1. Introduction

Driven by the automotive industry’s increased use of higher refined base oils, Group II capacity is increasing and Group I capacity is forecast to decrease. (Figure 1)

As shown in the pie chart (Figure 2), the lubricant market is dominated by automotive crankcase lubricants (48%). Marine constitutes only 7% of the total lubricant market. Over the past decade, several reasons had colluded to drive the proliferation of Group II base stocks:

- Better properties of Group II base stocks (e.g. oxidation stability)
- Manufacturing efficiencies
- Lack of new investment in Group I base stock plants

As a result, the supply of Group I base stocks is expected to fall from >50% market share in 2012 to less than a third in 2022; whilst Group II will continue to increase (Figure 3). Correspondingly, the demand for Group II which is largely driven by the automotive industry (Figure 4), is expected to increase; whilst Group I will drop over the same period of time.

Figure 1: Industry drivers for Group I and Group II base stocks

Figure 2: Global lubricant market

Group I base stocks had been traditionally used to blend trunk piston engine oils. These base stocks are produced using conventional techniques of distillation of the crude oil, followed by solvent extraction to remove most of the aromatic material and some of the naphthenics.
A Group II base stock has also undergone further hydrocracking and/or catalytic dewaxing to improve the low temperature properties and oxidation stability of the base stock. It is this further processing that provides the improved oxidation stability of the base stock.

The main challenge of using Group II base stocks in TPEO formulations is related to fuel contamination of the lubricant. This is a major concern since the majority of ocean-going vessels run their engines on heavy fuel oil (HFO). The asphaltenes that are present in the HFO has to be kept in solution and dispersed in the oil. Otherwise, the asphaltenes can agglomerate and create ‘Black Sludge’ within the engine. This is detrimental to normal engine operation and can cause high level of deposit formation leading to abrasive wear and/or choked oil galleries, leading to oil starvation.

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groups, nitrogen (amines, amides) and oxygen within various functional groups (ketones, amides, phenols, carboxylic acids) and also metals Ni and V complexed with nitrogen in porphyrin ring structures. The asphaltene component of heavy fuel oil is a key species which must be controlled in terms of its build up on engine surfaces. If the lubricant cannot control this, unacceptable levels of piston undercrown deposits develop and ‘black sludge’ covers colder parts of the engine.

Although Group II base stocks have better oxidation stability compared to Group I; they also have poorer solvency properties for aromatics/polar species. As such, even though lubricating oils blended using Group II base stocks tend to have a relatively slower rate of viscosity increase, they would have a corresponding debit in asphaltene handling due to poorer solvency. Hence, although Group II base stock with its better oxidation stability (amongst other properties) is favoured by the automotive industry, the same is not necessarily true for marine applications using HFO as fuel.

In the early stages of the study, Infineum conducted a field test to compare the field performance of TPEO formulations blended with Group I and Group II. Two TPEO candidates were formulated with the same additive technology. One formulation used Group I base stocks and the other used Group II base stocks.

The results were evident and showed that the engine lubricated with the Group I formulated oil had cleaner engine parts. In particular, the piston undercrown (PUC) was very clean with insignificant amounts of carbon deposits (Figure 7). The average PUC deposits thickness was only 138µm average versus the OEM limit of 478µm.

Conversely, the Group II formulation had significantly higher amount of deposits that exceeded the OEM maximum limits. This demonstrated the asphaltene handling deficiency of the Group II formulation. There was also high level of deposits on the ring and the piston (lands and grooves) and significant amount of sludge in the colder regions of the engine.

As such, a solution was crucial if Group I base stock supply continues falling; whilst Group II base stock supply

Figure 6: Comparison of TPEO Formulations using Group I and Group II Base Stocks

Figure 6 shows dirty engine parts covered with deposits and ‘black sludge’ when formulations that have not been specifically designed for blending with Group II base stocks are used in marine engines burning HFO. There is therefore a need to improve the performance of a Group II formulation and bring it to the same level as that of one blended with Group I base stocks.

If marine engines do not burn HFO, then asphaltene handling would not be a problem. However, that is not the case and will not be the case in the foreseeable future. Following this, Infineum initiated a study to investigate this issue with the objective of identifying a solution to enable the use of Group II base stocks in TPEO formulations.
increases.
The challenge is then to find a solution to formulate TPEO with Group II base stocks that has equivalent asphaltene handling properties as a standard Group I formulation.

3. Solving the Challenge

Salicylate detergent technology has been widely recognized to have excellent asphaltene handling properties. This is because the Salicylate soap is especially effective (versus other conventional detergents) in keeping the asphaltens in suspension and preventing agglomeration of the asphaltene molecules. Agglomerated asphaltene molecules can easily fall out of solution and deposit onto engine parts. Infineum’s proprietary salicylate detergent technology has had many years of extensive field performance experience and has obtained many marine OEM approvals for TPEO formulations blended in Group I base stocks.

However, as we had seen earlier, changing the base stocks from Group I to Group II will affect the asphaltene handling capability of the TPEO formulation.

To this end, Infineum developed a bench test as a means to measure asphaltene agglomeration using the focussed beam reflectance method (FBRM). Investigations were carried out using the FBRM, amongst other test methods to screen for potential solutions to asphaltene handling performance. The more promising solutions were then verified using marine engine tests; and finally, the selected solution was field tested in an actual marine engine in field service.

![Figure 8: Focused Beam Reflectance Method (FBRM)](image)

The main bench test method used to investigate asphaltene handling was the focused beam reflectance method (FBRM). The FBRM technique involves the use of a beam of laser light focused on the outside of a window (Figure 8) and measures the laser energy that is reflected back into a probe by backscatter from particles on or close to the window. The data is acquired on-line and in real time to give particle size data and population trends of particles in suspension. To measure the degree of asphaltene agglomeration, the lubricating oil sample is doped with HFO. This test method had demonstrated good correlation with engine test results; in particular, the Wärtsilä 4L20 and is therefore expected to be a good predictor of the asphaltene handling capability of a lubricating oil. Infineum had used this bench test extensively to screen various additive technology solutions. The performance of the selected additive technology solution was then verified by running it in the Wärtsilä 4L20 engine under controlled test conditions.

Following the investigations, Infineum has now developed an additive booster package which when used together with its existing salicylate-based TPEO additive technology, enables TPEO formulations using Group II base stocks to perform at the same level as those using Group I base stocks in asphaltene dispersancy, whilst bringing the oxidation benefits that the Group II base stock carries. The FBRM bench test was used to screen and confirm its performance; and this was followed by the Wärtsilä 4L20 engine test.

The FBRM test was run on 30BN, 40BN and 50BN oils using the same salicylate-based additive package either with or without the additive booster package, blended in Group I and Group II base stocks accordingly. (Figures 9, 10 & 11). The formulation using Group I base stock is the baseline or reference. All results from the FBRM are normalised to the Group I formulation. The Y-axis is the normalized number of asphaltene particles of a certain size. An equal amount of heavy fuel oil was added to all three oils and mixed to simulate asphaltene contamination of the lubricating oils.

![Figure 9: FBRM results, 30BN oils](image)
FBRM testing showed that at all three BN levels, the additive booster package provided a clear improvement in asphaltene handling for the formulation blended in Group II base stocks (i.e. Group II + Boost)
Asphaltene handling was either equivalent or better than the Group I formulation.
Subsequently, these three formulations were tested on a Wärtsilä 4L20 marine engine.

The results of the Wärtsilä 4L20 engine test correlated well with those of the FBRM. The results clearly showed that the Group I formulation performed better than the Group II formulation in PUC deposits. (Figure 12, top graph).
However, this debit was corrected in the formulation with the additive booster package technology (Group II + Boost) and the performance in PUC deposits control for Group I and Group II were similar. (Figure 12, lower graph)
Nonetheless, despite its asphaltene handling deficiency, Group II base stocks have several other benefits. These includ VI, Noack and Oxidation stability merits compared to Group I base stocks.

4. The Benefits

Having addressed the challenge of asphaltene handling for Group II in TPEO application, the next step is then to investigate if TPEO formulations can draw on the benefits of Group II base stocks as well.

There are three additional areas of particular concern in TPEO applications:
- Oxidation control
- Viscosity control
- BN retention

Oxidation is a main contributor to engine oil deterioration. Thermal stress and the presence of oxygen leads to the lubricating oil becoming oxidized and subsequently results in an increase in both oil viscosity and acid number as well as production of insoluble compounds. The GFC Oxidation test (GFC T021-A-90) which is a bulk oxidation test method was used to study this mode of oil degradation. This test was conducted under the following conditions:
- 500 ml of oil was put in a flask and heated to 170°C for 216 hours
- Air bubbled through the lubricant at a constant rate
Kinematic viscosities at 40°C and 100°C were measured at:
- start of test
- end of test
TBN was measured at:
- start of test
- an intermediate point
- end of test

Although it is not an exact replication of actual engine condition, it has been shown to differentiate the resilience of different TPEO formulations against oxidation under heat in accelerated bulk oxidation condition and is a useful screener to compare lubricating oils.

Using the same salicylate-based TPEO additive technology, four test oils were blended and tested using the GFC test method. One of the test oils was blended using Group I base stock and served as the reference. The other three were blended using different Group II base stock slates. It was evident that the three formulations using Group II base stocks, having undergone further hydrocracking and/or catalytic dewaxing had better oxidation stability that translated into significantly better oxidation control compared to the reference formulation using Group I base stock (Figure 13).

Figure 13: GFC Oxidation Test (Viscosity change)

Perhaps not surprisingly, the TBN retention performance (Figure 14) of the four oils mirrored that of the viscosity change shown in Figure 13. The three Group II oils performed discernably better than the Group I reference oil. (Figure 14)

Figure 14: GFC Test (TBN retention)

The acid generated in the GFC test came from the oxidation of the organic components. Consequently, if the base stock is more resistant to oxidation then one would expect less acid to be generated. This in turn means that less base in the detergent will be depleted in the neutralisation process. This reduced consumption of base correlates with the general understanding that Group II oils with their better oxidation stability will show a lower rate of TBN depletion in the oxidation test.

To summarize the observations in the GFC test:
- The reference oil using Group I base stock exhibited the highest rate of viscosity increase and TBN depletion
- There were no clear distinction between the three test oils using Group II base stocks in both viscosity increase and TBN depletion

Similar observations were also recorded in other GFC experiments that Infineum conducted on various other additive systems.

We can thus conclude that there were potential benefits to be gained from using Group II base stocks in TPEO formulations. The question now remains: whether the same benefit can be extracted from a Group II TPEO formulation in an actual marine engine test.

For this purpose, two test oils, one blended with Group I base stocks and the other with Group II, and using the same TPEO additive technology were field tested in a Wärtsilä 4L20 engine under controlled laboratory conditions for 420 hours. The test oils were contaminated with the same amount of HFO to more realistically simulate conditions in field service.
Figure 15: Wärtsilä 4L20 Engine Test (Viscosity change)

Firstly, the viscosity control performance was assessed. The test results showed a greater viscosity increase in the Group I test oil. The differences in viscosity increase between both tests oils may appear small. (Figure 15). However, it should be noted that the Group I test oil took 324 hours for its viscosity to increase by 25% whilst the same increase was observed only at 559 hours for the Group II test oil.

(Note: the test protocol called for 420 hours test duration. However, the test was extended for the Group II test oil to determine the additional time required to stress the oil to the same level as the Group I test oil.)

When translated into actual field operation, when the engine runs for thousands of hours, the benefits of using a Group II bases stock becomes obvious.

Next, the piston undercrown (PUC) deposits control was examined.

Figure 16: Wärtsilä 4L20 Engine Test (PUC Deposits)

The Group II test oil showed significantly less PUC deposits and therefore, performed better compared to the Group I test oil across the entire measured surface of the piston undercrown. This was in contrast with the earlier Wärtsilä 4L20 engine test results (Figure 7) where the Group II formulation was deficient in PUC deposits control. The difference here was that the additive booster package for the Group II test oil had effectively mitigated this deficiency and in fact, had actually enabled the Group II test oil to exceed the performance of the conventional Group I test oil.

The third area of concern for TPEO is BN retention. BN depletion is primarily dependent on the amount of sulfuric acid generated in the engine during combustion. This in turn is dependent on the amount of sulfur in the fuel. In effect, this performance cannot be influenced by the choice of base stocks. Instead, it would be the additive technology used in the TPEO formulation that determines how effectively the sulfuric acid is neutralized and in particular, the resilience of the base carried by the detergent against acid depletion.

Figure 17: Wärtsilä 4L20 Engine Test (TBN retention)

The results from the Wärtsilä 4L20 test did not show any significant difference between the two test oils. Both formulations performed similarly in terms of BN depletion rate.

The Wärtsilä 4L20 engine test had demonstrated that improved performance of TPEO blended with Group II base stocks can be unlocked with the use of the appropriate additive technology. In this case, it was an additive booster package that provided the performance to mitigate the asphaltene handling deficiency of Group II base stocks.

5. Testing in the Field

Having completed the screening and engine testing, the additive technology was then subjected to an actual field test to ascertain proof of performance in field service.
A TPEO test oil incorporating the additive booster package was formulated together with a standard TPEO additive package in Group II base stock. This was compared against a reference oil that had only the standard TPEO additive package blended in Group I base stock.

5.1 Engine Cleanliness
Several photographs of the engine parts that were taken at the end-of-test are shown here to illustrate the performance of the test oil. These pictures showed that the various engine parts (piston rings, piston undercrown and crankcase) remained clean after completion of the field test. (Figures 18, 19, 20, 21 & 22)

The engine had remained satisfactorily clean and its engine parts had only light deposits. Light carbon deposits were found on rings 1 and 2. (Figures 18 & 19) Again, only light deposits were found on the piston undercrown. The crankcase was very clean with no trace of sludge formation. This would not have been the case if the test oil lacked the necessary asphaltene handling capability. This demonstrated that the TPEO test oil which incorporated the additive booster package had good asphaltene handling properties and was able to perform well in the field, keeping the engine clean.
5.2 Used Oil Analysis

Used oil was sampled at regular intervals and the viscosity was measured (Figure 23). The green line shows the plot of the Group II formulation blended with the booster package (i.e. “Group II plus new technology”). It should be noted that some fuel contamination happened at around 4000 running hours. This caused a one-off spike in the viscosity measurement.

However, the gentler slope of the viscosity increase shows performance is better in the Group II formulation than the Group I formulation. This confirmed initial expectations that the Group II formulation would potentially deliver better performance in viscosity control because of the better oxidation stability of Group II base stocks.

Finally, the TBN retention was examined. (Figure 24) The Group II formulation with the additive booster package (green line), showed better TBN retention up to 3500 hours compared to the Group I reference and another oil which had used a standard TPEO additive package blended in Group II base stocks. Unfortunately, after 3,500 running hours the engine had fuel contamination and this caused a significant drop in TBN after 3500 hours. For the other two test oils which did not experience any fuel contamination, there was little difference in the rate of TBN decrease until possibly 5000 hours.

Overall the results showed a faster TBN depletion with the Group I formulation (the blue line) versus the two formulations using Group II base stocks (green and red line). However, this trend requires more field testing to confirm.

6. Conclusion

The following conclusions can be drawn from this extensive study:

• Group II base stocks bring both advantages and challenges:
  • Benefits in oxidation control that could potentially bring credits in viscosity control and TBN retention
  • Disadvantages in asphaltene handling that could result in high levels of deposits and sludge build-up in the engine

Nonetheless, it was shown that an additive system designed to work with Group II base stocks can overcome the deficiency in asphaltene handling. This had been confirmed by a comprehensive study that included bench testing, engine testing and field testing.

However, even though the benefits of Group II base stocks were clearly demonstrated in the engine testing and field testing, it should also be noted that field tests are highly variable due to the following reasons:

• Engine load patterns
• Degree of HFO contamination
• Engine maintenance schedule

Hence, the performance improvements of Group II TPEO formulations have to be verified by more field testing.

7. Reference


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