (“Knock Resistance”) is evaluating a number of methods, including the MWM method and the PKI Methane Number, for their use as a standard, based on transparent criteria for accuracy and ease of implementation. ISO/TC 28/SC 4/WG 17 (“LNG as a Marine Fuel”) is also considering different methods to use as a Methane Number standard for this arena.

Other methodologies are - or have been - applied as well. In this context, the so-called “AVL-method” has been widely in use but has not become an official standard. The company AVL has not made their method publicly available which is the reason why no clear references in standards or descriptions in the public space are found.

Older and more or less outdated standards are as follows:

- ISO 15403-1:2006. *Natural gas – Natural gas for use as a compressed fuel for vehicles - Part 1: Designation of the quality*.
- ISO/TR 22302:2014, *Natural Gas – Calculation of methane number*
- DIN 51624:2008-02, *Kraftstoffe für Kraftfahrzeuge - Erdgas - Anforderungen und Prüfverfahren*, Berlin, Feb. 2008. (*Automotive fuels - Compressed natural gas - Requirements and test methods*).

In ISO 15403-1 and ISO/TR 22302, two methods (GRI calculation ones) are described, in an *annex for informative purpose in the first one,* and a reference to the existence of AVL method is done but stating that it is a proprietary and confidential method.[1]

7.5 Gas quality per type

As mentioned before, a variety of parameters have been selected to determine quality of the gas (Table 11). These parameters are currently used within the existing European specifications.

Gas type	**Main Components**	**Heating Value, lower [MJ/Nm³]**	**Wobbe Index [-]**	**Methane Number [-]**	**Harmful Components**
Natural Gas LNG	Methane, Ethane	36 - 40 25	48 55	70 - 100 70 - 97	H_2S
LPG	Propane, Butane	89 - 116	75	32 - 10	
Oil Field Gas	Methane	36 - 89	60	40 - 100	H_2S
Sweet & sour	Eth. Prop. Butane				
Refinery Gas	Prop., Butane	89 - 116	75	32 - 10	H_2S
Digester Gas	Methane, CO_2, N_2	21	25	100 -140	H_2S, CHC *),
Landfill Gas	Methane, CO_2, N_2	16 - 20	15	160	dust, H_2S, CHC*), Halides
Bio Gas	Methane, CO_2, N_2	21	20	140	H_2S, CHC*)

Table 11: Gas quality per type.

*) CHC = chlorinated hydrocarbons.

Some gas types may be susceptible to changes in gas composition over time and during use. Due to changes in density, boil off rates of different components.

[1] Reference to 2015 GIIGNL Position Paper: “Position paper on the impact of including methane number in natural gas regulation”

Gas Quality Parameters	
Wobbe Index (WI)	hydrogen sulfide (H_2S)
calorific value (CV)	Mercaptans / Thiols (RSH)
density & relative density (RD)	Oxygen (O_2)
sooting Index (SI)	nitrogen (N_2)
incomplete combustion factor (ICF)	carbon dioxide (CO_2)
hydrocarbon dewpoint (HCDP)	halogens
water dewpoint (WDP)	ammonia (NH_3)
total sulfur (S)	impurities
carbonyl sulfide (COS)	particulates / solids / liquids
methane / methane number (MN)	odour

Table 12: Gas quality parameters used for European Standardisation. ref: CEN/TC 234/WG 11

Due to the presence of fluctuating concentrations of higher hydrocarbons in natural gas, an imbalance between the MN and WI is observed. Even though a high WI (>53 MJ/m^3) ensures a low MN (<70), a low WI does not mean a high MN due to the presence of an increased concentration of higher hydrocarbons. Similar results are found for admixtures of hydrogen. As such, a minimal MN is important to maintain an acceptable gas quality.

7.6 Examples

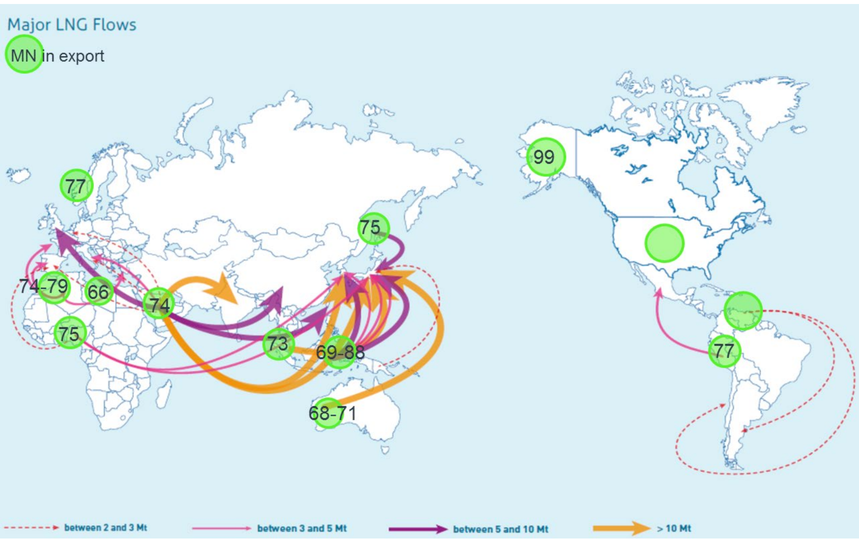


Figure 22 The average composition is chosen as being representative among compositions reported by the different receiving terminals on origin gas: GIIGNL 2015 Annual Report. MN calculated by EN 16726-2015

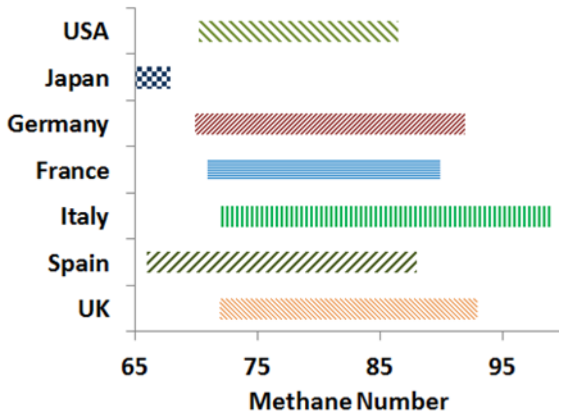


Figure 23 Quality range of pipeline gas from various countries

The European Association for the Streamlining of Energy Exchange (EASEEgas) has proposed a wide range European standardized Wobbe Index (Figure. 23, red bar). Interestingly, the national Wobbe Index ranges have historically been much narrower. The variation per location in each country is even narrower than the national range.

This relatively narrow local range of gas quality permits engine OEMs to optimize the engine performance to this specific location. A broad range of the allowed Wobbe Index, as proposed by AESEEgas/CEN, would increase the operating window of the engines. This may cause unstable engine operation, fluctuating exhaust emissions, cylinder peak pressure and knocking. Moreover, to maintain high performance levels and low emission operating parameters should be as narrow as possible. (ref: EUROMOT position paper, 4 April 2012, Methane number as a parameter for gas quality specifications.)

In addition, the AESEEgas proposed a limit for the total sulfur emission of 30 mg/m^3. This exceeds the concentration that is typically observed by about 10 times because less than 5 mg/m^3 is mostly seen today. This increase may not only impact catalyst performance but might also affect the cold corrosion in engines which will thus have to be operated at lower efficiency. Therefore, the EUROMOT recommends a lower total sulfur content in natural gas of 5 mg/m^3. (ref: EUROMOT position paper, 4 April 2012, Total sulfur levels in natural gas with special consideration of IC Engines.

8. Appendix 4

8.1 Wear Mechanisms

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

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

8.2 Abrasive Wear

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

8.3 Adhesive Wear

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

When the micro-welding (micro-seizures) is broken, the surfaces are roughened, and they may continue to penetrate the oil film during the contact. When micro-seizures are observed, it is a common practice to increase lube oil feed rate and reduce the pressure between the mating surfaces (reducing engine load). If not treated, the wear may evolve into macro-seizures (scuffing), causing momentarily high wear of the mating parts. If scuffing has occurred in the combustion chamber between piston ring and liner, the components must be exchanged or machined to remove the damaged layers.

8.4 Corrosive Wear (Cold Corrosion)

Corrosive wear occurs when there is a combination of a wear situation (abrasive or adhesive) and a corrosive environment. The rate of material loss can be very high; much higher than the sum of the individual contribution of wear and corrosion. This is because loose corrosion products are easily removed by wear to continually reveal fresh metal beneath, which in turn can corrode quickly. Likewise, stable oxide films that would normally limit corrosion (in the absence of wear) are instantly worn away. Corrosive wear may be found on the cylinder liner and piston ring running surface and is commonly referred to as “cold corrosion”. More information could be found in CIMAC cold corrosion guideline [2].

8.5 Analysis Methods

Different analysis methods can provide different results and require different interpretations.
The chart displays various Fe detection methods efficiency (vertical axis), and size of particles best measured with the corresponding Fe detection method.

- Inductively Coupled Plasma (ICP) or Atomic Absorption, can only measure element concentrations if particle sizes do not exceed 5 to 10 µm (microns) and without acid digestion prior to detection.
- X-Ray fluorescence is a technique used to determine concentrations of elements in solid, powdered and liquid samples providing they are introduced to the spectrometer in a homogeneous and reproducible form. XRF is primarily used for semi-quantitative scans to provide an insight into the elemental content.
- Analytical Ferrography is able to monitor magnetic particles from sub-micron to larger in size, covering normal, marginal and critical wear regimes.
- Automatic particle counting devices use light scatter where particles passing through a measuring cell obscure a light beam which in turn affects the reading.
- Chip detectors allow visual / microscopic inspection of ferromagnetic iron particles collected on a magnetic cartridge.
- Magnetic induction analysis provides a relative measurement of the Iron content in the oil using the “magnetic flux distortion” caused by a ferromagnetic samples. Measurement range is typically >5 µm (microns).

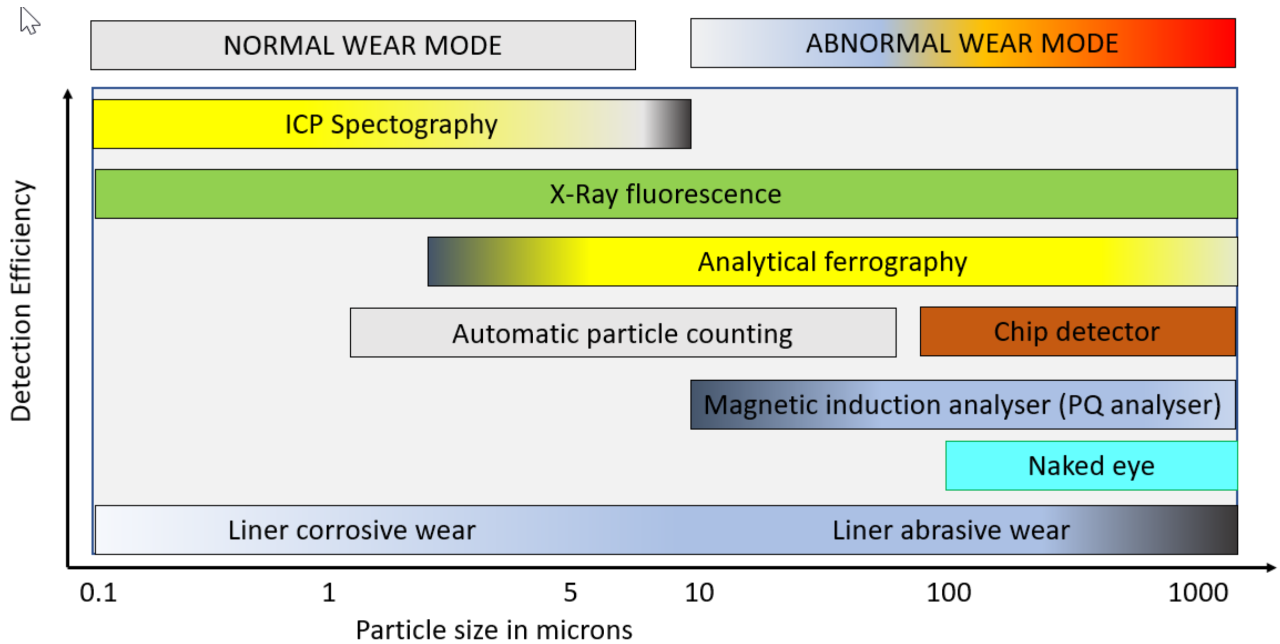


Figure 24: Various Fe detection methods

9. Glossary of terms

Absorption: Variation of peaks at specific wave lengths in FTIR (DIR), indicating deterioration, oxidation, nitration, reduction in additive concentration. See also "DIR" and "FTIR".

Air/Fuel ratio: Ratio of air mass to fuel mass present in cylinder at start of combustion.

Biogas: Gases derived from microbial or biochemical decomposition processes. Main components: methane, carbon dioxide, often H_2S.

CARB: California Air Resources Board.

CBM: Coal Bed Methane

CHP: Combined Heat & Power. Term for all engines generating heat and power (co- generation)

CNG: Compressed natural gas: methane stored at high pressure

Detonation: Uncontrolled ignition/combustion with very high flame speed. Severe pressure waves with hard noise known as knocking. High risk of mechanical/thermal damage.

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".

Dry Gas: Natural gas containing no hydrocarbons heavier than butane and pentane. Can contain up to 99 % methane.

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.

FPSO: Floating Production Storage and offloading

FTIR: Fourier Transform Infrared Spectrometry. Digital generation of spectral information.

HCCI: Homogeneous charge compression ignition

H_2S: Hydrogen Sulfide, acidic, poisonous, flammable gas found in bio and natural gases. Disagreeable odour. Robust alkalinity of gas engine lubricant required when present.

ICBE: International Carbon Bank & Exchange

ICP-AES: Inductively Coupled Plasma – Atomic Emission Spectroscopy. An Analytical method to determine the concentration of certain elements in a sample

ICP-MS: Inductively Coupled Plasma – Mass Spectroscopy. A more sensitive method than AES to determine the concentration of certain elements in a sample based on atomic mass.

Knocking: Hard metallic noise heard when gas engine fires in uncontrolled mode due to poor knock rating of gas. See "Methane Number" and "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.

Lean Burn Engine: Gas engines running on air excess, except in pre-chambers where gas is ignited. See also "Lambda Value" and "Stoichiometric Condition".

LEG: Liquefied Ethane Gas / Liquefied Energy Gas (natural or petroleum)

LHV: Lower Heating Value

LPG: Liquefied Petroleum Gas. Consists mainly of propane or butane or mixtures thereof. Liquid at ambient temperature when kept under pressure.

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.

Misfiring: Unstable or irregular combustion taking place when approaching too lean combustion causing variation in the start of combustion from cycle to cycle.

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).

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.

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.

PM: Particulate Matter

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.

Preignition: The ignition of fuel in an internal combustion engine taking place before the spark passes through the fuel, resulting from the presence of hot spots in the cylinder.

Selective Catalytic Reduction (SCR): Exhaust gas treatment system with urea or ammonia injected into exhaust gas to reduce NO_x. Catalyst poisoned by sulfur.

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.

Silica: Dust particles from landfill gas appearing in the lubricant. Very abrasive, resulting in excessive wear.

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.

Sweet gas: Natural gas containing less than 10 ppm H_2S.

Three Way Catalyst: Generally used in stoichiometric engines to convert harmful combustion components to H_2O, CO_2 and N_2.

Valve Recession: Excessive wear of valve seat and face caused by combined effects of metal abrasion, high temperature corrosion, functional sliding and adhesion.

Valve Guttering and Torching: Damage to exhaust valves due to high temperature corrosion.

Wet Gas: Natural Gas containing heavier hydrocarbons like ethane, propane, butane plus small quantities of hydrocarbons liquid at ambient temperatures.

Wobbe Index: Ratio of a gas's calorific value to the square root of its specific gravity. Indicates thermal input provided by gas at given temperature.

ZDTP/ZDDP: Zinc DiThio Phosphate or Zinc Dialkyl Dithio Phosphate. Lubricant additive used to fight oil oxidation and wear.

Zeppelin: Big gas container carrying militant non-smokers.

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Imprint

CIMAC e. V.

Lyoner Strasse 18

60528 Frankfurt

Germany

President: Prof. Dr. Donghan, Jin

Secretary General: Peter Müller-Baum

Phone +49 69 6603-1567

E-mail: info@cimac.com

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