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A MODEL FOR LUBRICANT STRESS IN MODERN MEDIUM SPEED DIESEL ENGINES AND ITS VERIFICATION IN A WÄRTSILÄ 4L20 LABORATORY ENGINE

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A MODEL FOR LUBRICANT STRESS IN MODERN MEDIUM SPEED DIESEL ENGINES AND ITS VERIFICATION IN A WÄRTSILÄ 4L20 LABORATORY ENGINE

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ABSTRACT

Engine manufacturers promote medium speed trunk piston engine designs equipped with flame rings on the basis of less bore polish and controlled, low oil consumption as a direct consequence of the virtual elimination of piston crown land deposits.

A model of the influence of oil consumption and oil charge on oil stress factors has been used to illustrate the increase in oil stress when such modern designs are introduced. The oil degradation as predicted by the model is compared with actual practices using as an example parameter the BN depletion rate.

Results from the full scale Wärtsilä 4L20 laboratory engine shed light on the actual BN degradation process and the effect different oil chemistries have. Also the operating environment for acceptable equilibrium oil conditions -at which no oil change would be required- is analyzed in detail and it is calculated that a minimum oil consumption of 0.5 g/kWh is required, in line with current recommendations by major engine manufacturers.

In addition, the test results reveal to what extent critical engine condition parameters like piston under crown cleanliness and fuel pump plunger sticking are affected not only by different levels of oil stress, but also by variation of oil chemistry.

Finally, the data generated in the controlled laboratory environment are shown to be consistent with information from service experience and may thus be used with confidence to guide selection of commercial lubricants.

NOMENCLATURE

R	Oil consumption	(g/kWh)
V	Sump size	(kg/kW)
t	Time	(h)
OSF	Oil stress factor	(kWh/g)
y	Fraction	(%)
F	Fuel consumption	(g/kWh)
S	Sulfur content	(% m/m)
BN	(Total) base number	
Subscripts		
t	oil life of t hour	
o	fresh	

INTRODUCTION

New engine design

During the current decade new engine design features have been introduced by many of the OEMs, the most notable being the flame ring. This additional ring installed at the top of the cylinder liner gives a mere clearance fit with the piston crown. Consequently, deposit build up on the crown land is controlled to the extent that as the piston tilts during thrust and anti-thrust motions rubbing of the crown land on the liner surface is minimal. Bore polish caused by such a mechanism is thereby prevented. With less or no bore polish, oil consumption will be much better under control. In addition, certain engine types feature design modifications that lead to substantial reductions in brake specific oil consumption (bsoc), leading to more rapid oil degradation, seen most readily in depletion of base number (BN). Whereas with the bsoc of the older engine designs, used oil properties will reach an acceptable equilibrium level, the new designs prevent an oil charge to reach acceptable equilibrium values for critical parameters like BN or anti-oxidant reserve, thus forcing complete oil changes rather than merely refreshing by oil top up [1].

Different service demands

The higher outputs achievable with modern engines have increased the capability of shipping companies to meet ever tighter/more demanding operating schedules. Cost pressures tend to force the purchase of the cheaper residual fuels. As fuel injection pressures have increased so has the risk of fuel contamination of the crankcase oil. A recent review of the implications of such contamination highlighted the most critical areas to be adversely affected by fuel initiated deposits [2]. Typically these were the **fuel pumps**, where plunger seizure render the engine inoperable, and **piston under crowns** where even piston seizure or burn-through occur. A common terminology to describe residual fuel derived deposits, namely black sludge, is widely used within the marine industry. In the case of medium speed diesel engines black sludge comprises asphaltenes precipitated from the oil phase[1].

The engine operator is required to take action before serious damage to engine components occurs. Proper adherence to maintenance intervals forms part of such actions. Also monitoring the condition and the lifetime of the engine lubricant is a key element in any professional maintenance schedule. The developments in engine design and service demands as described above may result in confusion and unclear situations with respect to lubricant maintenance. It is the purpose of this paper to try and enhance insight in the relation between, on the one hand, lubricant quality and quantity (i.e. total lube oil consumption), and on the other hand, the safe lubricant properties that should be adhered to warrant good operation.

First, the authors will discuss a lube oil stress model and use this with some operational examples to show the merits of adequate lube oil quality monitoring. Also the model gives key parameters that must be known if an economic choice of lubricant is to be made.

In the experimental section the authors will report some engine test data that verify the lube oil stress model and additionally give evidence of a relationship between used oil properties and engine condition, thus allowing improvement of the proper operator action on the basis of oil monitoring data.

ENGINE OPERATION AND LUBE OIL STRESS

Various studies in the past have shown a relationship between the actual oil consumption rate R (g/kWh, i.e. bsoc), the total quantity of oil in the engine per kW of power V (g/kW) and the time t (hr) the oil charge has been in the engine. Assuming that the quantity of oil lost through regular oil consumption is fully compensated by fresh oil added to the system, then an **oil stress factor** (OSF) may be defined according to [1]. OSF is expressed in kWh/g and is equal to the amount of power and related oil degrading processes that has been accumulatively absorbed by the oil charge over time t:

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

One can easily see that the exponential assumes the value zero at infinite time t, which means that the maximum value for OSF will be 1/R. In other words, OSF will gradually increase during the use of the lubricant and reach a maximum that is only dependent on the bsoc value.

The OSF concept may be used directly to apply as a criterion to change the oil charge. One has to assume in that case what the maximum allowable value is for the oil in use. It may be reasonable to assume that oils of different quality will have a different maximum stress level. Conversely, different engines will require

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[1] This should not be confused with the black sludge phenomenon of gasoline engines, which is caused by nitro-oxidative degradation of the oil.

oils of different OSF level to allow operation with infinite –or very low frequency- oil drain interval.

In putting this in economic perspective the usefulness of the concept may be appreciated: Table 1 shows the cost of oil at quality level A in a particular engine with a low bsoc. Oil changes are required if OSF exceeds 2

Table 1. Economic comparison of oils having different OSF limits

Parameter		**Oil A**	**Oil B**
Engine Power	kW	2,000	2,000
Oil price	unit/kg	50	65
Oil OSF limit	kWh/g	2.0	2.6
BSOC	g/kWh	0.4	0.4
Sump size	g/kW	550	550
Time to reach OSF limit (oil charge change)	hr	2,200	infinite
Oil consumed in 7000 h	kg	9,100	5,600
Effective oil cons rate	g/kWh	0.65	0.40
Cost for oil per year	**units**	**455,000**	**364,000**
Cost of initial fill *	**units**	**55,000**	**71,500**
Cost for disposal	**units**	**> 0******.**	**0**

* In practice, commercial reasons cause initial fill costs to be lower.

** Cost of disposal may vary, but invariably raise operational costs.

With oil B, which accepts a stress of 2.6 kWh/g, it may be clear that no oil change is required: the maximum OSF reached will be 2.5 (i.e. 1/bsoc). Whilst oil B is more expensive per kg, the savings made later on more than compensate this by not having to change the oil (and not having the cost of disposal of the used oil). In fact, the cheaper oil is used at an effective level of 0.65 g/kWh, which relates directly to the maximum allowable OSF of 2.

The above is only useful if the OSF limit of an oil is known. Therefore, a link between OSF and known oil properties is desirable. To this end, further extension of the model may be helpful. This may be done most usefully with the BN level of the oil. The prime process for BN reduction is acid neutralization. Most of these acids originate from the fuel sulfur compounds and thus relate directly to the amount of energy put into the oil. Following the assumptions in [1], the BN can be shown to decrease in direct relation with the OSF:

$$\mathbf{BN_t = BN_O - 0.35 * S * F * y * OSF} \qquad (2)$$

Hereby is S the sulfur content of the fuel (% m/m), F the fuel consumption (g/kWh) and y a factor relating to the fraction of S that actually enters the lube oil film as condensed oxides of sulfur. BN_0 is the fresh oil BN and BN_t is the BN at time t. The factor 0.35 converts chemical equivalents of S into chemical equivalents of BN. Factor y has to be found experimentally and will usually be characteristic for a particular type of engine and engine operation. Its value will usually be between 0.06 and 0.1 Applying (2) to the example of Table 1 results in a calculated BN value as shown in Table 2. Normally, a BN rejection value is known for the engine. If the oil BN reaches a value below the rejection limit -e.g. 50% of the original BN- the oil must be changed. Applying (2), the BN is calculated at time of oil change for Oil A and for both oils the equilibrium BN is given. This example helps to appreciate that under conditions as listed in Tables 1 and 2, Oil A reaches the limits of its useful life when the OSF has increased above a certain limit, (oil properties -exemplified by BN- drop below a limit), whereas Oil B may be further used at an equilibrium BN of 21 which is reached at the maximum OSF level of 2.5 (i.e. 1/bsoc). Important to note is that the level at which OSF equilibrates is fully determined by non-oil parameters.

Table 2 BN levels for oils having different OSF limits

Parameter	unit	Oil A	Oil B
Fuel Sulfur	% m/m	2.0	2.0
Fuel Consumption	g/kWh	195	195
y Factor	%	0.055	0.055
Fresh Oil BN	mg KOH/g	30.0	40.0
BN at Oil change	mg KOH/g	14.9	no change
BN at equilibrium	mg KOH/g	11.1	21.1

Before proceeding to further experimental verification of the above, it is important to discuss the criteria that determine fitness for further use of the oil

As can be seen from Table 2, a condemning limit of 50% of the original BN was assumed, but how is the correct condemning limit for BN (or any other oil parameter) determined?. Both the engine manufacturer and the oil supplier have to give input.

The engine manufacturer must indicate at what level alkalinity in the oil should give protection against corrosive wear. Depending on actual working temperature of cylinder liner and rings, it has to be estimated what level of alkalinity will still give sufficient neutralization capacity to prevent any corrosion by fuel sulfur species (this will be the safe **equilibrium** BN). Normally, in a medium speed engine with bsoc values around 0.7 to 1.0 this is not a problem and relatively low equilibrium BN levels will still provide sufficient protection even at relatively high fuel sulfur levels. However, due consideration must be given by the engine manufacturer that at very low bsoc little oil is carried to the top of the liners. The steady oil film present on the area provifding neutralisation of corrosive species will be thinner and more alkalinity per volume unit is required to achive the same protection as with thicker films that will be present at higher bsoc level.

The role of the oil supplier is to indicate what other properties are linked to the alkalinity providing molecules for which BN may also be a measure of residual capacity. It is well known that some BN providing additives also give detergency power to the oil: the ability of the oil to keep the engine clean. For certain alkaline additives, the BN also correlates with the anti-oxidant capacity of the oil. If this is so, then it is important to observe the BN of the oil not only as a measure of neutralizing capacity, but also as a measure of its detergent power and anti-oxidant reserve. However, this will depend greatly on additive technology and has to be verified in practice.

The direct implication of the above is that BN as a general indicator of the quality of the oil in use is probably underutilized. Often, simple rules of thumb are used to determine the minimum BN level (50% or 25% of fresh oil BN). More data are required to couple required BN (or detergency) to the performance level of the engine.

Other parameters apart from BN are usually monitored as well. The authors have not attempted to include these in the model to link it to OSF. For completeness sake some comments will be given in the context of this paper. The two most important parameters are viscosity and amount of contaminants, combustion soot or insolubles.

Viscosity in particular is a parameter that is set by the engine manufacturer to warrant proper hydrodynamic lubrication of bearings and interfaces according to the design parameters set for the engine. Also the cooling capacity of oil jets will depend critically on the viscosity of the oil. The throughput of oil flows may reduce to an unacceptable level if the viscosity increases too much. As a safe criterion therefore, the requirement must be set to stay in grade (of the SAE viscosity class). Factors that influence increase in viscosity most are increase of insolubles suspended in the oil and formation of (oil) oxidation products.

Insolubles in the oil may increase as a result of the action of the oil's detergent. A properly designed medium speed engine lubricant will release these insolubles easily in the lube oil separator or centrifugal filter system. By doing so, the ideal conditions are created for the oil to be in use on a permanent basis. Indication of too high insolubles level may be a sign of a too small or incorrectly functioning lube oil cleaning system. It is often a sign of incomplete combustion as well. It must be corrected immediately. If insolubles level remains high, all –or part- of the oil must be changed to prevent damage to the engine.

Oxidation resistance may be related to the alkaline additive, but often it is provided for by supplementary additive systems that are not routinely checked for its active presence. High viscosity may be an indirect indication of the oil being stressed at a too high level, and thus requiring replacement.

A crucial role, finally, for any oil monitoring program is to look for critical levels of wear metals in the oil. Here functions the oil as a powerful warning system. An early indication of too high levels for metal elements that originate from bearing shells or other critical engine components allows the operator to take timely action.

In summary, BN may be considered as an important parameter currently available to monitor the fitness for purpose of the oil. A useful model is available to predict its fate. In the following this will be verified experimentally.

EXPERIMENTAL PROGRAM

Engine, lubricants and fuel

The Wärtsilä 4L20 medium speed diesel engine in the Shell Marine Diesel Laboratory is equipped with a DC generator. Although this set up would allow operation at varying speed and load, a test procedure was selected that comprised a 500-hour duration at a load set at 110% of nominal output of 600 kW and at a constant speed of 1000 rpm. The engine parameters are summarized in Table 3.

Table 3: Wärtsilä 4L20 Test Engine

Bore	mm	200
Stroke	mm	280
Speed	rpm	1000
Output	kW	660
Exhaust temp.	°C	460
Oil inlet temp.	°C	82
Testduration	h	500
Sump size	l	250
Oil consumption	g/kWh	0.15 – 0.30
Fuel consumption	g/kWh	198

After the initial tests, the lube oil consumption appeared to be very low at a constant and controlled level of 0.15 to 0.3 g/kWh. In combination with the small wet sump system (250 l, i.e. 348 gram of lube oil per kW delivered) this does create an average oil stress level after 500 hours of 1.3 kWh/g, which is similar to the level reached after 2000 hours commercial operation with a sump size of 750 g/kW and bsoc of 0.6 g/kWh. This is considered sufficient to qualify the 500-h procedure as a valid lubricant evaluation tool. Indeed, the lubricant BN was seen to drop to 1/3 of its original value. It was decided to continue with the initial test procedure and use it for all program parts discussed in this paper.

Table 4 Test fuel properties

Property	Unit	min	max
Kin. viscosity, 50°C	mm^2/s	326	410
Density @ 15°C	kg/m^3	998	982
CCAI		843	853
Asphaltenes	%m/m	6.3	10
Micro carbon residue	%m/m	12.1	16.9
Sulfur	%m/m	3.18	3.41
Vanadium	mg/kg	67	90
Sodium	mg/kg	8	30
Aluminium	mg/kg	1	8
Nickel	mg/kg	19	38
Silicon	mg/kg	2	12
Initial Boilin Point	°C	186	228

Consecutive batches of residual fuel of 380mm^2/s @ 50°C and about 3.3%m/m sulfur content were acquired for the test program. Table 4 summarizes the variation in fuel properties during the test program.

No significant variations in fuel consumption were seen over the full program and taking into account the accuracy of the monitoring method used, a value of 198 +/- 2 g/kWh is assumed.

Oil consumption is carefully monitored and oil charge maintained at the original starting level throughout the test. The rate of top-up is seen as an important parameter when the validity of the test is to be judged: a lube oil consumption higher than 0.4 g/kWh is considered as making the test too mild, and will disqualify the test if not corrected within 24 hours.

At the end of the test after 500 h., component ratings are conducted according to manual 12 of the Coordinating Research Council (CRC) by CRC calibrated raters. In doing so, data are obtained on a scale from 0 to 10 (10 being clean) for piston ring grooves and piston lands. Liner cleanliness was rated as well, but this is not reported here further as no significant discrimination was found. Ratings for fuel pump lacquering and piston under crown deposits were introduced in the course of the test program when these performance aspects manifested themselves as being highly relevant in the CEC IL047 working group investigation [2].

During the test lube oil samples are taken at 24-hour intervals and analyzed for alkalinity, viscosity and level of contamination. At the end of the 500-h test period a further analysis is carried out by determining the content of various wear metals and the thermo-oxidative properties.

In the program, 15 different lubricants were tested. The series included eight commercial oils of BN 30 from the major lubricant suppliers, four oils of BN 40 of which 3 are commercially available and three oils with an alkalinity of around 48 BN, of which one is currently commercial. A selection of these was run two or three times to determine the engine test repeatability.

The results

The available rating results for piston lands, ring grooves and under crown and for the fuel pump are summarized in Fig 1a, 1b, 2 and 3.

Test repeatability was calculated on basis of the pooled variances of multiple tests on the same oil. The bars shown at each data point reflect the calculated confidence limits required for differences to be 85% significant. At this confidence level, a number of oils are different with respect to piston land cleanliness and also with respect to under crown fouling. For the other two rating factors i.e. ring groove fouling and fuel pump rating, no significant differences are seen but for ring groove cleanliness a similar trend is observed as seen for piston land cleanliness (Fig. 1b).

During the test series it became apparent that the under crown rating procedure, responding to the color of the layer and not to its thickness or depth, needed supplemented by more detail. Therefore, at a certain stage a deposit thickness measurement protocol was introduced to determine a weighted average thickness of the layer that sometimes was found on the piston under crown. Obviously, this does relate directly to the prime function of the oil/metal interface i.e. to cool the piston.

A thicker layer will seriously reduce the heat transfer effectiveness and may result in piston damage. The rating results obtained are shown in the lower part of Fig 2. Oils are in the same order for ease of comparison. The data highlight that a low cleanliness rating (e.g. Oil A and B) could correlate equally well with no or a lot of deposits.

The fuel pump rating must be judged against the additional observation whether the pump plungers were stuck at the end of test or not. Indeed, the occurrences of pump sticking tend to go together with low cleanliness rating. The ranking of cleanliness, however, is difficult due to high variation of the result. Therefore, the trend is not as clear as could be seen for the piston land rating.

To verify the BN depletion model, first a value for the y parameter was calculated per oil sample using the actual oil consumption up to the moment of sampling and the BN value actually measured. Next, an average value for the y parameter was calculated which together with the value for overall oil consumption is used in equation (2) to calculate for each oil sample a value for BN as predicted by the model. In Fig 4 the result is shown for three oils of different fresh oil BN level. The left-hand part shows the results for the 500 hours of the actual test and it is seen that, taking into account the accuracy of the BN determination, the model predicts quite well the actual BN level. In the right hand part the model is used to predict the – hypothetical- equilibrium values that would have been reached if service had continued.

It is seen that, indeed, equilibrium sets in but that, at the low oil consumption level employed, impractical equilibrium values are attained. Even with the highest fresh oil BN of 48, an early oil change is mandatory.

This illustrates the conclusion reached in Table 1, that very low operational lube oil consumption will eventually result in a higher actual figure when the oil change quantities are incorporated.

On basis of the model discussed earlier in the paper, the authors postulated that the detergency power of the oil might be related to the BN level of the oil, depending on the additive technology used. Therefore, it may be expected that for those technologies that exhibit the BN-detergency link, the end of test BN level of the oil must reflect the engine condition found at the end of the test.

To verify the hypothesis, the used oil BN data may be plotted against engine rating results. The result is summarized in Fig 5a,b, c and d for land, groove, piston and fuel pump rating. Although the BN has by no means reached its equilibrium value, a trend is apparent that the higher the used oil BN the lower the chance of obtaining a lower rating result.

The large spread of the data points at the used oil BN of around 10 mg KOH/g reflects the different oil technologies employed. Most of the oils contain technologies unknown to the authors. Only the data points marked with squares represent known technology. This additive system is one that links detergency to BN. The data in Fig 5 do support the assumption that at least for this particular additive system higher oil BN will result in enhanced engine cleanliness and continued good engine condition.

DISCUSSION

With the exploration of the oil stress model, the authors have attempted to make clear that a lubricant in a modern medium speed engine may become overloaded. Primarily non-oil related factors like fuel quality, sump size and bsoc determine this load, whereas the oil quality determines the maximum allowable load.

In the experimental part, oils have been tested and the results have been analyzed in an attempt to establish oil characteristics that relate to the condition of engine components. Such characteristics should indicate correctly the quality not so much of the fresh oil but of the actual oil in use, preferably of the oil under equilibrium conditions.

BN has been found to correlate quite well with the accumulation of oil stress and may be used on that account alone as an indication of the load put onto the oil.

In addition, BN will in certain cases be related to the detergency power of the lubricant. Comparing various overbased alkaline detergent additives in use in marine lubricants one might appreciate this further. It is known (e.g. described in [3]) that the overbased alkaline part of the additive just adds neutralizing capacity to the oil. This part consists of inorganic salts like $CaCO_3$ and $Ca(OH)_2$, which are held in the oil by Ca, salts of organic sulfonates, (sulfurised) phenates or salicylates. The latter group of products may provide to a greater or lesser extent the detergency power to keep engine components clean as well as providing additionally anti-oxidant properties (in particular salicylates and sulfurised phenates which belong to the chemical class of ‘hindered phenols’).

The inorganic salts will never be in the oil ‘alone’, there will always be the detergent salt to solubilise the inorganic compounds (if the detergent salt would become used up, the inorganic part would inevitably precipitate and no BN would be detected anymore). The additives will be called ‘highly overbased’ the higher the ratio of inorganic over organic material. Extra use of the latter class of components may be suitable to create high BN oils. However from the above it may be clear that this does improve neither the detergency nor the anti-oxidancy very much. It also means that in that case BN of the oil in use is not directly related anymore to such properties as detergency or anti-oxidancy.

For the oils marked with squares in Fig 5, the additive technology is based on salicylates with strong anti oxidancy and detergent power and does not make use of such highly overbased products. The general oil quality may thus be monitored by means of BN.

The results indicate a lack of suitable oil monitoring parameters, like for instance anti-oxidancy or residual detergency that could be useful to predict the status of the other oils shown in Fig. 5.

Enhanced anti-oxidancy, as potentially present in oils containing for example, sulfurised phenates or salicylates, has an additional advantage that depletion of BN through loss of organic salt oxidation (resulting in inorganics precipitation) will be retarded. The process of wasteful depletion is minimized.

One must of course be careful not to overestimate the amount of useful BN as explained by van Dam et al. recently [4] as there may always be a risk of ‘artificial’ BN provided by salts of depleted products. As argued by Barnes before [3], choice of the right BN method is essential. Therefore, both the ASTM D2896 method, and the ASTM D4739 method were used initially to determine the BN. The differences between the two methods have been always within the experimental error. Because of better precision, the D2896 method has been used on a routine basis for most of the time.

A major advantage of using permanently an oil that reaches a high equilibrium BN with strong detergency is that the engine condition remains at a high level, thus increasing the time between overhauls.

A good example of the latter is obtained with one of the 50 BN oils tested in the program reported in this paper. This oil is being evaluated in a Wärtsilä 16V46 engine in China over a period now of more than 8.000 hours and reached -as predicted- an equilibrium BN of 25 after ca 4000 hours. The cleanliness of the engine is largely similar to that of a new engine with virtually no piston under crown deposits (measured at 6000 hours).

Further confirmation of the powerful performance of such oils is currently in progress.

CONCLUSIONS

- A full scale medium speed test engine running on heavy fuel has proven its suitability as lubricant development tool: in 500 h. tests good correlation was found with field performance for which a period of several thousands of hours was required. In addition, the tests confirmed oil condition to be as predicted by an oil stress model based on engine operating parameters.

- The role of lubricant quality level has been quantified using the oil stress model. On that basis, engine condition may be predicted, provided careful calibration is carried out: each lubricant technology that was tested requires potentially a different oil property to monitor its residual performance capacity.

- For oils manufactured by the authors company, BN appears to be suitable, in combination with information on oil stress level as defined in this paper. It allows the engine operator to optimize the selection and use of the engine lubricant. The operation of a low bsoc engine in combination with a top tier lubricant may outperform -in terms of cost-performance- the use of a standard lubricant at a higher overall bsoc level.

- Further suitable oil parameters may still be desirable to predict more precisely the condition of certain critical engine components on basis of used oil condition. In particular a routine method for anti-oxidancy is required.

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Fig 1a Piston land rating
Oils in order of decreasing performance

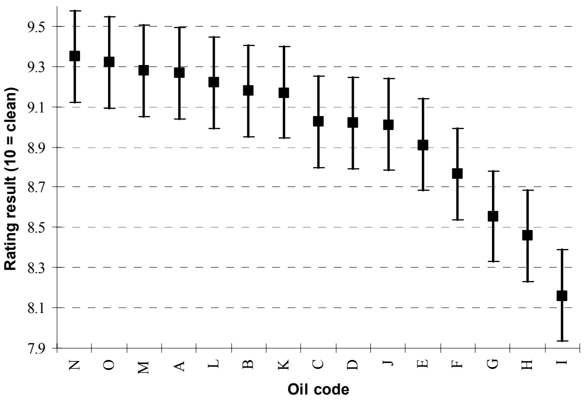


Fig. 1b Piston ring groove rating
(Oils in same order as for land rating)

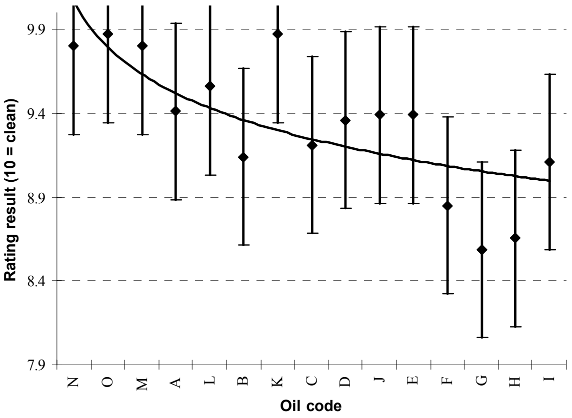


Fig 2 Piston undercrown rating (top)
and deposit thickness (bottom)
- oils in order of decreasing piston land cleanliness -

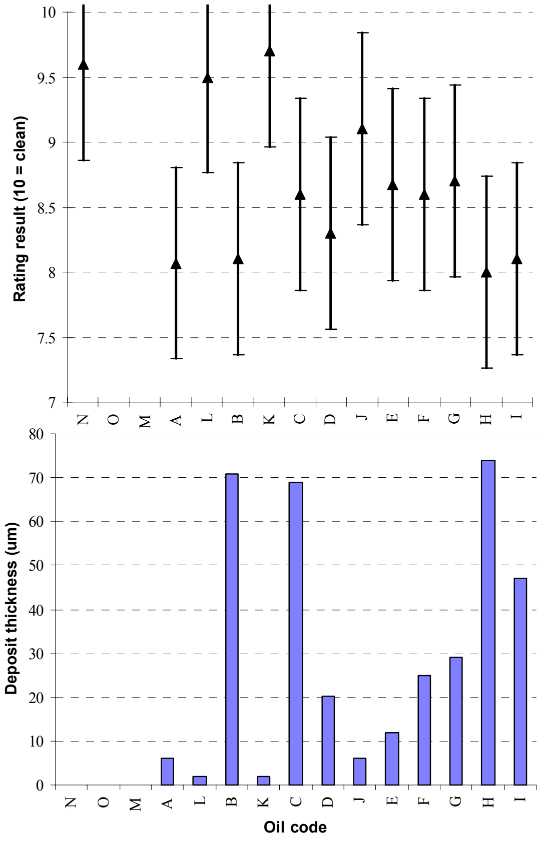


Fig 3 Fuel pump rating
(oils in order of decreasing piston land rating)

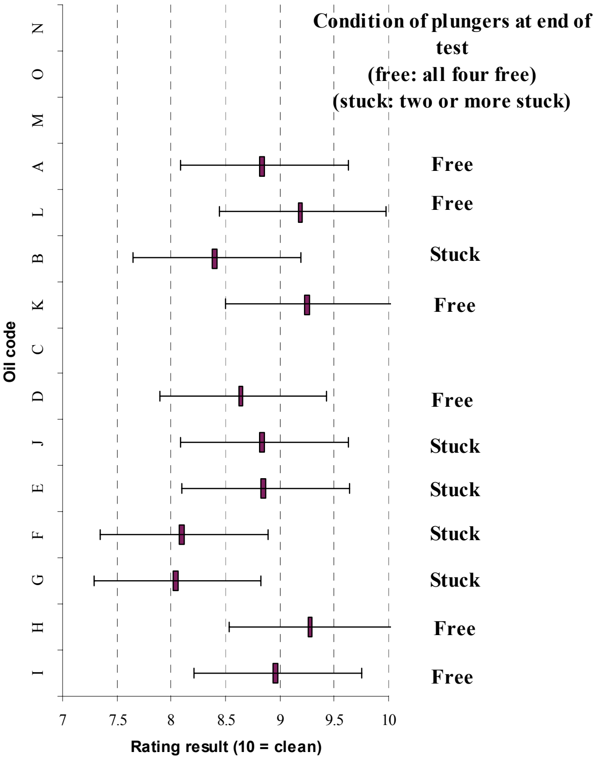
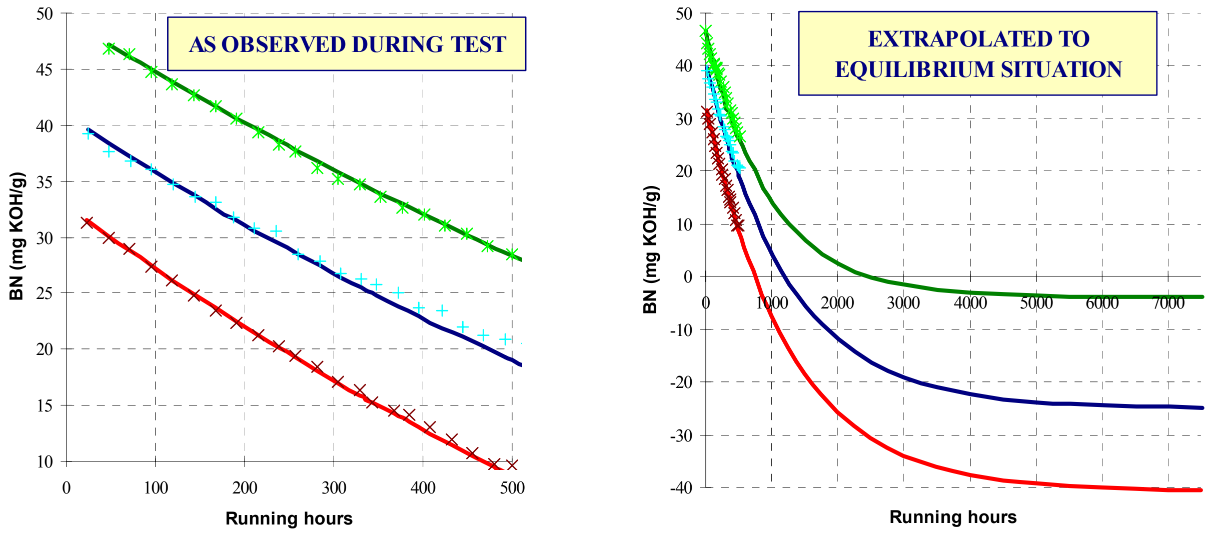


Fig 4 Measured and Calculated BN for three oils at different BNo



Solid lines: Calculated TBN; Marked points: Measured TBN

Fig 5a Piston land rating against used oil BN

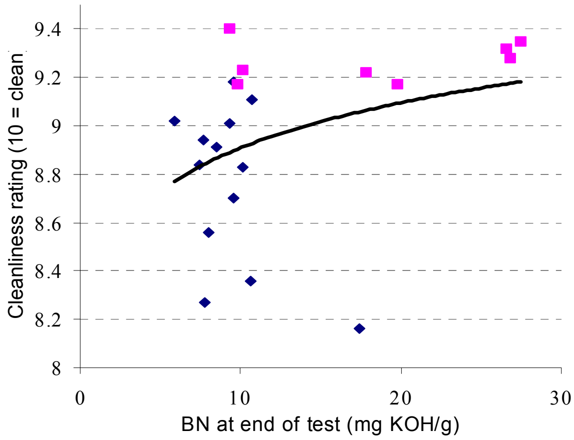


Fig 5b Piston ring groove rating against used oil BN

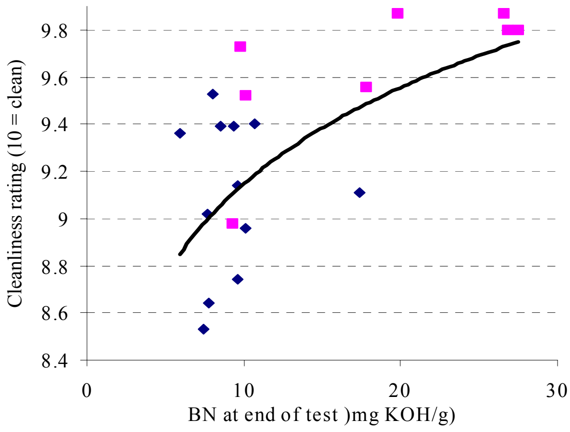


Fig 5c Piston under crown rating against used oil BN

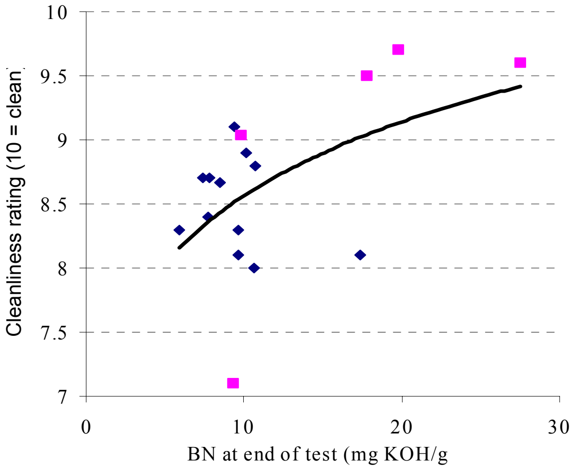


Fig 5d Fuel pump rating against used oil BN