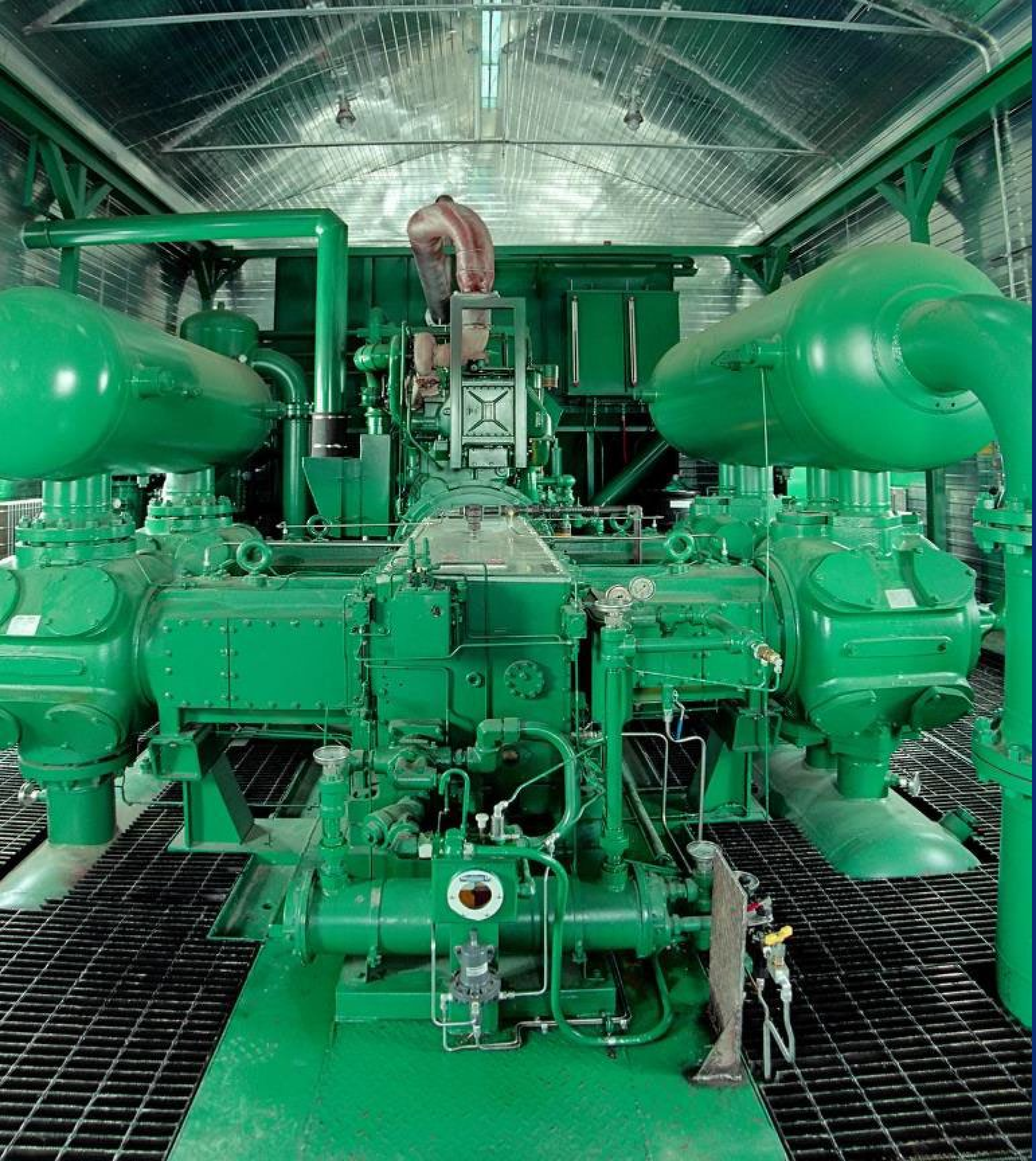


Natural Gas Engine Operational Considerations

Revised October 2022

the human Chevron energy company™

Table of Contents

Objective

This educational deck is to provide ancillary information to help in the sales process of natural gas engine and reciprocating compressor frame opportunities.

Types of natural gas

Methane

In on-road transportation vehicles, methane is mostly used in compressed form, with compressed natural gas (CNG) being the most common, along with liquefied natural gas (LNG).

Biogas

Biogas is produced by anaerobic decomposition of animal and plant material, manure, sewage sludge, and organic waste.

Biogas contains approximately 25-65 percent methane.

Landfill

Landfill gas contains approximately 40-60 percent methane and contains a considerable number of contaminants, like biogas.

It may also contain siloxanes, and compounds of chlorine and fluorine that is derived from household and industrial wastes that can present challenges in engines burning the gas.

Well Head

Well head gas is produced at the well head and may contain hydrogen sulfide (H2S).

Gas that contains a moderate amount of H2S is often referred to as sour gas.

Engines that burn biogas or landfill gas require engines oils that will protect the engine from corrosive acids formed from contaminants in the fuel. The base number (BN) of engine oils designed for biogas and landfill gas is higher than gas engine oils designed for engines that burn natural gas.

Operational Attributes of Engines

Brake Mean Effective Pressure (BMEP) Engine

What is BMEP?

BMEP stands for Brake Mean Effective Pressure, it measures pressures during combustion and is an indication of how highly stressed the engine is.

- BMEP correlates closely to engine output relative to engine displacement
- BMEP is the ‘average’ cylinder pressure on the piston during the power stroke

BMEP of stationary gas engines has increased resulting in an increased load on modern engines.

High BMEP

A high BMEP value results in

- Reduced capital costs for a given KW output in kilowatt hours ($/kW)
- Improved efficiency
- Increased power output of a given engine
- Higher engine temperatures and stresses

BMEP Increase

BMEP is increased by

- Increasing compression ratio
- Turbocharging and/or supercharging to force more air and fuel in
- Improving after-cooling (colder, more dense air)
- Improved volumetric efficiency, i.e. reducing air flow losses

The Effects of Engine Load at De-rating from Caterpillar LEXE08320-00

- At low load (less than 50% rated load), gas engines may not have enough cylinder pressure to maintain oil control in the cylinder.
  - This allows the oil to work its way past the rings into the combustion chambers, leading to increased ash deposits.
  - These deposits change the compression ratio, which can reduce the detonation margin. If the detonation margin is reduced sufficiently, detonation can occur. Detonation will decrease the life of the engine, damage components and lead to unplanned shutdowns or failures.
- Caterpillar recommends not loading natural gas generator sets in any application below 50 percent of their rated load for any duration, and the ideal range for operation is at 70 percent load and above.
- Extended operation of gas generator sets at low loads can lead to deposit build-up on the valves, spark plugs, and behind the piston rings. In extreme cases deposits in the cylinder can develop, causing cylinder liner polishing.
- Additionally, natural gas engines run rich at low loads to maintain combustion and ensure that the engine does not misfire.
  - A rich air-to-fuel ratio causes the engine to deviate from the expected emissions levels, potentially leading to non-compliance with required emissions regulations.
  - Also, a rich air-to-fuel ratio increases temperatures and can accelerate component wear.

The effects of engine load at de-rating from Caterpillar LEXE08320-00

Low-load operation will have an impact on all after-treatment components, causing emissions targets to be missed and ultimately leading to engine shutdown.

Time limits for low load operation of natural gas generator sets

Engine Load	Time Limit
0 to 30 percent	30 minutes
31 to 50 percent	2 hours
51 to 100 percent	Continuous[1]

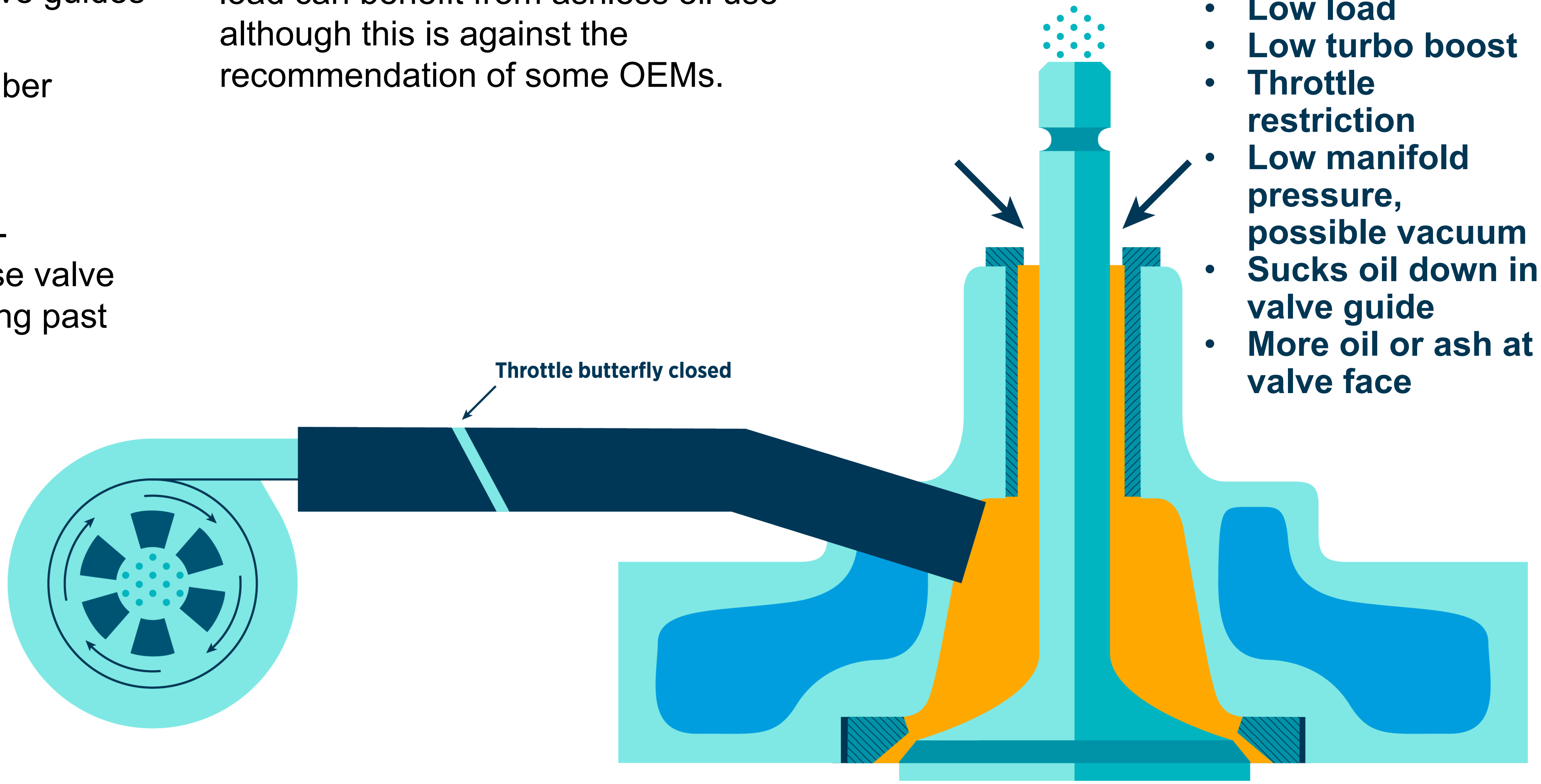
[1]For continuous operation, the manifold air pressure must be greater than the atmospheric pressure.

Additional considerations of low load on engines

Ashless oil

- Low intake manifold pressure/vacuum may pull additional oil past valve guides and piston rings resulting in
  - Increased combustion chamber deposits
  - Increased oil consumption
- Small naturally aspirated (non-turbocharged) engines may use valve guide seals to reduce oil coming past the valve guide

- Some small engines running at reduced load can benefit from ashless oil use although this is against the recommendation of some OEMs.

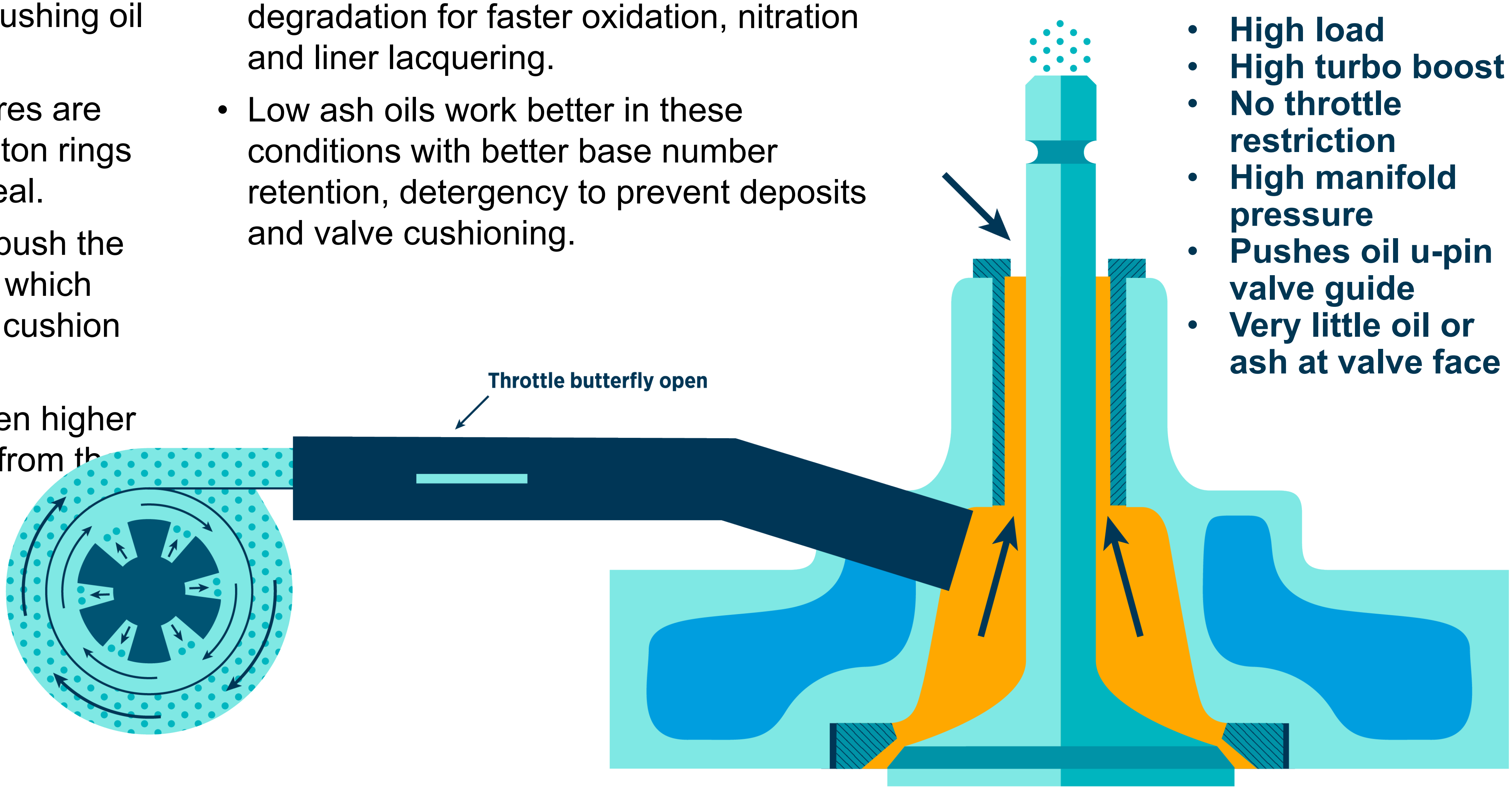


- Low load
- Low turbo boost
- Throttle restriction
- Low manifold pressure, possible vacuum
- Sucks oil down in valve guide
- More oil or ash at valve face

Additional considerations of high load on engines

Low ash oil

- When operated at high loads the intake manifold pressure is positive pushing oil up the guide.
- Intake and combustion pressures are also higher helping to push piston rings against the liner for a tighter seal.
- Higher combustion pressures push the valves harder against the seat which can accelerate wear if the ash cushion is absent.
- Engine temperature is also often higher which helps flash off moisture from th oil sump.
- Elevated temperatures may increase oil degradation for faster oxidation, nitration and liner lacquering.
- Low ash oils work better in these conditions with better base number retention, detergency to prevent deposits and valve cushioning.



Caterpillar
Gas Engines

Caterpillar markets CAT, MAK, MWM and Perkins brands of gas engines

CAT

The cornerstone of the Caterpillar brand portfolio including G3304 through G3616 engine series produced primarily in the USA.

Photo: 767 KW Caterpillar #G3516 SITA, Natural Gas generator set, 4160 Volts for Sale | Surplus Record

MAK

Used in medium-speed marine applications.

Offers main propulsion engines from 1,020 kW to 16,000 kW.

As of 2022, currently not producing engines.

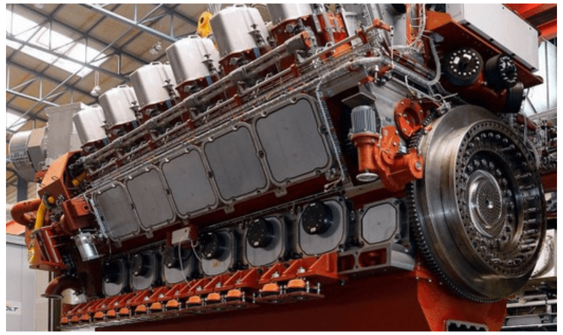


Photo: Caterpillar Delivers First MaK M 46 DF Dual Fuel Marine Engine (gcaptain.com)

MWM

Produced in Mannheim Germany, these engines operate on a wide range of gaseous fuels with power outputs between 400 and 4,300 kW.

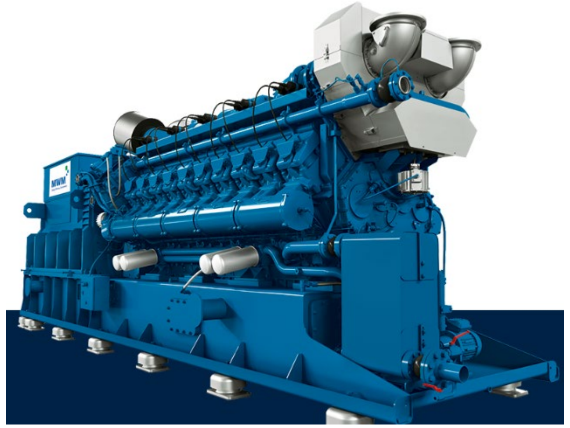


Photo: Gas Engines / Gensets - MWM

Perkins

Global supplier of gas and diesel engines in the 4-2000 kW / 5-2800 hp range.

Largest portion of sales is in the European market.

Photo still: (10) 1 MW Perkins 4016-61 TRS Natural Gas Genset- Kes Energy - YouTube

INNIO Gas Engines

INNIO markets Jenbacher and Waukesha brands of gas engines

Jenbacher

Equipped with a power range of 250 kW to 10 MW with fuel flexibility to run either on natural gas or a variety of other gases including hydrogen.

More than 15,500 operate in more than 100 countries.

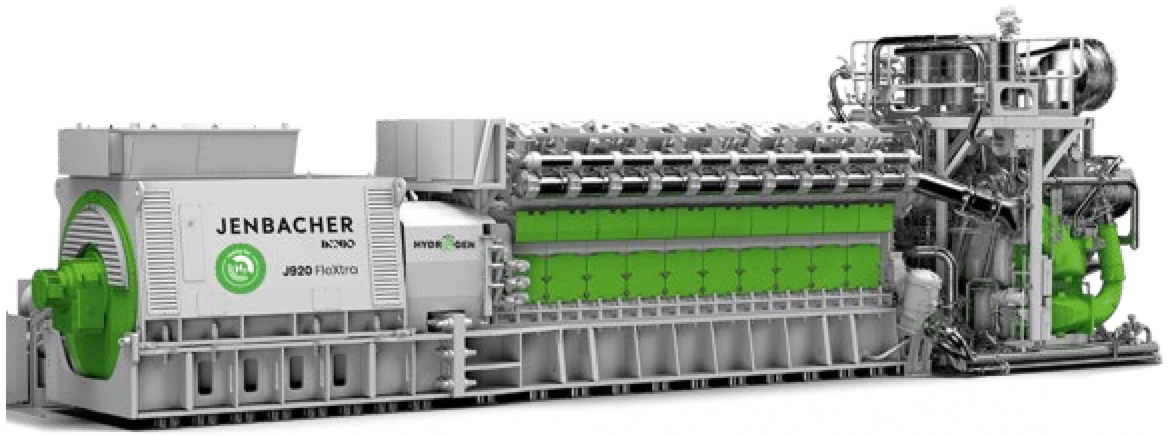


Photo: INNIO's Jenbacher and Waukesha gas engines - INNIO

Waukesha

Designed for both rich-burn (stoichiometric) and lean-burn configurations.

Capable of operating on a wide range of fuels, from 400 to 2,350 BTU / sq ft.

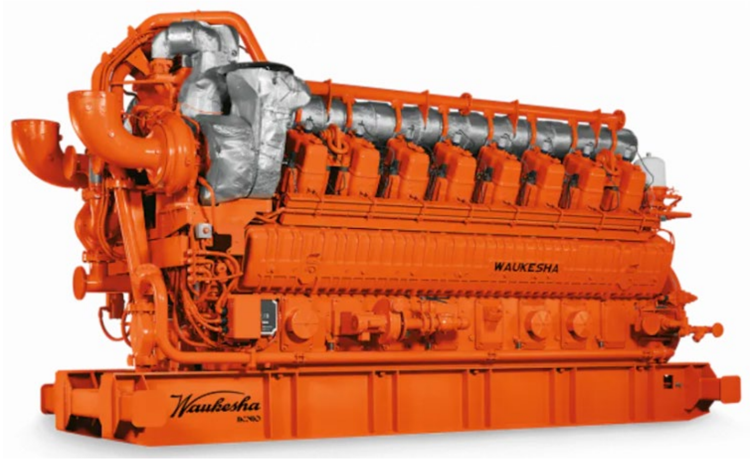


Photo: Jenbacher and Waukesha Gas Engines | INNIO

Cooper Engines

Cooper markets Ajax and Superior brands of gas engines

Ajax

Two-stroke cycle engine and integrated reciprocating compressor frame

Rated for 22 to 845 hp (16 to 630 kW)

Photo: Ajax Engines | New, Refurbished, Remanufactured & Rebuilt Ajax Engines | Production Engine & Pump (productionengineandpump.com)

Superior

Four-stroke cycle engine rated for 400 to 2,700 hp (300 to 2,000 kW)

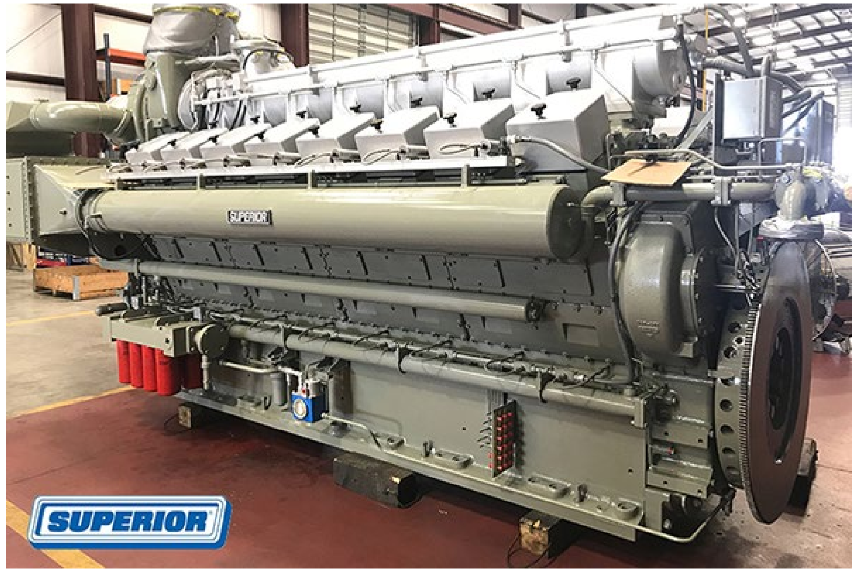


Photo: Superior Engines - Cooper Machinery Services (cooperservices.com)

Base Number (BN)

Base Number (BN) and Test Methods

- **Base number (BN) is a test measure of the alkalinity of an engine oil**, reflecting the quantity of base expressed in milligrams (mg) of potassium hydroxide per gram (mgKOH/g).
- BN measures an engine oil's alkaline reserve, which neutralizes acids generated in the combustion process when fuel is burned. Acids aggressively attack metal surfaces, so it is very important to formulate engine oils with sufficient alkaline reserve to help prevent engine wear.
- Many OEMs have established an in-service engine oil condemning limit of 50% of new oil BN. This is verified by oil analysis of the used engine oil using ASTM test methods. OEMs do not always specify which test methods should be used.

New oil – data sheet

ASTM D2896

Uses perchloric acid to neutralize the alkalinity in the oil. Yields a higher number than the test method typically used for used oil analysis.

Used oil analysis

ASTM D4739

Uses hydrochloric acid to neutralize the alkalinity in the oil and produces a number lower (~0.5 to 1.0 for gas engine oils) than ASTM D2896.

Customers

Using natural gas engines and following OEM recommendations for condemning limits for BN may consider requesting the lab to report BN using the default test, ASTM D2896, instead of ASTM D4739.

Lower numbers

Produced by ASTM D4739 oil analysis reports may create a false assumption that the engine has reached its useful life. This could prompt customers to prematurely change the oil when it is not necessary.

Base Number (BN)

High starting BN: does not necessarily predict the actual longevity of the alkaline reserve or the rate of depletion.

Competitive engine oils: many advertise high BN numbers that are rapidly depleted.

Comparing two different oils with different BN numbers: does not always tell the whole story.

Base Number (BN)

Alkaline reserve: can be achieved in an engine oil by using a combination of detergents, dispersants and antioxidants.

- **Detergents**
  - Main BN component
  - A 'hard' base that allows the BN to deplete slower than dispersants
  - Controls deposits in the hot areas of the engine such as pistons
  - Direct neutralization of combustion
- **Dispersants**
  - A weaker base component described as a 'soft' base
  - Allows the BN to deplete faster than detergents
  - Helps prevent engine deposits by suspending soot particles which can be acidic in nature
- **Antioxidants**
  - The weakest base component
  - Helps reduce the rate of oxidation and viscosity increase
  - Contributes to a soft base

Landfill, well head or sour gas

When using landfill, well head or landfill gas, where the level of methane is below 80 percent and contains a higher level of sulfur and/or organic components such as carbon dioxide (CO_2), hydrogen sulfide (H2S) and chlorine or fluorine, a greater concentration of alkaline reserve is required.

Balanced formulation is critical

An engine oil's base number (BN) in the product's specification can be increased using a soft dispersant additive.

- The soft dispersant is typically used up very quickly within the first 20 to 30 percent of operation
- A competitive engine oil posting a higher BN than a comparable HDAX® gas engine oil may have much worse BN retention
- Acid neutralization is an important factor to consider in an engine oil's performance and engine oil drain extension capability

Some types of detergents do not neutralize weak acids effectively and

- Can appear to do a better job with BN retention
- May not fully neutralize all combustion acids
- Can cause an increase in wear, even though the BN looks sufficient in used oil analysis

A balanced formulation for optimized lubricant performance is critical to

- Neutralize the acids formed—optimize base number retention
- Disperse soot, reduce wear, oil oxidation, and minimize deposit formation

OEM Approval
Field Tests

OEM approval field tests

overview

The field test process is aligned with the OEM's field test guidelines.

- Three phases for field tests are:
  - **Pre-test measurements**
  - **Mid-test measurements**
  - **End of test inspection**
- The complete field test process, including all the roles and responsibilities between Chevron and the customers/owners of the gas engines are described in a written Field Test Agreement.
- A detailed written report is prepared to include all phases of the test.

- The test is initiated by installing new, pre-measured power assemblies (two).
- During the field test, used oil samples are collected and analyzed periodically to monitor oil condition. Operating data is collected.
- Duration of the test can vary between 4,000 hours to 8,000 hours (one year) in various types of engines.

OEM approval field tests

overview

Pre-test measurements are established and compared to OEM guidelines.

- **Pre-test measurements**
  - **Rings:** measure and record end gaps
  - **Pistons:** measure and record ring side clearances.
  - **Cylinder liners:** measure and record the lateral and longitudinal diameter
  - **Valve recession:** measure and record stem height of each valve
- Borescope inspection of the test engine

- The engine oil is drained from the day tank, connecting pipe and test engine and flushed with test oil
- The oil filters are replaced
- The day tank is replenished with the test oil and the test is started

OEM approval field tests
overview

Mid-test measurements are conducted to obtain an indication of performance.

- **Mid-test measurements**
  - **Valve recession:** measure and record stem height of each valve, if critical
- Borescope inspection of the test engine

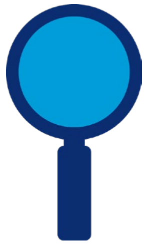
- Provide any technical support to test site personnel as required regarding the lubricant under test and help them to assure proper control of test program
- Maintain records for engine load, emissions and oil consumption

OEM approval field tests

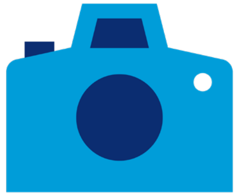
overview

Final inspection is conducted to fully assess wear and deposits.

- **End of test inspection**
  - **Perform general observation** of overall engine condition, power assemblies and connecting rod bearing condition, leaks, damage, operatonal issues, scratches, wear patterns, unusual marks or conditions
  - **Take dimensional measurements** of valve recession, pistons, rings and liners
  - **Determine sludge, lacquer and carbon deposits by standardized rating** of the parts and by photographing test assemblies



- **Perform borescope inspection** of the test engine
  - All power assemblies and determine which units (typically two) will be removed for full inspection
    - May be pre-determined by the units with new or measured parts in the pre-test
    - Take dimensional measurements on the test assemblies
- Take photographs to document conditions of critical parts



OEM approval field tests

overview

Final inspection includes taking dimensional measurements.

Dimensional measurements

- **Pistons (removed):** with rings installed, measure ring side clearances and compare to OEM guidelines and record.
- **Rings (removed):** measure gaps with rings placed in a cylinder diameter bore standard and record.
- **Cylinder liners (in engine):** measure lateral and longitudinal diameters using a bore dial guage, properly calibrated by referencing to a bore diameter standard and record.
- **Valve recession:** measure and record stem height of each valve using a measurement bridge with dial micrometer, compare to previous measurements and calculate recession wear rates, compare to OEM guidelines.

OEM approval field tests

overview

Final inspection includes Deposit Rating.

General overall engine condition

- Non-test power assemblies

Power assemblies

- Piston crown
- Rings
- Lands
- Grooves

Crankcase area

- Top deck
- Rocker assembly
- Rocker cover
- Crankcase covers
- Crankcase interior

FIELD TEST	FR-		**PISTON DEPOSIT SUMMARY**
TEST OIL			
ADDITIVE			SOT Engine Hrs. / START DATE
BASE OIL			
LOCATION			
ENGINE TYPE	CAT		EOT Engine Hrs. / END DATE
ENGINE NO	UNIT		

SUMMARY	PISTON NO.	NAME: RRAN	CATEGORY:	DATE:

			GROOVES						LANDS							UNDER CROWN		UPPER SKIRT		PIN BORE		
			No. 1		No. 2		No. 3		No. 1		No. 2		No. 3							FRONT		REA
CARBON		Factor	Area	Dem	Area	Dem	Area	Dem	Area	Dem	Area	Dem	Area	Dem	Factor	Area	Dem	Area	Dem	Area	Dem	Area
HEAVY		1.0 x													1.0 x							
MEDIUM		0.50 x													0.50 x							
LIGHT		0.25 x													0.25 x							
VARNISH		Sub Total =													Sub Total =							
	1.0	9.0 x													9.0 x							
L	1.5	8.5 x													8.5 x							
	2.0	8.0 x													8.0 x							
A	2.5	7.5 x													7.5 x							
	3.0	7.0 x													7.0 x							
C	3.5	6.5 x													6.5 x							
	4.0	6.0 x													6.0 x							
Q	4.5	5.5 x													5.5 x							
	5.0	5.0 x													5.0 x							
U	5.5	4.5 x													4.5 x							
	6.0	4.0 x													4.0 x							
E	6.5	3.5 x													3.5 x							
	7.0	3.0 x													3.0 x							
R	7.5	2.5 x													2.5 x							
	8.0	2.0 x													2.0 x							
	8.5	1.5 x													1.5 x							
	9.0	1.0 x													1.0 x							
	9.5	0.5 x													0.5 x							
	10.0	0.0 x													0.0 x							
TOTAL		Sub Total =													Sub Total =							
UNW =															TOTAL :							

TOTALS	G1	G2	G3	L1	L2	L3		UC	US	PBF	PB
1G2 =											
WD1 –											
WDK –											

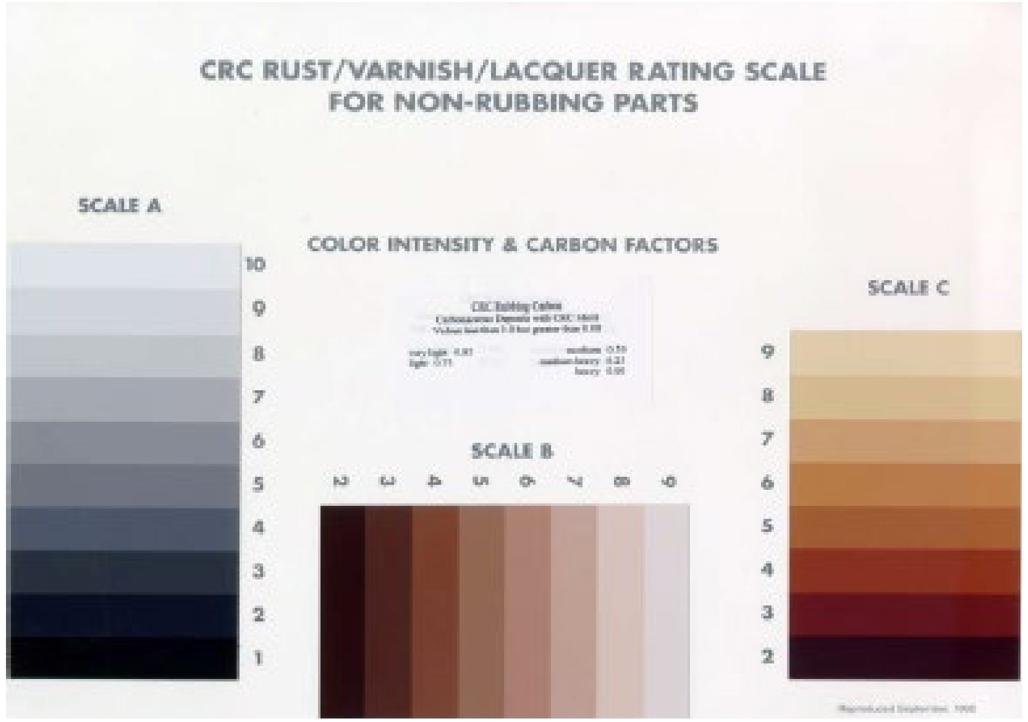
TOP GROOVE FILL:	2nd GROOVE FILL:	T L H C:	T L F C:	Oil Cooler Gallery:

OEM approval field tests

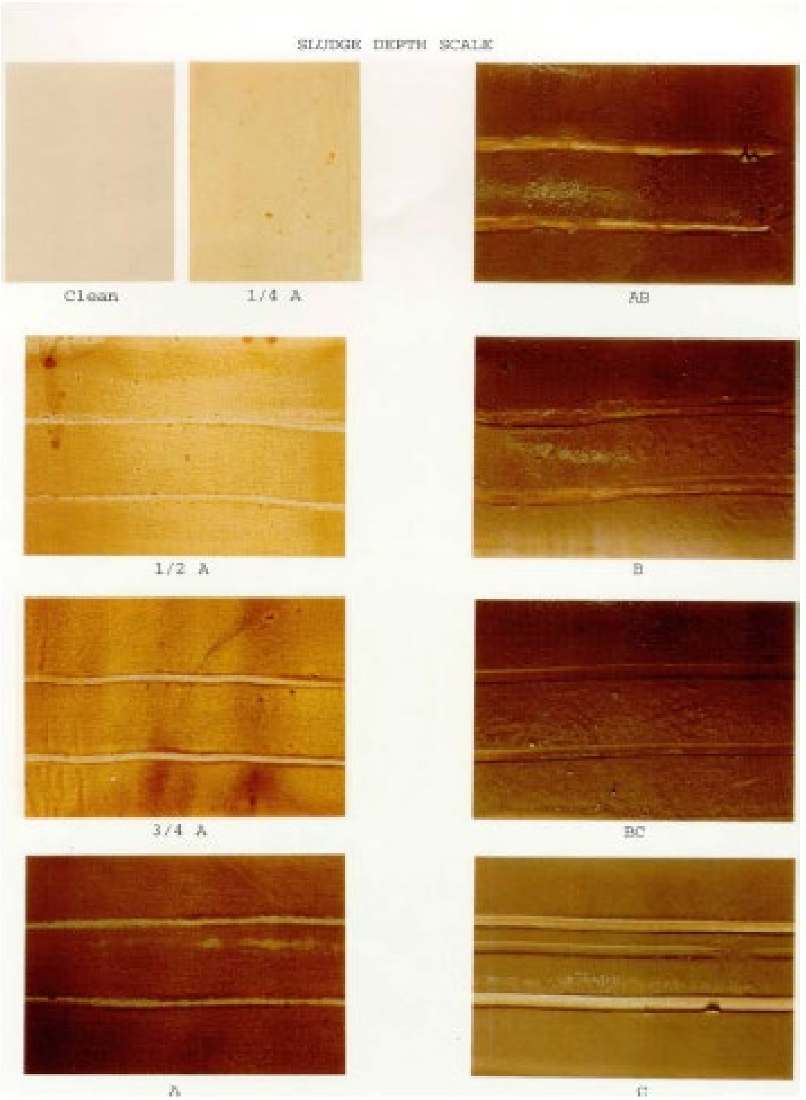
overview

Final inspection includes rating lacquer, deposits and sludge.

- Deposits are rated by comparing observed surface conditions with the appropriate CRC reference sheets.
- Numerical demerits are calculated for each component and recorded.



- Like deposits, sludge is rated by comparing visually observed surface indications with the CRC reference sheet.
- A numerical value is assigned for each component and recorded.



Used oil analysis schedule

ASTM D5185: Elements by Inductively Coupled Plasma-AES

ASTM D445: Kinematic Viscosity at 40°C and 100°C

ASTM D2896: Base Number (BN)

ASTM D664: Acid Number (AN)

ASTM D664: Initial pH

DIN 51453: Oxidation by FTIR

DIN 51453: Nitration by FTIR

ASTM D6304: Water content by Karl Fischer

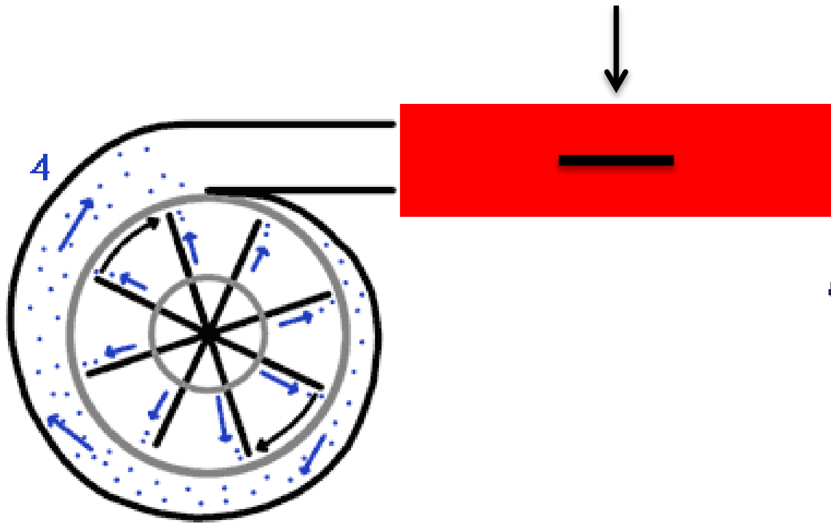
ASTM D893: Pentane insolubles

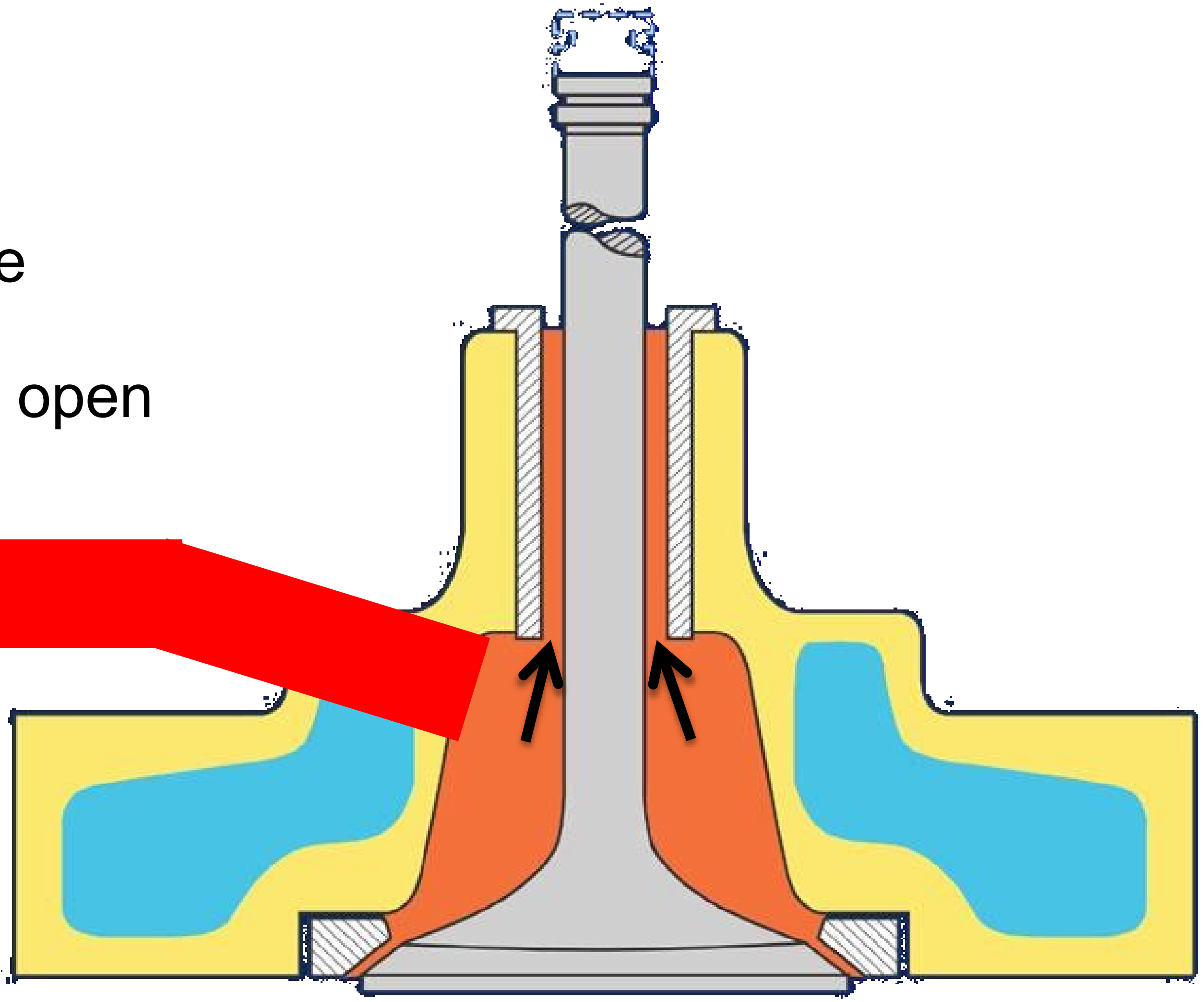
Soot content by IR

Glycol content by IR

High load
High turbo boost
No throttle restriction
High manifold pressure
Pushes oil up in valve guide
Very little oil/ash at valve face

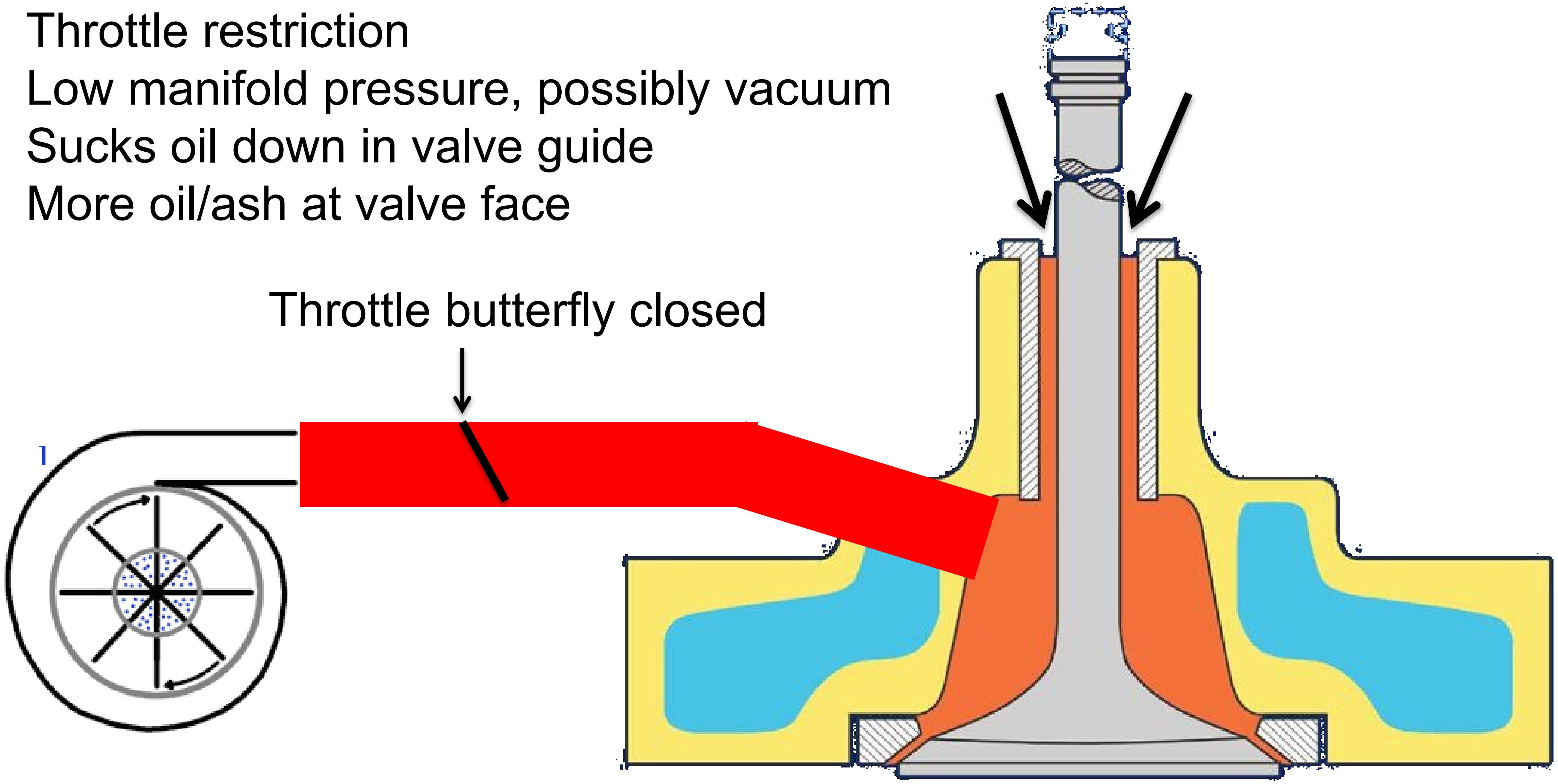
Throttle butterfly open





Low ash oil

Low load
Low turbo boost
Throttle restriction
Low manifold pressure, possibly vacuum
Sucks oil down in valve guide
More oil/ash at valve face



Ashless oil