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Oil stress investigations in Shell's medium speed laboratory engine

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Abstract: Stress on the medium speed engine lubricant is increasing due to a combination of factors such as engine design, the need for operators to extend time between overhauls and the wide range of residual fuel oils available in terms of composition and quality. Concerning engine design, higher power output is being achieved from the same engine size and oil volume in circulation, oil consumption has reduced through wide use of the anti-polishing ring. In addition, greater fuel efficiency and lower exhaust emissions requires more precise fuel injection with higher fuel injection pressures which require additional measures to reduce fuel contamination of the lubricant.

Shell's full scale Wartsila 4L20 engine was upgraded in April 2002 to a higher output (Brake Mean Effective Pressure of 27.3 bar) and provides a unique laboratory tool to test lubricant performance in medium speed engines. To mimic the effects of fuel contamination of lubricant in the field, heavy fuel is deliberately added to the lubricant. The engine has been used to study the main Oil Stresses of lubricants for medium speed engines operating on heavy fuel: acid stress (largely from sulphur acids), thermal/oxidative stress and asphaltene stress (from fuel).

For piston undercrown (PUC) deposits, asphaltene stress of the lubricant and thermal/oxidative stress (in the thin oil film context) are primary factors. Rapid growth of PUC deposits with time is seen in the laboratory engine at a point that corresponds to a particular used oil condition. For oil technology based on salicylate detergent chemistry, BN reflects to an extent lubricant detergency and anti-oxidancy as well as its acid neutralisation capability. Here PUC deposit growth correlates with used oil BN and there is a break point at a BN level of 20 mg KOH/g. Below this level rapid PUC deposit growth occurs. Keeping the oil quality (and detergency) above this break point will prevent excessive PUC deposit growth. In a related manner, a higher initial BN for such an oil technology will maintain PUC deposits at a lower level for a longer time. Benefits for a higher BN oil are also seen for piston ring belt deposits and fuel pump lacquer.

Thermal/oxidative stress of used oils in the laboratory engine test is higher than that experienced in the field, based on measurements of residual antioxidancy with differential scanning calorimetry. For oil technology such as that based on salicylate, a higher BN oil gives a greater degree of anti-oxidant reserve.

PUC deposit levels are strongly influenced by the batch of heavy fuel. In the field this means that a high quality lubricant with a sufficient margin of performance should be used to cope with any variations in fuel composition.

Heavy fuel contamination of the used engine lubricant was found to be the main cause of increased oil viscosity. In view of the strong negative effects of heavy fuel contamination of engine lubricant, major challenges are for a) engine builders to reduce the level of contamination through improvements in hardware, and b) lubricant formulators to design lubricants that can better cope with this contamination.

1. INTRODUCTION

Global competition and deregulation continues to drive the Marine and Power industry to control very closely the running costs of ships and power plants and to optimise utilisation. For technical managers this translates into a relentless focus on:

- Eliminating unplanned downtime/outages,
- Reducing maintenance costs,
- Extending time between overhauls, and
- Fuel flexibility (the ability to use as wide a variety of fuel qualities as possible)

Engine builders are at the forefront of tackling the challenge of lower costs for the industry. To keep down capital cost, higher power output is being achieved with the same engine size and often with the same oil volume in circulation. In pursuit of longer life for cylinder liners, the use of “anti-polishing” rings (also known as “flame” or “fire” or “carbon scraping” or “cuff” rings) is now almost universal in trunk-piston engines. These rings maintain the oil consumption of the engine at a low level. These engine changes (higher power output, lower oil volume and lower oil consumption) increase the stress on the oil in terms of the kWh experienced per gram of oil. In addition, greater fuel efficiency and lower exhaust emissions requires more precise fuel injection which in turn requires higher fuel injection pressures (as high as 2000 bar) which require additional measures to reduce fuel contamination of the lubricant.

Fuel quality: At the same time, growing demand for gasoline and other ‘white products’ has changed heavy fuel oil production. The refining industry is adopting advanced technologies to improve the high-end yield from each barrel of crude, resulting in changes to the composition of heavy fuel oil. Straight-run product is becoming less common and fuels blended with cracked refinery streams now account for heavy fuels supplied in most major markets. This has led to an extension of the fuel oil supply chain and a growing belief in the market that heavy fuels are now more variable in composition and quality than they used to be. In spite of greater use of standard industry specifications in the purchase of marine fuels, operators across the industry and around the world report a rising number of incidents involving fuel stability, combustion quality and unexpected effects in use.

Lubricants: The net result of these engine and fuel trends is that lubricants are more highly stressed since they have to work harder, hotter, in more compact and lower oil consuming engines and accommodate a wider spectrum of fuels. The particular demands on the lubricant will vary from engine to engine, but there are three main oil stresses, discussed in the next section.

2. OIL STRESS

The main stresses experienced by a lubricant for a medium speed engine operating on heavy fuel are acid stress, thermal/oxidative stress and asphaltene stress. These stresses and their consequences for the engine and oil condition are summarised in **Table 1**. Although there are other stresses, the three in Table 1 are considered the most important for this type of engine lubricant based on the laboratory engine studies described in this paper.

Table 1 - Oil stress in medium speed engine lubricants

Stress:	**Caused by:**	**Consequences for engine and lubricant:**
Acid Stress	Sulphur acids, oxidation acids	Corrosive wear, deposits. BN loss and shorter oil life
Thermal/ Oxidative Stress	Higher temperatures giving accelerated thermal/oxidative breakdown of lubricant and fuel	Deposits, sludges, corrosive wear of bearing material, piston hot corrosion (from high piston undercrown deposits). Oil thickening and shorter oil life
Asphaltene Stress	Fuel (asphaltene) contamination of lubricant	Deposits, lacquers, sludge, fuel pump sticking, piston hot corrosion (from high piston undercrown deposits). Oil thickening and shorter oil life

Acid Stress: Acids entering the lubricant originate from combustion of fuel sulphur and, to an extent, from oxidation of fuel and lubricants hydrocarbons. The lubricant has a certain level of basicity for neutralising these acids, expressed as the Base Number (BN) which for higher BN oils is measured by the ASTM D2896 method (unit: mg KOH/g of oil). BN depletion is the result of acid neutralisation and rapid BN depletion is the most obvious sign of high oil stress. More highly rated engines deplete BN faster for a given fuel sulphur level due to the higher sulphur throughput into the engine. If the BN falls too far, corrosion can occur, not only on the liners but also in the piston ring belt. To avoid this most engine builders advise a minimum BN level of 20 mg KOH/g or around this number for engines running on heavy fuel oil. To maintain the correct level of BN of the used lubricant, there needs to be a matching of the **base level of the fresh oil** to the **engine type** (rated power, fuel and oil consumption) and the **fuel sulphur level.** A useful aid to achieve matching of these parameters for a particular engine application is the Oil Stress Model [1].

Thermal/Oxidative Stress: Oxidation of the lubricant, if not controlled, will lead to unacceptable oil thickening and the formation of sludges and lacquers in cooler areas of the oil system. In addition, so-called weak acids of oxidation can lead to corrosion of the bearing material. Control of oxidation in the thin lubricant film context is important, e.g. for piston undercrown cleanliness. A well formulated engine lubricant must have an adequate level of oxidation inhibition provided by additives and high quality base oils.

Asphaltene Stress: Asphaltenes will enter the engine lubricant through two routes, blowby and the fuel injector pumps/pump drive. The asphaltenes through the blowby route will be burnt or partially burnt fuel whilst those by the fuel pump route will be in raw fuel. Unstable fuel and fuel/lube mixtures can form lacquer on pump components, leading to sticking or "hanging" of the fuel pumps when the engine is started. In addition, fuel contamination of the oil increases the likelihood of "black sludge" in engine components, filters and oil ways. Worst of all, fuel is not designed like lubricant to be thermally stable and will tend to form deposits in the hottest parts of the engine: proper cooling in these areas is vital to avoid excessive build-up of deposits. The most critical are the piston undercrown (PUC) and piston groove deposits. At the piston undercrown deposits form an insulation layer and prevent the lubricant cooling the piston that can lead to hot corrosion of the piston crown. A modern engine lubricant must be specially formulated to cope with asphaltenes, in particular to disperse them and prevent them forming deposits on engine surfaces.

In addition, ineffective control of any of the above three areas of oil stress will lead to shortened oil life, usually through BN loss or viscosity increase, this clearly being undesirable in a climate where longer times between overhauls are being sought.

3. STUDYING OIL STRESS WITH THE SHELL W4L20 LABORATORY ENGINE

In 1994 a full size Wärtsilä 4L20 research engine was installed in the Shell laboratory at Amsterdam to develop the concept of Oil Stress for medium speed engines running on heavy fuel. The use of the Oil Stress Model to study engine, fuel sulphur and lubricant factors was reported as a CIMAC paper [1]. At that time, the predominant concern was **Acid Stress**, namely depletion of the lubricant's Base Number.

In April 2002, Shell's Wärtsilä 4L20 was uprated to a Brake Mean Effective Pressure (BMEP) of 27.3 bar, the Shell laboratory believed to be the first customer for Wärtsilä with this configuration. A comparison of the engine parameters of this "D" output mode with the former "B" output engine (BMEP of 22.5 bar) is shown in **Table 2.**

Table 2 – Shell W4L20 laboratory engine methods

		B output	D output#
Bore	mm	200	200
Stroke	mm	280	280
Speed	rpm	1000	1000
Output (constant)	kW/cyl	165	200
BMEP	bar	22.5	27.3
Fuel injection pressure	bar	1300	1500
Peak combustion pressure	bar	175	200
Injection timing	°BTDC	12	12
Exhaust temp.	degC	460	470
Oil inlet temp.	degC	65	65
Test duration	h	500	320 - 500
Sump size	l	250	250
Oil consumption	g/kWh	0.2 - 0.4	0.1 - 0.2
Fuel consumption	g/kWh	229	226
Fuel sulphur	%m	3.2 - 3.4	3.2 - 3.5
y-factor (see text) ##	%	0.068	0.072
Test measurements:		PUC deposit thickness Piston groove and land deposits Piston ring wear Liner wear and lacquer Fuel pump lacquer and stick Crankcase and rocker deposits Detailed used oil properties	

Final test method with 2.5% heavy fuel added to the sump and top-up
Based on tests carried out with the same lubricant

The exhaust temperature for the D output mode was higher by 10 °C and templug measurements showed that temperatures on the piston undercrown and piston (crown, lands and grooves) were on average higher by 15 and 8 °C respectively. In addition, the oil consumption of the D output test was reduced to 0.1-0.2 g/kWh compared to the earlier 0.2-0.4 /kWh and to mimic the effects of fuel contamination, heavy fuel oil was deliberately added to the lubricant. These improvements in the test method allow a study of the effects of thermal/oxidative stress and asphaltene stress, in addition to acid stress.

3.1 Engine operation and lube oil stress

The Oil Stress Factor, OSF, is defined as below [1], [2], [3].

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

Where R is the specific oil consumption (g/kWh), t is the oil hours (h) and V is the specific oil volume (g/kW).

In terms of physical and chemical processes, the OSF (in kWh/g) reflects the energy each gram of oil has been exposed to over time t and therefore OSF is directly related to the amount of combustion products, soot, acids and insolubles that have entered the crankcase.

This parameter allows different engines and conditions to be compared and an assessment made of their relative severity in terms of oil stress. For example, the Oil Stress Factor and BN depletion of a 50 BN lubricant tested in the new Shell W4L20 D output test are compared in **Figure 1a and 1b** to a typical Marine and Power engine in the field.

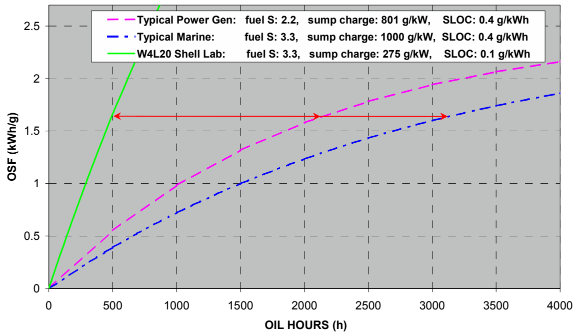

Figure 1a - Oil Stress Factor versus time, lab engine versus the field

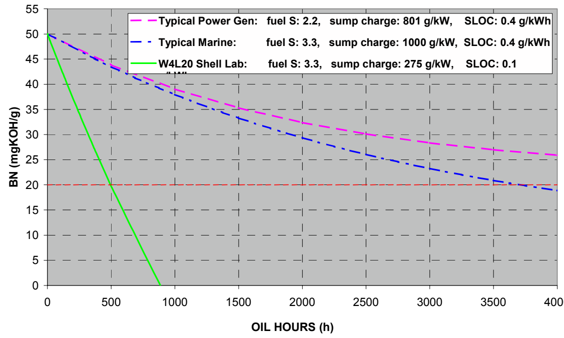

Figure 1b - BN depletion versus time, lab engine versus the field

This shows that at around 500 hours the engine test, due to its low specific oil volume and oil consumption and the relatively high fuel sulphur level used, gives around the same level of Oil Stress and BN depletion as 3,000 - 4,000 hours experienced in the field. This increased severity affects engine performance (e.g. piston undercrown deposits) making the engine a powerful tool for discriminating between lubricants, illustrated later.

The OSF concept and the above equation (Eq. 1) can be extended with the BN level of the used oil and it has been shown that BN decreases in direct relation with the OSF at time t [1], [2], [3]:

$$BN_t = BN_0 - 0.35 * S * F * y * OSF_t \qquad \text{(Eq. 2)}$$

Where BN_t and BN_0 are the BN at time t and the initial (fresh oil) BN respectively, S is the sulphur content of the fuel (%m/m), F is the fuel consumption (g/kWh). The factor 0.35 converts chemical equivalents of S into chemical equivalents of BN. The factor y is an empirical number that is characteristic of a particular engine and engine operation and a particular lube oil technology. It is the rate of lubricant BN depletion normalised for differences in engine power, oil consumption, fuel consumption and fuel sulphur content. It is useful for determining whether acid stress on the lubricant has changed.

3.2 Development of a new Shell W4L20 engine test method

To measure the effect of changing from B to D output tests and of adding fuel as a contaminant, comparative engine tests were carried out with a 40 BN reference oil (labelled R40) with these three test variants. For the third test variant, a level of fuel contamination of 2.5% heavy fuel was used both for the initial oil charge and the top-up oil, this level being determined through discussions with Engine Manufacturers on the typical level of heavy fuel thought to contaminate used oils in service.

Changes in oil properties for the 40 BN reference oil are shown in **Figures 2a to 2e** and are discussed below.

3.2.1 BN depletion

Figure 2a suggests that the rate of BN depletion increases as one moves from B to D and D + fuel tests. Increased BN depletion from B to D tests would be expected due to the higher fuel throughput (and sulphur acids arriving in the luboil) combined with the lower oil consumption of the D output test (around 0.2 compared to 0.3 g/kWh for the B output test).

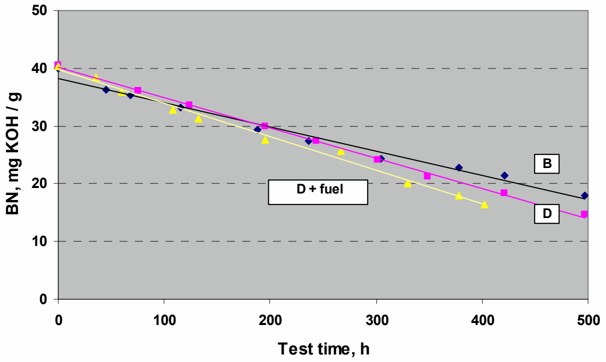

Figure 2a - Influence of test method, BN with time

The above equation (Eq. 2) can be used to calculate the y factor for the three engine methods.

Plots to determine the y factors, as the gradients of straight lines, are shown in **Figure 2b**.This shows that the y factor for the B output test is slightly lower than those for the D output and D + fuel tests (0.068 compared to 0.072) indicating that the D output and D + fuel tests are slightly more severe. The y factor calculated means that for the Shell W4L20 engine around 0.07% of the fuel sulphur ends up in the lubricant as sulphuric acid where it is neutralized by the alkalinity of the lubricant. The values for B versus D + fuel engine modes were confirmed by further engine tests with the same oil technology. Thus although the engine factors that deliver acids to the lubricant, such as combustion characteristics, blowby and luboil wetting of the liner, are similar for the two Wärtsilä 4L20 engine modes they are slightly more severe for the D + fuel mode.

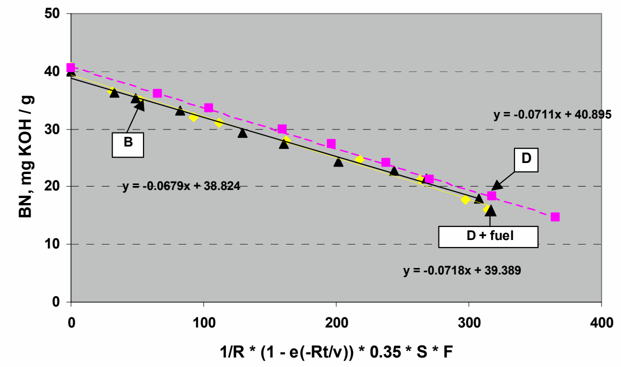

Figure 2b - Plot to determine the y factor (see text)

3.2.2 Viscosity and insolubles

Figure 2c shows that viscosity increase with time is slightly greater with the D compared to B output test but that addition of fuel substantially increases the rate of viscosity increase so that the Engine Manufacturer's limit (25% increase on initial viscosity) is met after only 400 hours, at which point this test was stopped. The viscosity data can be normalised for changes in oil consumption (g/kWh) and specific oil volume (g/kW) across tests using the Oils Stress Factor determined by the earlier equation (Eq. 1).

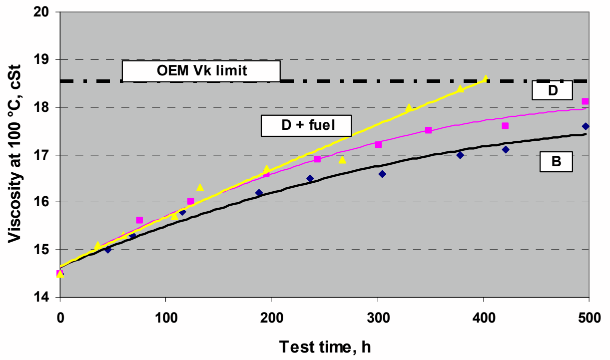

Figure 2c - Influence of test method, viscosity with time

Plots of viscosity versus the Oil Stress Factor for the three test modes are made in **Figure 2d.** This shows very clearly that the B and D output tests give the same viscosity change with Oil Stress Factor whereas the D + fuel test data show that for a given Oil Stress (say of 1.0) the viscosity is significantly higher.

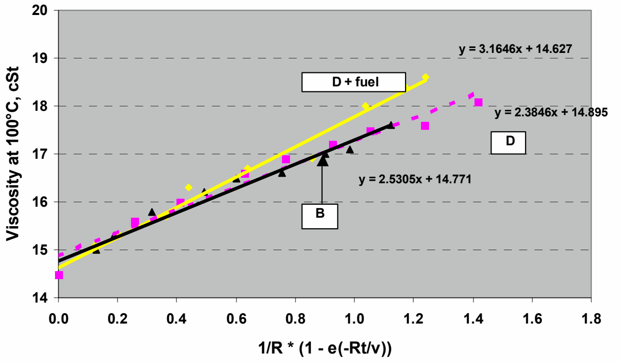

Figure 2d - Viscosity versus Oil Stress Factor

Figure 2e shows the Index of Contamination (IC), a measure of total insolubles. IC is measured by paper chromatography followed image analysis of the used oil spot. The IC value increases to around 1.5% at the end of test but the evolution of IC with time is similar between the engine test modes. The Merit of Dispersancy (a measure of dispersancy using the same measurement technique) of used oils from engine tests without fuel contamination started at around 90% then dropped fairly quickly to around 60% where it stayed relatively stable for most of the test. In contrast, with fuel contamination dispersancy dropped to a stable level of around 45%. This difference likely reflects the negative influence of heavy fuel contamination on the ability of the lubricant to disperse insoluble material.

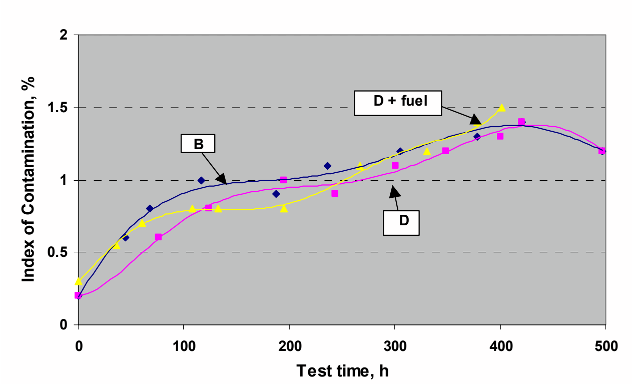

Figure 2e - Influence of test method, insolubles with time

3.2.3 Piston undercrown deposits

Measurements of thickness of deposits on the piston undercrown (PUC) showed that B and D output tests gave similar deposit levels (around the 0 to 10 micron range following 500 hours) but that with the addition of fuel contamination deposits rose to >100 micron after only 400 hours of test. This shows the profound influence of heavy fuel contamination on the formation of PUC deposits that can increase deposits by a factor of 10.

It was decided to fix the test method for the new test with 2.5% fuel contamination since the test was more severe in terms of Oil Stress and had the potential for discriminating between lubricants in terms of viscosity control and PUC deposit control.

3.3 Lubricant effects

Tests with the final method (D + fuel) on 30, 40 and 50 BN reference oils (R30, R40 and R50) with the same additive technology are shown in **Figure 3a-3d**. Results may be compared directly between these tests without need for normalisation of data since each test experienced low and similar oil consumption. As well as monitoring oil condition during the test and measuring engine condition at the end of test, intermediate deposit measurements were made by pulling one piston at intervals during the test and measuring PUC deposits and piston land deposits with rings in place. The piston in question was then re-installed and the engine continued on, with the turn-around time from engine stop to engine restart of only 3-4 hours.

Figure 3a shows BN depletion for the three oils, the 30 BN oil reaching a BN of 10 mg KOH/g at the end of the test (320 hours for the 30 BN oil). Although this level is well below that recommended by the Engine Manufacturers, checks on used oil condition revealed that wear metals levels did not increase which shows that, for a very limited time at least, this level of BN can be run in an engine without causing acid corrosion problems but with an influence on PUC deposits, see below.

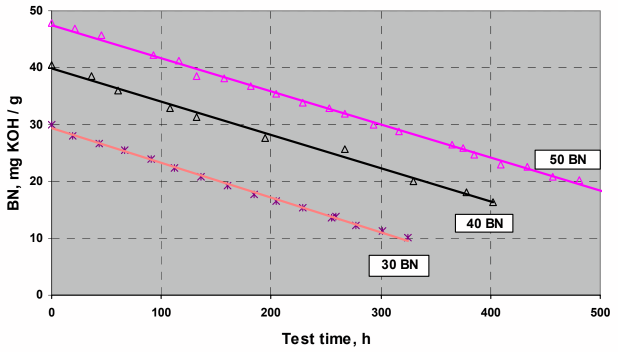

Fig 3a - BN with time for three lubricants with different initial BN

Figure 3b plots the viscosity profiles, showing that the 30 BN oil viscosity climbed the soonest and reached the Engine Manufacturer's limit in only around 320 hours. This can be compared to the 50 BN oil which reached this limit at around 500 hours.

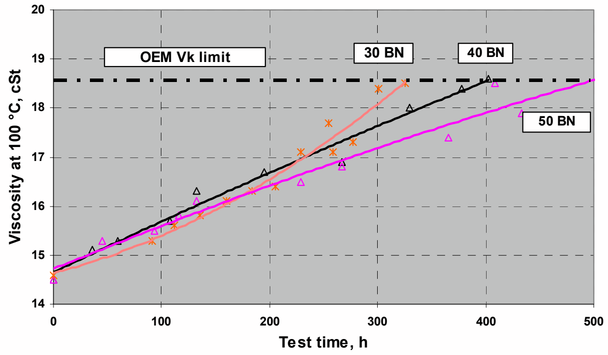

Fig 3b - Viscosity with time for three lubricants with different initial BN

Piston undercrown deposit thickness measurements (**Figure 3c)** show a rapid, accelerating increase in PUC deposits and (again) this occurs earliest for the 30 BN oil and latest for the 50 BN oil. The PUC deposit behaviour of the 30 BN oil reflects a more rapid deterioration of oil properties, particularly oil detergency (discussed later).

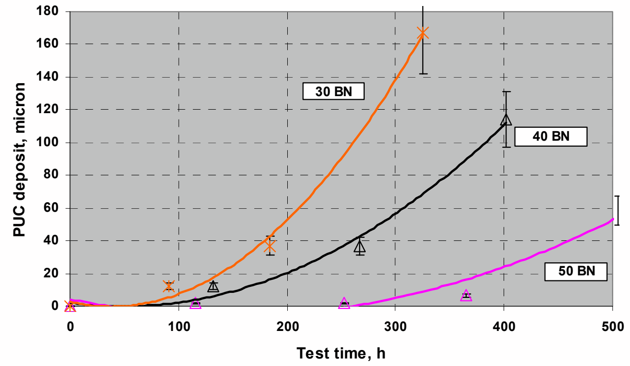

Fig 3c - PUC deposits with time for three lubricants with different initial BN

A different 40 BN oil (coded S40) was tested in duplicate to evaluate engine test repeatability and discrimination. The PUC deposit results are compared to the reference oil R40 and shown in **Figure 3d**.

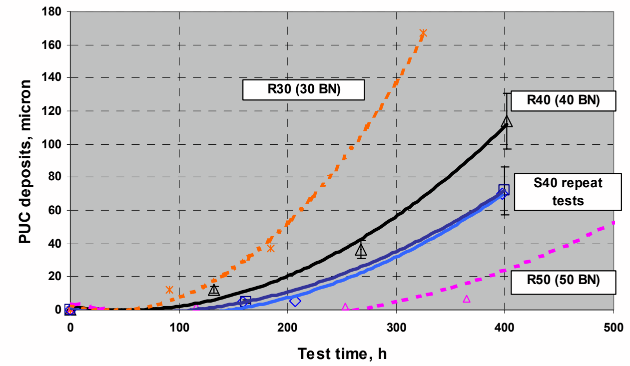

Fig 3d - PUC deposits with time for two 40 BN lubricants (full lines)

They show that S40 gave improved control of PUC deposits with time, this difference judged to be statistically significant based on PUC deposit repeat measurements. The data show that the engine test can discriminate between different 40 BN oils. The duplicate tests on S40 (two solid blue lines) have PUC deposits at 400 hours of 70 micron in the first test and 72 micron in the second test. This is surprisingly good test repeatability and other repeat tests (including with earlier B output tests) indicate a more realistic PUC deposit repeatability at 95% confidence of ± 15%, these error bands being shown in Figures 3c and 3d.

Piston belt cleanliness (lands and groves) and fuel pump lacquer are also evaluated at the end of the engine test, the latter giving pump stick if severe enough. The piston cleanliness results showed that piston lands were similar for the 30, 40 and 50 BN oils tested but top grove cleanliness for the 30 BN oil was worse than that for the 40 and 50 BN oils. Fuel pump lacquer results on the plunger and barrel are plotted in **Figure 4** and show that the 50 BN oil (R50) gives directionally cleaner results compared to the 30 and 40 BN oils.

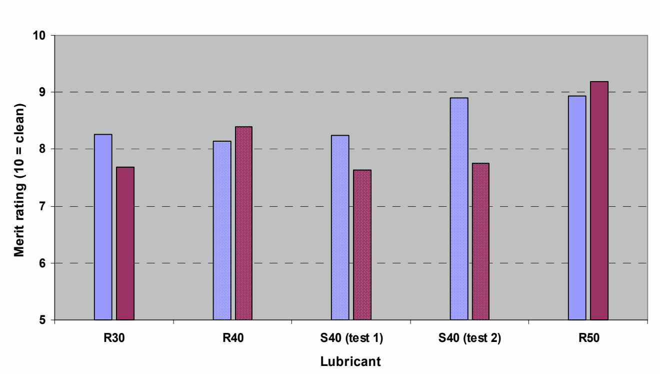

Fig 4: Fuel pump rating (blue bar is plunger, brown bar is barrel)

Thus both the piston cleanliness and fuel pump lacquer results show that the 50 BN oil has the overall highest performance. Since these tests were carried out, a fuel pump without a sealing ring on the plunger has been installed in the engine to simulate older fuel pump designs in the field, where mixing of fuel and lubricant will occur and give more lacquer and potential for stick. The pump without a seal shows lower (= worse) lacquer ratings allowing better discrimination between different lubricants and fuels.

4. DISCUSSION

4.1 Thermal/Oxidative Stress

A measure of thermal/oxidative stress on the lubricant in the thin film context can be made through high pressure Differential Scanning Calorimetry, DSC (method: isothermal mode at 210 °C with high pressure oxygen atmosphere) that gives the induction period (IP) in minutes. The longer the IP of a used oil, the time before accelerating oxidation, the greater its anti-oxidant reserve. Plots of IP with engine test time for the 30, 40 and 50 BN reference oils tests with the D + fuel mode (including a repeat test with the 30 BN oil) are shown in **Figure 5**.

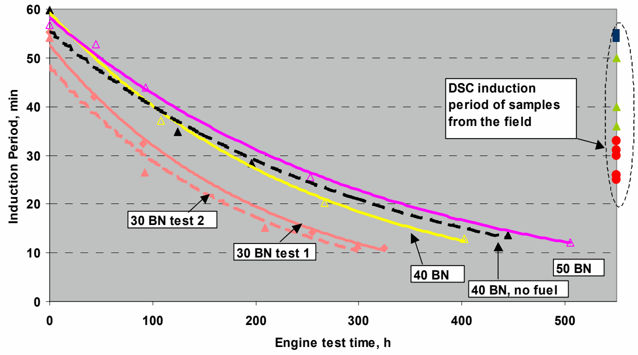

Figure 5: Residual antioxidancy (by DSC) of used oils

This shows that anti-oxidant reserve of the three lubricants decreases with time. The 30 BN oil reaches the lowest point first because its starting anti-oxidancy was lower. For comparison sake, Figure 5 also includes measurements of DSC induction period of several samples from the field from three engines (two Marine and one Power). This shows that the Shell W4L20 laboratory engine samples, with induction periods of 60 to 11 minutes, are more oxidatively stressed in the thin film context towards the end of test than the field samples with values of 55 to 25 minutes.

The additional plot (with black dashed line) of the 40 BN oil test without fuel contamination gives a shallower reduction in anti-oxidant reserve with time (compared to the yellow line) showing that where contamination is present there is more oxidative stress to the lubricant through the oxidation of the heavy fuel.

Separate measurements of the actual level of oxidation of used oil samples of the 30 BN oil, measured by differential infrared (DIR) spectroscopy and using the characteristic carboxyl peak at 1720 cm^{-1} showed a maximum level of 2. Thus although anti-oxidant reserve had been dramatically reduced in the test, this level of oil oxidation was still very low. This indicates that although *bulk oil oxidation* is not playing a significant role in the phenomena seen in the engine, oxidation in the *thin film* situation and in the presence of fuel will likely be important. Overall, the results show that a high performance lubricant is needed to cope with thermal/oxidation stress in severe engine applications.

4.2 Piston Undercrown deposits and Oil Stress

The results in Figure 3c and 3d show the importance of controlling deposits in the high temperature region of the PUC. This is especially true if fuel is present in the lube oil (as demonstrated in section 3.2.3). Deposits on the piston undercrown may rise excessively and as little as a few hundred microns of deposit may raise the temperature of the piston into the danger zone for hot corrosion. In the worst case the piston will burn through and/or crack and fail.

Why do the PUC deposits build-up almost exponentially with test time rather than plateau? The data indicate that once deposit build-up starts, deposition accelerates with time and this is most likely due to the non-equilibrium conditions in the laboratory engine where used oil properties rapidly deteriorate as the test progresses. This contrasts to a substantial proportion of field experience where used oil condition is near to or at equilibrium and deposit build-up would be expected to equilibrate at a finite value. However, this finite value of PUC thickness will depend on used oil condition, with poorer used oil condition expected to give a higher equilibrated PUC level. Nevertheless, as illustrated earlier, the laboratory test enables deposits to be built up rapidly to levels of the same order as sometimes seen in the field, but within 500 hours rather than several thousand hours.

It is instructive to plot the PUC deposit data versus used oil BN. This is shown in **Figure 6a** for several tests on lubricants of differing initial BN but having the same additive chemistry. The results show that once BN drops to below ca. 20 mg KOH/g, deposits start to increase rapidly. It is well known that some BN providing additives also give detergency power to the oil, to keep the hot surfaces of the engine clean. And certain alkaline additives also provide anti-oxidant capacity.

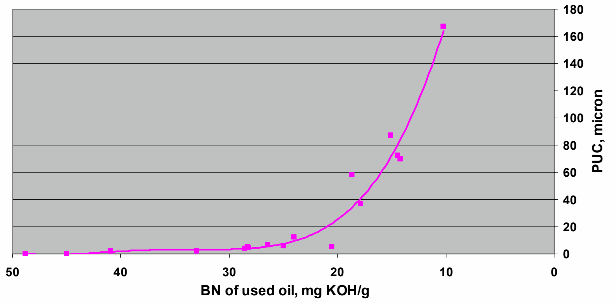

Fig 6a: PUC deposits versus used oil BN

For the lubricant technology shown in Figure 6a the alkaline additives are based on salicylate detergent chemistry which imparts both detergency and anti-oxidancy to the oil and explains why BN provides an overall measure of oil performance in this case. A correlation of PUC deposits with used oil BN may be less apparent with other lubricant technologies since not all sources of BN have such powerful detergency and anti-oxidancy.

Another interpretation of Figure 6a could be that acid stress (giving BN loss) results in high PUC deposits. However the relatively low levels of oxidation acids seen in used oils from the 4L20 test combined with the absence of piston ring and liner corrosion show that acid stress is under control. Thus the primary influences on PUC deposits would appear to be asphaltene stress and thin film thermal/oxidative stress which become more critical at lower lubricant detergency (lower BN) levels.

4.3 Effect of fuel batch

Additional 4L20 engine tests with another batch of test fuel (batch 15) have shown that the growth of PUC deposits with used oil BN is less pronounced than with the earlier fuel (batch 14) discussed so far in this paper (see **Figure 6b**).

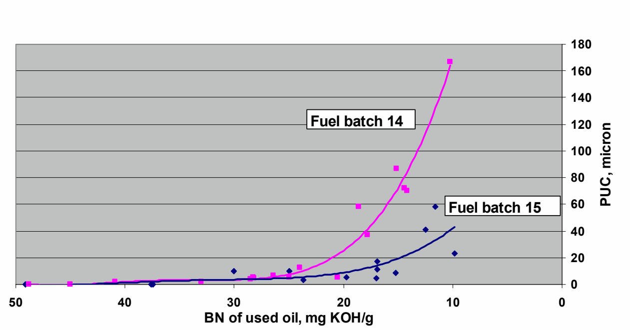

Fig 6b: PUC deposits versus used oil BN, two series of tests with different batches of heavy fuel

Thus fuel composition will strongly influence PUC deposit growth even if the standard analytical properties of the fuels are quite similar, as shown in **Table 3.** This means that any engine test comparisons across different lubricants need to be made with the same fuel batch.

Table 3 - Properties of the heavy fuels used for engine tests

Property	Unit	Batch 14	Batch 15
Kinematic viscosity, 50°C	mm^2/s	426	378
Density, 15°C	kg/m^3	0.9905	0.9882
CCAI		850.3	849.2
Asphaltenes	%m/m	7.0	6.9
Micro carbon residue	%m/m	16.1	14.7
Sulphur	%m/m	3.35	3.54
Vanadium	mg/kg	73	106
Sodium	mg/kg	11	19
Aluminium	mg/kg	1	4
Nickel	mg/kg	24	32
Silicon	mg/kg	2	7
Initial boiling point	°C	208	212

From a practical viewpoint the results show that a high quality lubricant with a sufficient margin of quality should be used in order to cope with the variations in fuel composition that occur in the field. From a research perspective, a better understanding of heavy fuel composition on medium speed engine performance, particularly on PUC deposits and fuel pump lacquer, is needed in the future.

4.4 Viscosity increase and Asphaltene Stress

What are the main causes of viscosity increase for a medium speed engine giving high oil stress (as shown in Figure 3b) among, for example, soot, oxidation, fuel contamination (asphaltenes) and other insolubles? Oxidation would appear to be an unlikely cause on the basis of the low level of oxidation measured in a used oil from the laboratory engine, discussed earlier. One possible cause is asphaltenes. To investigate this used oils ex the 4L20D were analysed for asphaltene content together with used oils (based on same oil technology) from the field covering five Marine/Power engines of different makes. Asphaltene content was measured by size exclusion chromatography which is under investigation within the CEC group [4]. A plot of viscosity at 40 °C versus asphaltenes is shown in **Figure 7** (viscosity at 100°C versus asphaltenes gives a similar plot).

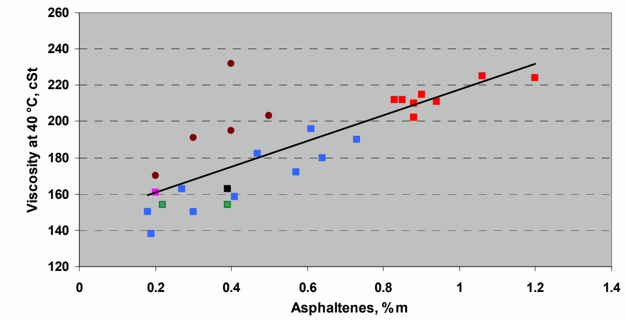

Figure 7: Viscosity versus asphaltene content of used oils

This shows a distinct trend of increased viscosity correlating with increased asphaltenes with the conclusion that fuel contamination of the lubricant is a primary cause of viscosity increase. The Shell W4L20 engine test samples (blue labels) lie close to the correlation line at its lower part showing that the engine test is reproducing field experience in most cases with the exception of one particular set of field samples (with brown circular labels) that diverge from the correlation. This suggests that although asphaltenes from fuel are an important cause of viscosity increase, there can be other causes, for example soot or another form of insolubles. Further investigation is in progress focusing on the nature and type of the particles in these used oil samples. Standard analyses such as n-heptane insolubles and toluene insolubles measurements did not reveal particularly high contaminant levels that could be correlated with the high values of viscosity at 40 °C (in the range 200-

230 cSt). In principle, n-heptane insolubles gives total insolubles and the difference between n-heptane and toluene insolubles gives a measure of lubricant-derived degradation products.

In view of the negative effects of heavy fuel contamination of the lubricant on PUC deposits, viscosity increase and fuel pump lacquer, a major challenge for the future is for a) engine builders is to reduce the level of heavy fuel contamination of the lubricant, and b) for lubricant formulators to design lubricants that can better cope with this contamination.

5. CONCLUSIONS

- The Shell W4L20 medium speed engine running on heavy fuel has been modified to run at a BMEP of 27.3 bar, from an original value of 22.5 bar, resulting in high Oil Stress (in kWh/g). A laboratory method with this engine has been developed for lubricant evaluation that includes deliberate contamination of the lubricant with heavy fuel to mimic this occurrence in the field. With this severe engine test procedure a duration of 320 – 500 hours is equivalent, in terms of Oil Stress and BN depletion, to several thousands of hours in the field.

- Oil and engine performance of different lubricants have been interpreted in terms of Oil Stress, its three main components in medium speed engines operating on heavy fuel being acid stress, thermal/oxidative stress and asphaltene stress from fuel contamination.

- Lubricant BN depletion is higher for the higher engine output mode, as would be expected from higher acid stress resulting from higher fuel sulphur throughput into the engine combined with lower oil consumption. In addition, brake specific BN depletion of the higher output mode is slightly more than that of the lower output showing that the engine factors that deliver acids to the lubricant are slightly more severe for the higher output mode.

- For piston undercrown (PUC) deposits, asphaltene stress of the lubricant and thermal/oxidative stress (including oxidative stress of the fuel) in the thin lubricant film context are primary factors. Thus heavy fuel contamination of the lubricant is a primary cause of PUC deposits.

- For oil technology such as that based on salicylate detergent chemistry, BN reflects to an extent lubricant detergency and anti-oxidancy in addition to its acid neutralisation capability. With such an oil technology, PUC deposit growth correlates with used oil BN, there being a break point at a BN level of 20 below which rapid PUC deposit growth occurs. Keeping the oil quality (and detergency) above this break point will prevent excessive PUC deposit growth and the resulting piston over-heating and hot corrosion. In a related manner, a higher initial BN for such an oil technology will control PUC deposits at a low level for longer. Benefits for a higher BN oil are also seen for piston ring belt deposits and fuel pump lacquer.

- Thermal/oxidative stress of used oils in the latter part of the Shell W4L20 laboratory test is higher than that experienced in the field, based on measurements of residual antioxidancy with scanning calorimetry. For oil technology such as that based on salicylate, a higher BN oil gives a greater degree of anti-oxidant reserve.

- PUC deposit levels in the laboratory engine are strongly influenced by the batch of heavy fuel. In the field this means that a high quality lubricant with a sufficient margin of performance should be used to cope with any variations in fuel composition. In the research context, since standard analytical properties of the fuels tested did not give insights to explain the engine differences it is recommended that further work should be carried out on the relationship between engine deposits and heavy fuel composition.

- Asphaltene contamination of the used engine lubricant increases oil viscosity. A general correlation of viscosity increase with increased asphaltene level (from fuel contamination) was found though one set of field samples was off this correlation suggesting another cause of viscosity increase in this case.

- In view of the strong negative effects of heavy fuel contamination of engine lubricant, major challenges are for a) engine builders to reduce the level of contamination through improvements in hardware, and b) lubricant formulators to design lubricants that can better cope with this contamination.

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