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Achieving the right viscosity for marine lubricants in a sustainable future

Lubricants

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ABSTRACT

Two-stroke marine engine OEM specifications in practice have driven Marine Cylinder Lubricants (MCLs) to have a kinematic viscosity of more than 18.5cSt at 100°C. To blend most MCLs to such viscosity, traditional heavy neutral API Group I base oils (BO) alone are insufficient and a thickener needs to be applied. Due to its properties as well as the historic availability and cost-effectiveness, API Group I bright stock (BS) has become the typical thickener of choice in MCL formulations.

There are several important industry trends impacting the availability of Group I BO and BS. The evolving low-sulfur and low-viscosity specification requirements for automotive engine oils have played a major role. As a result, the manufacturing of Group I BO and the associated BS production have been downsizing globally, and the lubricant industry at large has witnessed regional supply shortage and price increase of Group I BO and BS. The International Maritime Organization (IMO) marine engine regulations have also driven the maritime industry toward lower sulfur fuel oils which demand lower base number (BN) MCLs that typically require more BS to get to the specified viscosity. Toward the future, the IMO green-house gas (GHG) targets, emerging new fuels, and growing sea transport will drive further increments both in MCL performance requirements and in MCL consumption rates. The marine lubricant industry therefore needs to consider other thickening options and their technological readiness levels to ensure it can continue to achieve the right viscosity and desired performances for marine lubricants in a sustainable future.

We have been continuously exploring pathways to overcome the BS challenge for MCLs. Our view is that proper chemical or physical forms of any constituent in an MCL formula can, in theory, offer thickening effect. From this point of view, we have categorized the MCL thickening chemistries and physics in our studies into alternative thickeners, base oil thickeners, additive component thickeners, and non-thickeners (lower viscosity MCLs). This paper will showcase bench, engine and field testing results on these MCL thickening pathways.

Alternative thickeners are direct replacements of the conventional BS thickener. Performances of two chemistry types of alternative thickeners are presented in MCLs of 40BN and 70BN from their bench testing, laboratory engine testing and field trials on commercial vessels. It is demonstrated that these two different chemistry types of alternative thickeners do not perform the same.

A base oil thickener refers to a higher viscous BO that thickens a less viscous BO. A heavy API Group II BO with kinematic viscosity equivalent to BS is evaluated as a BS replacement in bench testing, on laboratory engine and in field trial. Test results have displayed its piston deposit and ring / liner wear control performance equivalent to BS.

Additive component thickeners are additive components with thickening propensity that simultaneously offer other performance benefits. An additive thickener of dispersancy performance is presented in this article. Laboratory engine and field testing results show that an appropriate dose of the dispersancy thickener in a 40BN MCL can reduce BS dependence appreciably and improve piston cleanliness.

Finally, lower viscosity for MCLs is discussed as an approach to minimize usage of thickeners. Lower viscosity for MCLs is an explorative pathway that has both opportunity and risk associated with it. This article will display field testing data on lower viscosity MCLs with kinematic viscosity at 100°C below the normally accepted 18.5cSt.

1 INTRODUCTION

To establish desired lubrication regime and guarantee scuffing-free operation of piston ring and cylinder liner contact in applications with diversified fuels and under varying operating severities, OEM specifications of low-speed two-stroke marine engines in practice have driven Marine Cylinder Lubricants (MCLs) to the kinematic viscosity at 100°C (KV100) of minimum 18.5cSt [1-5], which corresponds to SAE 50 or higher viscosity grades. To blend most MCLs to such viscosity, traditional heavy neutral API Group I or II base oil (BO) plus typical MCL additive packages are insufficient - The highest viscosity BO that is typically available from Group I or II BO on global market has an average KV100 of 12.0cSt by itself, and the additional increase in KV100 from the additive system adds by ~2cSt - and the remaining viscosity will need to come from a thickener. Due to its properties as well as historic availability and cost-effectiveness, API Group I bright stock (BS) has become the typical thickener of choice in MCL formulations.

How long BS remains the thickener of choice for MCLs is an open question. Several important industry trends have been impacting the availability of Group I BO and BS. The evolving low-sulfur and low-viscosity requirements for automotive engine oils (AEO) have played a major role. The trend toward replacing Group I with Group II and III BOs in AEO has progressed steadily for decades. As a result, the manufacturing of Group I BO and the associated BS production have been dwindling globally, and the lubricant industry at large has witnessed regional supply shortage and price increase of Group I BO and BS as well.

The IMO marine engine regulations have also driven the maritime industry toward low sulfur fuel oils as well as lower carbon fuels. According to OEM lubrication strategy, operating on low sulfur or lower carbon fuels entails low BN or low ash MCLs which typically require more BS to get to the desired viscosity due to reduced treat rates of high viscous additive packages. For example, BS wt% in MCLs blended with one same package and targeting the same KV100 at 18.5cSt in Group I BO ascends from 3% up to 23% when BN descends from 140BN down to 70BN. It is true with lower BN scenarios where MCLs of various BNs are blended with different packages. For instance, with the same KV100 target at 18.5cSt, BS wt% accounts for 31% in a 40BN MCL with a package and for 33% in a 15BN MCL with a different package. Toward the future, the more stringent IMO GHG targets, emerging or future fuels accompanied by their unique combustion chemistries, high-performing engine design and demanding operations, as well as growing sea transport will drive further increments both in MCL performance requirements and in MCL consumption rates, and thus high quality and quantity demands for thickeners.

The impact of internal combustion engine lubricant trending has been exacerbating the BS supply-demand imbalance. As forecast by 2023 Kline report [6], somewhere between 2022 and 2027 there will be a disconnect between API Group I BS supply and demand; availability of performance-proven API Group II BS around 2027 is expected to alleviate the BS supply-demand imbalance, but total BS supply deficits at less extents are still anticipated till 2042 (Figure 1). Of the BS consumers, marine lubricant sector is not the major one and it has been competing with automotive and industrial gear oils, monograde AEOs, greases, as well as process fluids for the limited BS quantity [7,8]. The marine lubricant industry needs to explore thickening options other than BS and promote their technological readiness levels to ensure it can continue to achieve the right viscosity and desired performances for marine lubricants in a sustainable future.

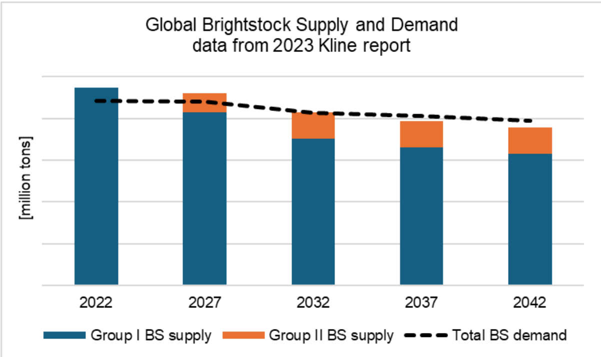
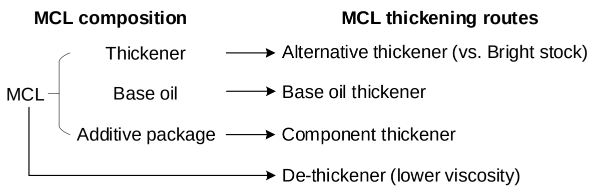


Figure 1. A forecast of global brightstock supply-demand balance (data source: *Kline Basestocks Intelligence Center)*

2 MCL THICKENER CONCEPTUAL SYSTEM AND THICKENING ROUTES

Through R&D practices, we have formulated our MCL thickener conceptual system and non-BS thickening routes as illustrated underneath.



Our view is that proper chemical forms of any constituent in an MCL formula or physical states of an MCL can, in theory, offer thickening effect or reduce BS usage. From this point of view, we classify and differentiate the non-BS thickener options and routes in our studies into alternative thickeners, base oil thickeners, additive component thickeners, and non-thickeners (lower viscosity MCLs) in contrast with the conventional BS thickener in MCLs. In brevity, we present below working definitions of the thickener options and thickening routes defined in our exploring studies.

Alternative thickener (AT)

Alternative thickeners, or performance thickeners as dubbed in grease industry, are direct replacements of the conventional BS thickener, and they can be blended either in the same way as BS into BO, or into MCL additive packages (depending on their compatibility with the packages) and then the thickened packages into BO. Two types of polymeric chemistries as BS alternatives are covered in this article and both are of polymeric chemistry but synthesized via different monomers, and therefore they assume varied chain lengths or molecular weights (Mw), structures/configurations and chemical activities or reactivities. Evaluation results of analogs of the two polymeric chemistry types of alternative thickeners at complete replacement of BS in MCLs are presented in this article.

Base oil thickener (BT)

Base oil thickener refers to a higher viscous base oil that thickens a less viscous base oil. Strictly speaking, BO thickener is a misnomer because both BO and thickener in an MCL formula are *de facto* carrier fluid of the additive package. BO and thickener are complementary in physicochemical properties (e.g., additive solvency). When they are of disparate chemistry types, the high-viscosity carrier fluid is labeled as alternative thickener. A heavy API Group II base oil of KV100 equivalent to BS is evaluated at complete replacement of BS in this article.

Additive component thickeners (CT)

Additive component thickeners are molecules that demonstrate thickening propensity while exhibiting their designed or expected functions. Thickening additives are blended into additive packages because they are of and compatible with commonly used functional additives. Reduction of BS usage in MCLs in the presence of dispersancy thickener varies with both the optimized dose of the dispersancy thickener and the treat rate of the additive packages under study. Formulation of well-designed dispersancy thickeners can help achieve the right viscosity without use of BS. This article presents the field testing results of one dispersancy thickener that can reduce BS usage below 1wt% in a 40BN MCL formula.

De-thickener (DT)

'De-thickener' is coined to denote an MCL formulating approach of minimizing usage of thickeners. Lowering viscosity of MCLs is an explorative de-thickener approach. The philosophy is that, by lowering finished oil viscosity and accompanied by well-tailored formulation chemistry, levels of BS or alternative thickeners can be reduced or removed without sacrificing field performances. A potential benefit from the lower viscosity de-thickener approach is gaining fuel economy without deteriorating tribological reliability. Field testing performances of MCLs of KV100 down to low-end of SAE 50 viscosity grade and SAE 40 viscosity grade range are compared in this article. The allowable extent of de-BS is dependent of the viscometrical requirements by OEMs. Pros and cons of the de-thickener approach are detailed in the last section of this article.

3 ALTERNATIVE THICKENERS

Pre-screening of alternative thickeners for MCLs has been exercised from a balanced perspective of polymer chemistry, formulation appetite, and alternatives cost. Two hydrocarbyl types of polymeric chemistries that are constructed from different monomers have been singled out as commencements in the alternative thickener initiative – each type assumes its own distinctive structural and/or reactive features on the primary level but both polymeric types are commonly characterized by molecular weight on the secondary level. No-harm MCL bench and engine testing have been conducted to rank the polymeric chemistries, and one candidate in each type that offers the highest thickening efficiency is further tested in sea trial to demonstrate its real-world performance unless a different alternative thickener candidate stands out with outpeered bench and/or engine testing performances.

3.1 Polymeric ATs in terms of chemical types (Type I & Type II) and molecular weights

3.1.1 Laboratory bench testing

Three polymeric chemistries designated as Type I and Type II with varied molecular weights were selected and blended respectively at complete replacement of BS in the same high-performance MCL baseline in API Group II base oil to 40BN and KV100 of 18.5cSt.

Oxidation resistance capability (thin oil layer and bulk oil phase) and deposit formation tendency (thermally induced lacquer) of the three test oils were evaluated against the reference oil (same formula features as test oils except for BS as thickener) under conditions of in-house marine bench testing protocols (Differential Scanning Calorimetry, Modified IP-48 and Komatsu Hot Tube). Testing results of the three test oils with polymeric alternative thickeners were displayed and compared against reference oil in Figure 2 (*Note: direction of arrow along with Y-axis title on all graphs in the article points to better performance*).

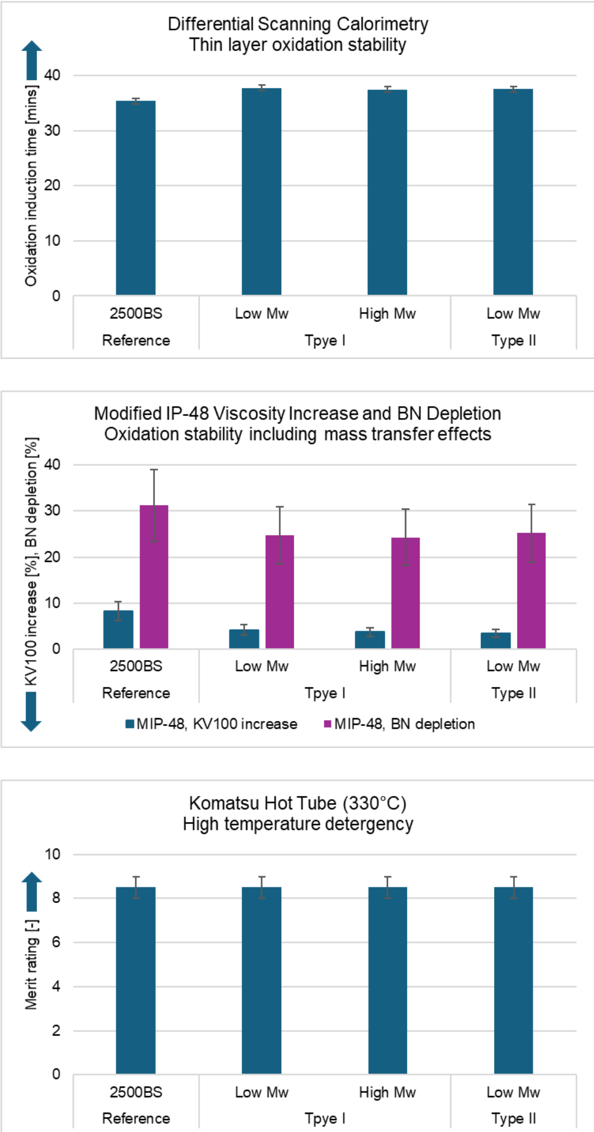


Figure 2. Bench testing results of a high-performance 40BN MCL package in Group II BO with BS vs. polymeric alternative thickeners in terms of chemical types and molecular weights.

It is observed that test oils with the three polymeric chemistries, regardless of their types (I, II) and molecular weights (high, low), have demonstrated equivalent oxidation resistance and deposit reduction performance among themselves, and the overall performances exhibited by the three test oils are equivalent to or slightly better than the reference oil thickened by BS.

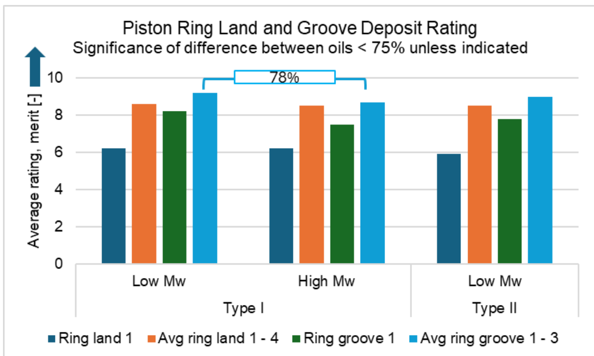
3.1.2 Bolnes engine testing

As an intermediate MCL testing protocol bridging bench testing and sea trial in component screening and formulation development, two Bolnes 3DNL engines are installed by Oronite at its Rotterdam research facility. These three-cylinder two-stroke crosshead diesel engines can be operated on a variety of liquid fuels in the split lubrication mode. Key characteristics of the two Bolnes 3DNL engines are listed in Table 1.

Table 1. Bolnes 3DNL setup and operations

Design/Operation parameters	Set values
Bore (mm)	190
Stroke (mm)	350
Power (kW)	375
BMEP (bar)	15
Speed (rpm)	510

Deposit formation in the ring pack area and wear of ring-liner contact are critical performances under radar when looking for alternative thickeners for MCLs. These performances were compared among the three polymeric chemistries of Type I and Type II as thickeners in the same 40BN MCL baseline under proprietary operating conditions using low-sulfur fuel oil (Figure 3). Overall, deposit merit rating (the higher the better) and deposit quantity (the lower the better) on the critical piston ring lands/grooves and rings did not appear statistically significant (Significance of difference <75%) among the three polymeric alternative thickeners. In terms of wear on rings and liners, differences of the wear magnitudes were statistically insignificant among the three test oils in general. Figure 4 displayed the photographic views of the ring pack area of end-of-test (EOT) pistons from each test oil. From a balanced perspective between piston ring deposit formation tendency and total ring wear severity, the high molecular weight polymeric chemistry of Type 1 behaved slightly better than its two counterparts and it was chosen for field testing.



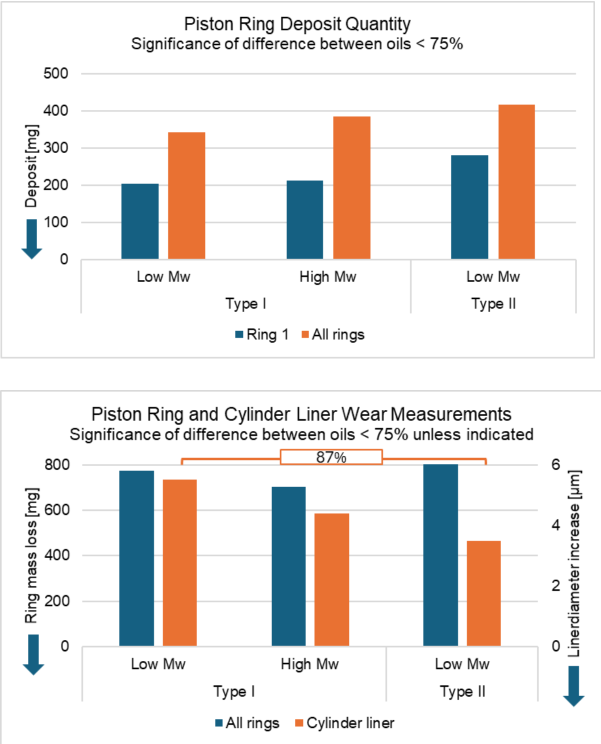


Figure 3. Bolnes testing results of a high-performance 40BN MCL package in Group II BO thickened by three polymeric alternative thickeners in terms of chemical types and molecular weights.

40BN MCL in Gp II BO thickened by low Mw polymer of Type I

40BN MCL in Gp II BO thickened by high Mw polymer of Type I

40BN MCL in Gp II BO thickened by low Mw polymer of Type II

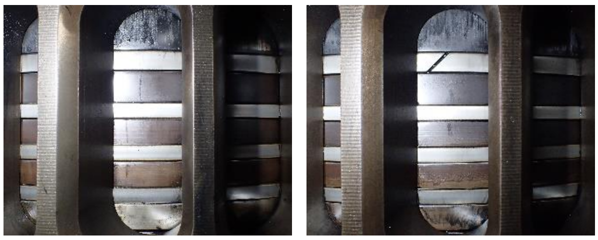
Figure 4. EOT Bolnes 3DNL piston exterior of representative status or intermediate appearances from test oils described in Figure 3.

3.1.3 Field testing

The high molecular weight polymeric alternative thickener of Type I (designated as AT1), because of its equivalent overall Bolnes engine testing performances in terms of deposit and wear to its two counterparts and its relatively higher thickening capability, was further tested as a representative in a 70BN MCL blended with a commercial MCL package in Group II BO to demonstrate its field performance. The reference oil was blended with the same package in Group II BO/BS to the same BN and KV100 target (18.5cSt). The field testing was accomplished on an MAN B&W 6S90ME-C Mark 8 engine with split lubrication configuration for 4162 main engine run hours (MERH). During the test period, the engine was operated on high sulfur fuel oil with sulfur content between 3.0wt% and 3.5wt%.

EOT scavenge port inspection was conducted without removing a piston or pulling a piston. Figures 5 through 7 displayed, respectively, the SOT / EOT photographs of the piston ring pack area, carbon demerits (the lower the better) of key piston regions, as well as ring and liner wear rates from the test oil against the reference oil. The test oil did show at least equivalent performance to the reference oil. Specifically:

- The piston lubricated with the test oil showed good deposit control or lower carbon accumulation on both crownland and ring lands (Figures 5 & 6).
- The ring pack lubricated with the test oil were found with beveled edges and good tension (Figures 5 & 6).
- The ring coating wear rates from the test oil was equivalent to or lower than the reference oil (Figure 7).
- The liners were found in good condition. Liner wear rate (solid line) for the test oil was equivalent to the reference oil (Figure 7).



SOT: Test oil (left) vs. Reference oil (right)

EOT: Test oil (left) vs. Reference oil (right)

Figure 5. EOT visualization of maneuver side of piston ring pack area from 70BN test oil blended in Group II BO / AT1 vs. 70BN Reference oil blended in Group II BO / BS.

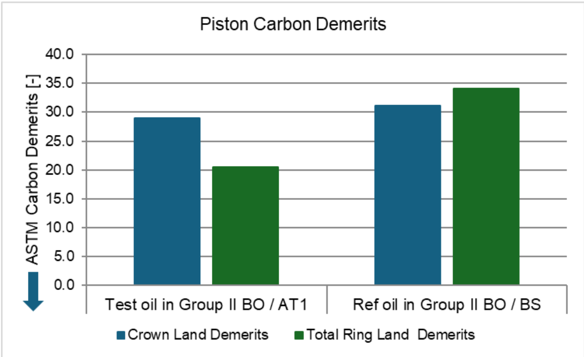


Figure 6. Carbon demerits on key piston regions from 70BN test oil blended in Group II BO / AT1 vs. 70BN Reference oil blended in Group II BO / BS.

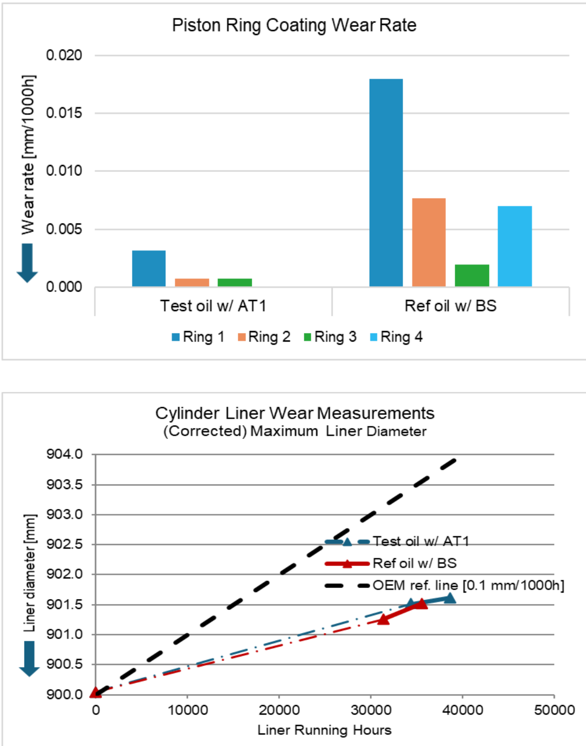


Figure 7. Piston ring wear in terms of Alu coating thickness loss rate (upper) and cylinder liner wear in terms of corrected maximum liner diameter (lower) from 70BN test oil blended in Group II BO / AT1 vs. 70BN Reference oil blended in Group II BO / BS.

Given the satisfactory overall performances of the test oil versus the reference oil, the 70BN MCL test oil blended in Group II BO thickened with the high molecular weight polymer of Type I alternative thickener obtained Category I Non-Objection Letter (NOL) from MAN ES.

3.2 Polymeric ATs in terms of chemical types (Type A & Type B) and molecular weights

3.2.1 Laboratory bench testing

Three polymeric chemistries designated as Type A and Type B with varied molecular weights were selected and blended respectively at complete replacement of BS in the same baseline in API Group II base oil to 70BN and KV100 of 19.5cSt. The same bench testing philosophy and approach described in section 3.1.1 were employed. Testing results of three test oils with polymeric alternative thickeners of varied molecular weights under Type A and Type B were displayed and compared against reference oil in Figure 8.

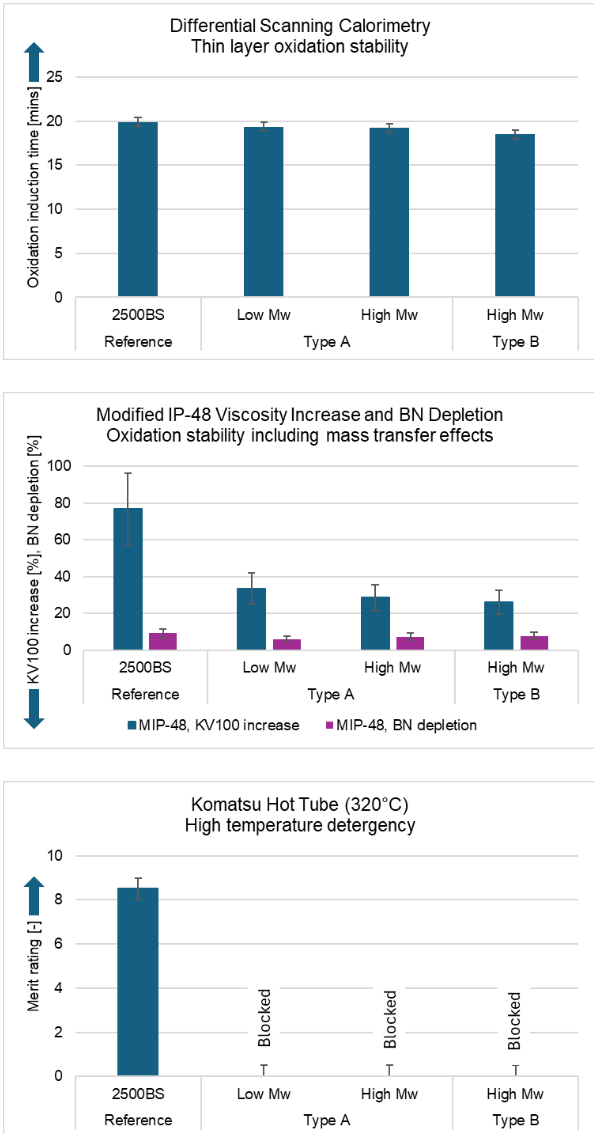
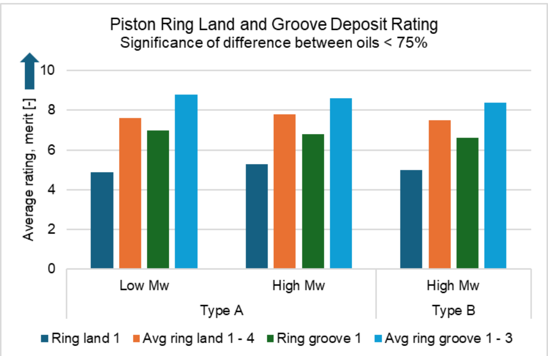


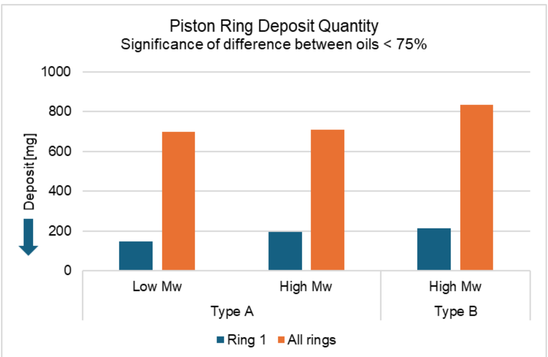
Figure 8. Bench testing results of a commercial 70BN MCL package in Group II BO with BS vs. polymeric alternative thickeners in terms of chemical types and molecular weights.

It is observed that test oils with the three polymeric chemistries, regardless of their distinct chemical and structural variances, do not demonstrate distinguishable disparities in the selected oxidative and deposit-forming bench testing. It is also interesting to note that, despite their equivalent or better performances in comparison with conventional BS in the bulk phase ageing (MIP-48), they all lead to increased sludge formation at high temperature, or their high temperature detergency characteristics have deteriorated rapidly as compared with conventional BS thickener.

3.2.2 Bolnes engine testing

Following the same Bolnes engine testing program on polymeric alternative thickeners characteristic of molecular weight and Type I or II, deposit formation in the ring pack area and wear control of ring-liner contact were compared among the three polymeric chemistries characteristic of molecular weight and Type A or B as thickeners in the same 70BN MCL baseline under proprietary operating conditions using high-sulfur fuel oil. Figure 9 exhibited the cleanliness and wear status of the key piston regions from the alternative thickeners of Type A and Type B. Generally, deposit rating (the higher the better) and quantity (the lower the better) on the critical piston areas do not appear statistically significant among the three alternative thickeners of Type A and B, which were substantiated by the cleanliness visualizations in the ring pack area of EOT pistons from each test oil (Figure 10). In terms of wear magnitudes on rings and liners, the three test oils were statistically insignificant in general.





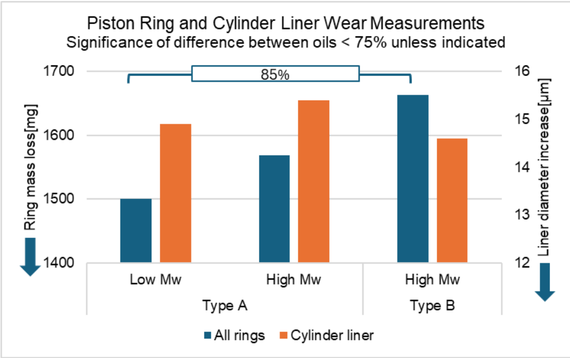


Figure 9. Bolnes testing results of a commercial 70BN MCL package in Group II BO thickened by three polymeric alternative thickeners in terms of chemical types and molecular weights.

70BN MCL in Gp II BO thickened by low Mw of Type A

70BN MCL in Gp II BO thickened by high Mw of Type A

70BN MCL in Gp II BO thickened by high Mw of Type B

Figure 10. EOT Bolnes 3DNL piston exterior of representative status or intermediate appearances from test oils described in Figure 9.

Given the equivalent deposit formation and wear performances, the polymeric chemistry of high Mw and Type B was chosen in next-stage field testing because of its relatively higher thickening efficiency than its two counterparts – The three alternative thickeners account for 7.0wt% (Low Mw / Type A), 6.8wt% (High Mw / Type A) and 6.3wt% (High Mw / Type B) in the finished oils.

3.2.3 Field testing

Field testing was initiated with the objective to obtain OEM approval for use of the selected high Mw / Type B alternative thickener (designated as AT2). The test oil was blended with a commercial MCL package in Group II BO thickened by AT2 targeting 70BN and KV100 of 18.5cSt. The reference oil was an MAN ES approved MCL blended using the same commercial MCL package in Group II BO thickened by BS to the same BN and KV100 targets. The field testing was accomplished on an MAN B&W 6S90ME-C Mark 8 engine with split lubrication configuration for 4000 MERH. The engine was operated on VLSFO.

From piston appearance, deposit thickness in ring grooves and on ring backsides, as well as cylinder liner wear rate, it was obviously seen that:

- Piston cleanliness of the test oil thickened by AT2 was better than or at least equivalent to the reference oil thickened by BS. No detrimental effect was observed for the test oil thickened by AT2 vs. the reference oil thickened by conventional bright stock (Figures 11 and 12).
- There was very low liner wear during test for the test oil thickened by AT2 vs. the reference oil thickened by conventional bright stock (Figure 13).
- Wear rate of Alu coat over field testing period was monitored on ring 1 of one unit for test oil and one unit for reference oil. Both wear rates were naught.

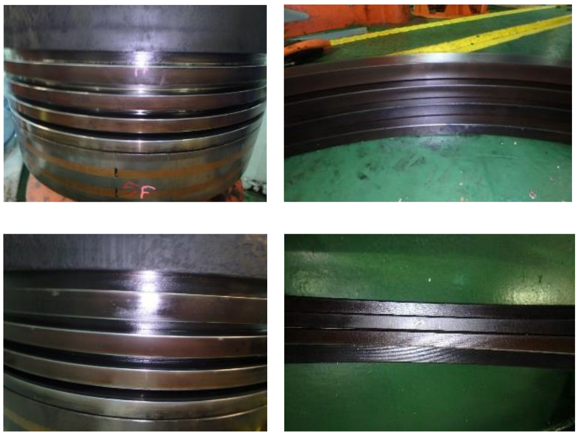
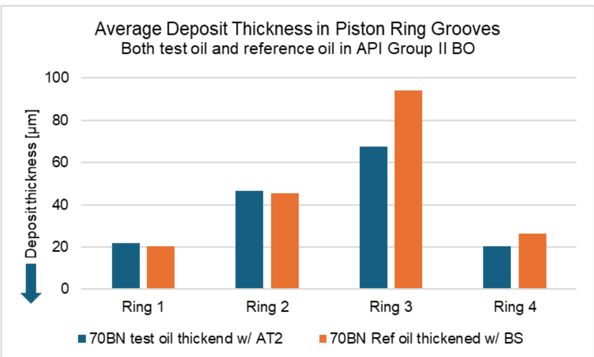


Figure 11. Ring lands, ring grooves and ring backsides of test oil (upper) and Reference oil (lower).



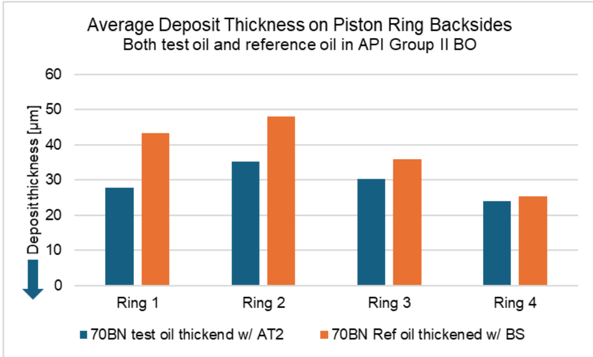


Figure 12. Deposit thickness for test oil vs. reference oil in piston ring grooves and on the backside of piston rings.

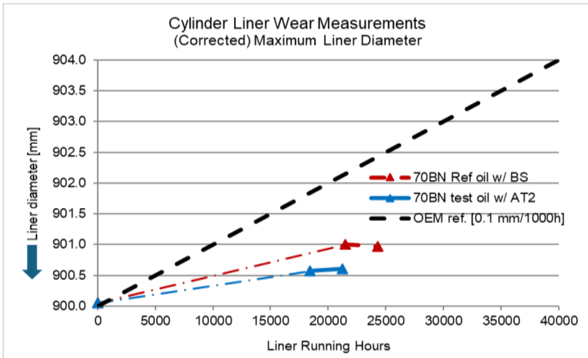


Figure 13. Cylinder liner wear in terms of corrected maximum liner diameter from 70BN test oil blended in Group II BO / AT2 vs. 70BN Reference oil blended with the same MCL package in Group II BO / BS.

Given the satisfactory overall performances of the test oil versus the reference oil, the 70BN MCL test oil blended in Group II BO thickened with the high molecular weight polymer of Type B alternative thickener obtained Category I Non-Objection Letter (NOL) from MAN ES.

It is not possible to directly compare the 70BN test oils thickened by AT1 (high Mw of Type I) and AT2 (high Mw of Type B) in their detergency capabilities or piston deposit control performances demonstrated in the field because they were field tested in different scenarios and their EOT piston deposits have been characterized by different parameters. However, both test oils have shown deposit formation performances equivalent to or slightly better than the same 70BN reference oil with BS in their field testing, which implies that impact of the two selected polymeric alternative thickeners on detergency or piston cleanliness are equivalent in 70BN MCLs. From the perspective of cylinder liner wear rates of both 70BN test oils, the wear rates in both scenarios with AT1 and AT2 are much lower than the reference oils but the test oil thickened by AT2 behaves slightly better than the test oil thickened by AT1.

4 BASE OIL THICKENER

Of petroleum crude-sourced bright stocks, there are API Group I BS and Group V BS which are extracted, respectively, from paraffinic and naphthenic feedstocks using conventional BS production scheme (solvent de-asphalting). In addition, there are alternate bright stocks from petroleum crudes but by non-conventional BS production scheme which brings them to API Group I or II levels [7,8]. In our study, an alternate BS from paraffinic crude and of API Group II characteristics, ExxonMobil's EHC 340 MAX™ from its global EHC™ Group II slate [9], was evaluated as an MCL thickener. Selection of this product as a BO thickener, labeled as BT below in the context, was based on our years of testing and usage learnings in cooperation with a longtime customer.

4.1 Bench testing

An in-house developed commercial 40BN MCL package was blended at the same treat rate in Group I BO plus Group I BS and BT, respectively, as reference oil and test oil. A pair of 100BN MCL reference oil and test oil were blended using an in-house developed commercial 100BN MCL package in the same BO and thickener combinations as their 40BN MCL counterparts. In the blends at both BN levels, BT usage was lower, which was attributable to its slightly higher thickening efficiency than BS (Table 2).

Table 2. Compositions of 40BN and 100BN MCLs blended in Group I BO thickened, respectively, by Group I BS vs. Group II BT, and percentages of BO and thickeners (BS or BT) in mixture of BO and thickener.

KV100 target = 18.5cSt		Gp I BO %	Thickener %
40 BN	BS40	65.4	34.6 (BS)
	BT40	67.1	32.9 (BT)
100 BN	BS100	86.5	13.5 (BS)
	BT100	87.5	12.5 (BT)

The reference oils and test oils were evaluated using the MCL bench testing program as described in Section 3.1.1, with results being displayed in Figure 14.

Overall, substitution of conventional Group I BS by Group II EHC 340 MAX™ yielded equivalent oxidative stability and deposit formation tendency of MCL formula at both 40BN and 100BN levels. Since BO type and level at the desired KV100 target at each BN segment remain nearly unaltered, it can be stated that Group II EHC 340 MAX™ could act as a full BS replacement from the perspective of the investigated bench testing performances.

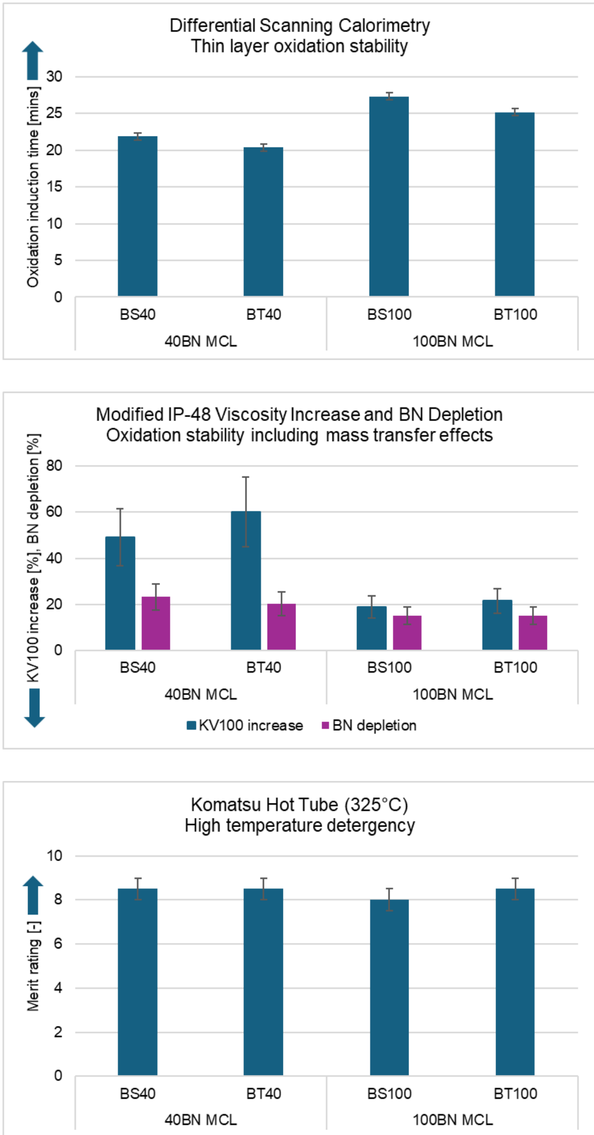


Figure 14. Bench testing results of 40BN and 100BN MCLs in Group I BO thickened, respectively, by Group I BS vs. Group II BT

4.2 Bolnes engine testing

Because the conventional Group I BS thickener and Group II EHC 340 MAX™ demonstrated the performance equivalency in oxidative stability and deposit formation tendency, a Bolnes testing matrix was designed which included two pairs of MCLs at 40BN and 100BN levels based on different commercial MCL packages and BO + thickener combinations (Table 3). An objective of the Bolnes engine testing was to further learn the performance of EHC 340 MAX™ as a Group II BO thickener. The Bolnes engine configuration and testing protocol remained the same as in Section 3.

Table 3. Compositions of 40BN and 100BN MCLs blended with different combinations of BO type and thickener type.

KV100 target = 18.5cSt		BO type	Thickener type
40 BN	40Test1	API Gp II	API Gp I (BS)
	40Test2	API Gp I	API Gp II (BT)
100 BN	100Test1	API Gp II	API Gp I (BS)
	100Test2	API Gp I	API Gp II (BT)

In Figure 15, deposit formation in the ring pack area and wear of piston rings were compared between the test oil pairs at, respectively, 40BN and 100BN levels. It was apparent that, at each BN level, the test oil in Group I BO thickened with Group II EHC 340 MAX™ exhibited tantamount ring pack area deposit formation tendency and comparable piston ring wear severity to the same BN counterpart in Group II BO thickened with Group I BS.

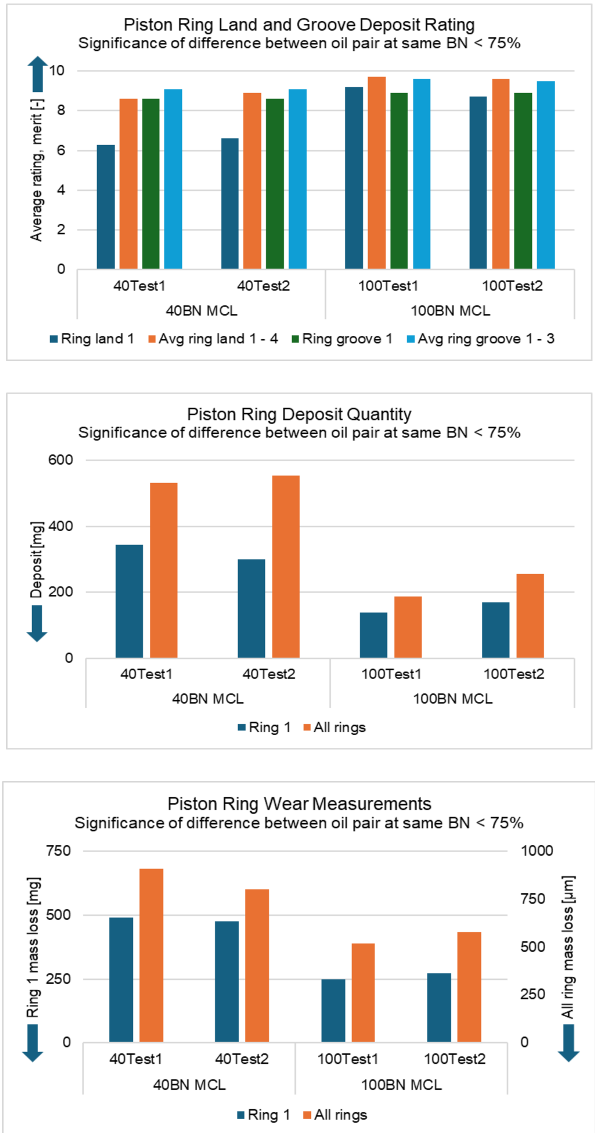


Figure 15. Bolnes testing results of 40BN and 100BN MCLs blended in different combinations between BO type and thickener type as described in Table 3.

4.3 Field testing

Driven by the encouraging bench testing and engine testing performances displayed by Group II EHC 340 MAX™ as thickener vs. Group I BS thickener, a field testing was conducted on an MAN B&W 6G70ME-C Mk 9.2 Tier II / Tier III engine to evaluate 100BN test oil blended by Group I BO / EHC 340 MAX™ (100Test2) against a Category II 100BN reference oil blended in Group II / BS. The vessel was operated exclusively on ultra-low sulfur distillate fuel with sulfur below 0.1wt%. The trial lasted close to 2000 MERH.

Key end-of-test inspection results were exhibited in Figure 16 through 18. Main findings were:

- The carbon deposit buildup on the piston crownlands of test oil unit and reference oil unit were similar.
- Ring packs of test oil unit and reference oil unit showed excellent cleanliness except for carbon deposit buildup on one position of the backside of the first ring for the test oil unit.
- All rings had free movement in the grooves and good tension, with smooth running faces and beveled edges. Wear of Alu coating on all rings lubricated with test oil was slightly lower.
- All liners were found in good condition.

Figure 16. Photographic comparison between piston ring lands and grooves (exhaust side) as well as ring backsides (left: 100BN test oil with Group II EHC 340 MAX™ thickener; right: 100BN reference oil with Group I BS thickener).

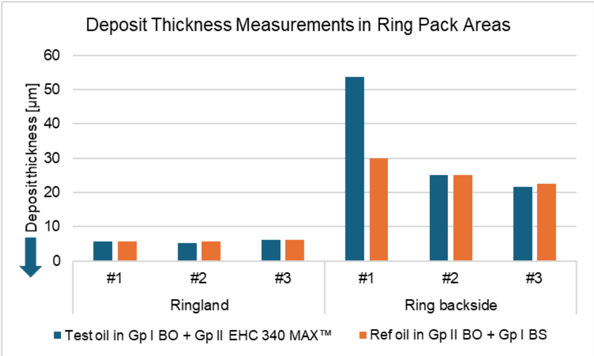


Figure 17. Deposit thickness from 100BN test oil blended in Group II BO / EHC 340 MAX™ vs. 100BN reference oil blended in Group II BO / BS on lands and backside of piston rings.

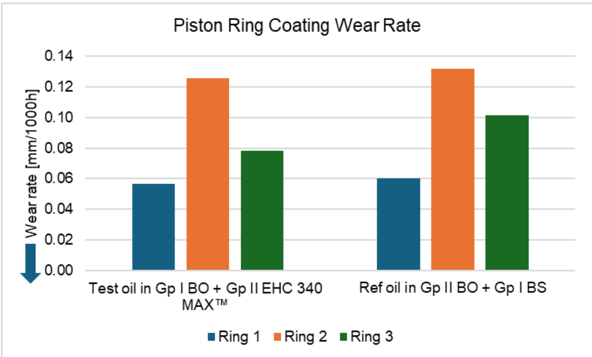


Figure 18. Piston ring wear in terms of Alu coating thickness loss rate from 100BN test oil blended in Group II BO / EHC 340 MAX™ vs. 100BN reference oil blended in Group II BO / BS.

5 COMPONENT THICKENER

It is not uncommon that some additive components in DI packages, except for viscosity modifiers, possess inherent thickening effect while playing their designed functions, or via their interaction or interlocking with other DI components. Dispersants belong to such types of components. Some conventional succinimide dispersants, in addition to dispersancy designed into their molecules, have also demonstrated thickening efficacy owing to the polymeric hydrocarbon chains grafted on their succinimide architecture. One type of Oronite dispersant has been found to be of apparent thickening effect in MCL formulations. An MCL package targeting 40BN MAN ES Category II performance level was formulated via this dispersancy thickener balanced with other additive components. With this package at an appropriate treat rate, very little BS (<1.0wt%) was required when blending a 40BN MCL of KV100 at 18.5cSt in Group I BO.

The above finished oil was tested on a vessel driven by MAN ES two-stroke engine of Mk > 9 and operated on distillate fuel (S <0.1wt%) in parallel with a 100BN Category II reference oil in Group I BO thickened by BS. Deposit rating and wear measurement on test units were performed at EOT of >3500 accumulated testing hours. Deposit formation characteristics on critical piston regions and ring/liner wear performances were exhibited in Figure 19 and Figure 20.

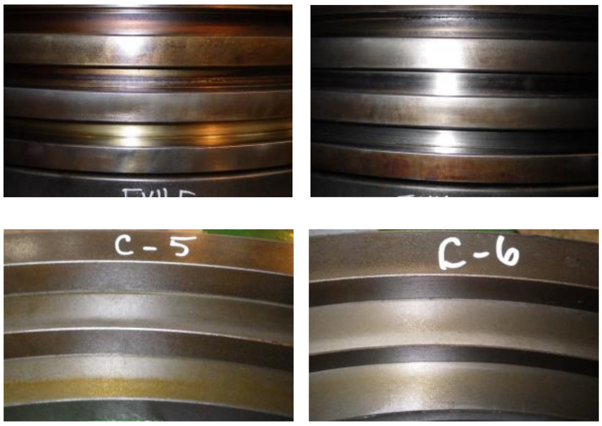


Figure 19. Photographic comparison between piston ring lands and grooves (exhaust side) as well as ring top and backsides (left: 40BN test oil in Group I BO based on a package with a selected dispersancy thickener; right: 100BN reference oil in Group I BO / BS).

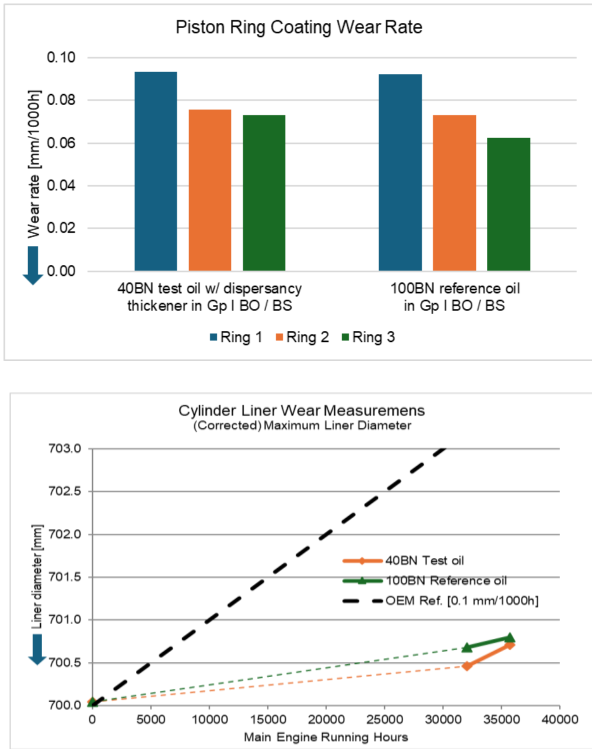


Figure 20. Piston ring wear in terms of Alu coating thickness loss rate (upper) and cylinder liner wear in terms of corrected maximum liner diameter (lower) from 40BN test oil with a selected

dispersancy thickener in Group I BO / BS vs. 100BN reference oil blended in Group I BO / BS.

The overall performance in terms of piston cleanliness and wear reduction of the 40BN test oil with the dispersancy thickener has attained Category II performance level enabling it to gain NOL from MAN ES. It is indicated that dosing dispersancy thickener in MCLs is a practically effective way of achieving KV100 target and meanwhile obtaining high performance with minimum conventional Group I BS.

6 DE-THICKENER

Incorporation of thickener in MCLs is to uplift viscosity to the desired viscosity magnitude or SAE viscosity grade, so thickener usage or need will be unarguably reduced if viscosity target of MCLs is set low. It is seen in Figure 21 that a small decrease of KV100 of finished oil (FO) would result in a large reduction of BS usage in a 70BN MCL series. For example, when KV100 target is decreased by about 13% from 17.0cSt of C9071 oil to 14.8cSt of C9076 oil, the BS usage can be reduced by about 74%!

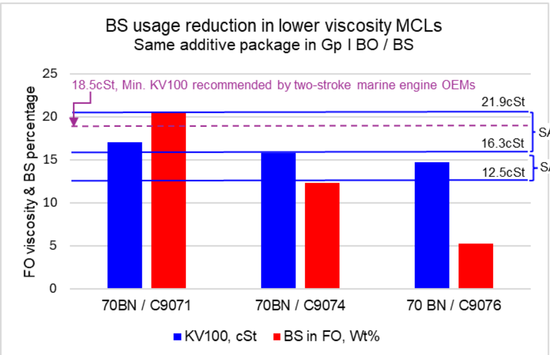


Figure 21. Reduction of bright stock usage in 70BN MCLs via lowering of KV100 target or SAE viscosity grade.

Lowering viscosity of MCLs has pros and cons from formulation flexibility and engine performance perspectives, as briefly summarized below.

- (pro) Reduction of BS usage or dependence.
- (pro) Fuel economy gain. Lowering KV100 by 1cSt can result in 0.5 to 1.0% fuel savings depending upon engine design [10,11]. In Bolnes operations, nearly 0.2% fuel economy improvement was reported when KV100 of MCL was lowered from 19.5cSt to 16.5cSt [12].
- (con) Increase of piston deposit due to lower solvency of deposit precursors owing to reduced BS-derived aromaticity.
- (con) Lubrication failure due to oil starvation or breakdown of hydrodynamic lubrication film in the piston ring-cylinder liner contact.

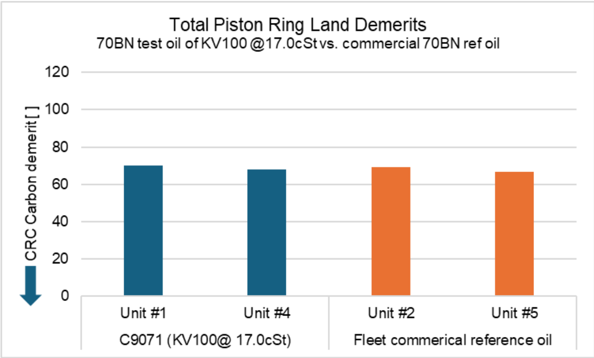
To strike the balance between the pros and cons, it is necessary to investigate how piston cleanliness and piston ring-cylinder liner wear would be impacted when viscosity of MCLs is trending downside at given S levels in fuel oils.

In response, field testing of three 70BN MCLs (coded as C9071, C9074 and C9076) were performed and compared with a 70BN fleet commercial reference oil. The three test oils were blended using the same market general package at the same treat rate in API Group I BO / BS. Their viscosity characteristics were listed and described in Table 4.

Table 4. Description of low viscosity 70BN MCLs blended with the same package in Group I BO / BS.

	KV100 cSt	SAE vis grade (KV100 range)	KV100 feature
C9071	17.0	50 (16.3 -21.9)	Lower end of SAE50
C9074	15.8	40 (12.5 – 16.3)	Upper end of SAE40
C9076	14.8	40 (12.5 – 16.3)	Mid of SAE40

Field testing of the three low-viscosity 70BN MCLs were conducted on MAN B&W 6S90ME-C engine against the common 70BN fleet commercial reference oil (KV100 = 18.5cSt) for 1754MERH, 1950MERH and 5762 MERH respectively in the back-to-back manner. Scavenge space and liner inspections as well as drip oil analyses were implemented and compared between the test oils and the reference oil in Figures 22 through 24. For rough comparison of deposit demerit and wear severity when KV100 of test oils goes down, same Y-axis scales were plotted.



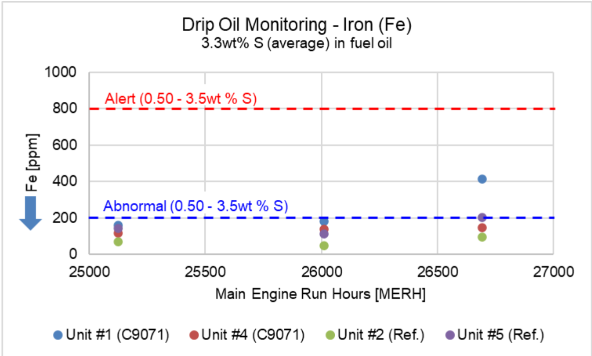
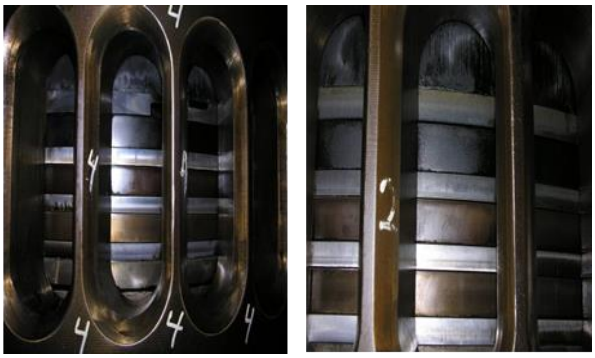
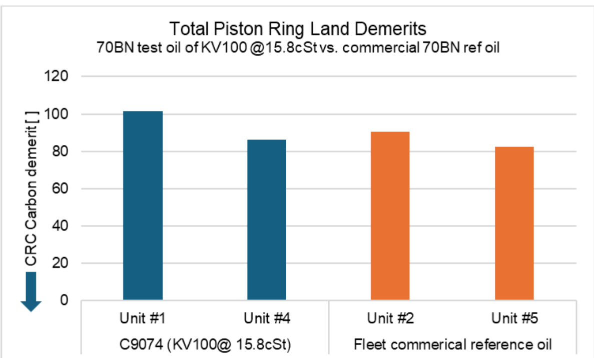


Figure 22. Piston ring pack area cleanliness (left: C9071, right: Reference oil), total piston ring land demerit and drip oil Fe trending of low-viscosity C9071 vs. 70BN fleet commerical reference oil. The average level of sulfur in the fuel oil over this test period is 3.3wt%.





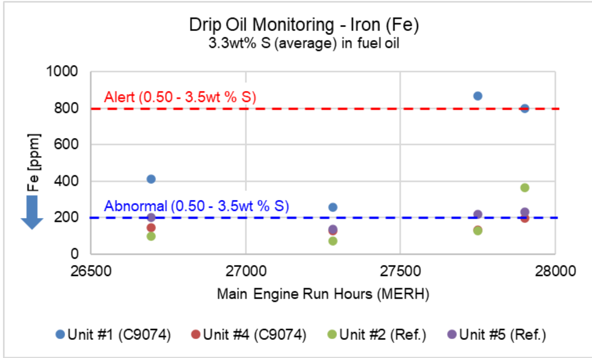
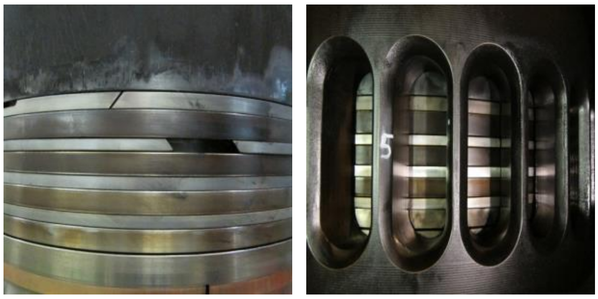
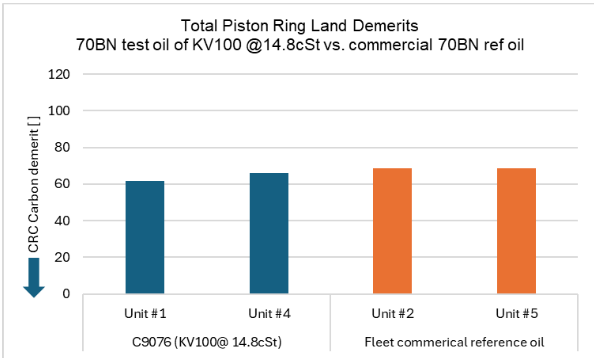


Figure 23. Piston ring pack area cleanliness (left: C9074, right: Reference oil), total piston ring land demerit and drip oil Fe trending of low-viscosity C9074 vs. 70BN fleet commerical reference oil. The average level of sulfur in the fuel oil over this test period is 3.3wt%.





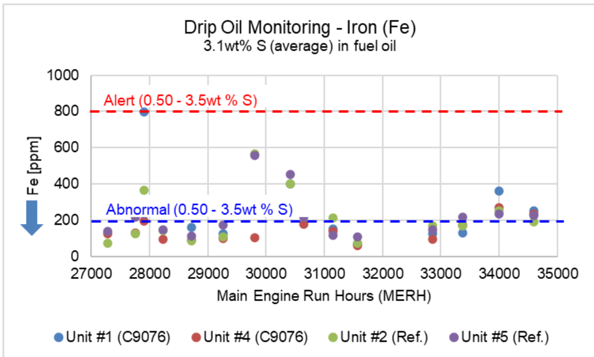


Figure 24. Piston ring pack area cleanliness (left: C9076, right: Reference oil), total land demerit and drip oil Fe trending of low-viscosity C9076 vs. 70BN fleet commerical reference oil. The average level of sulfur over this test period is 3.1wt%.

Impact of viscosity lowering via reduced usage of high-aromatic BS on cleanliness in the piston ring pack area and wear in the ring/liner contact is a case-by-case issue. Among the critical contributors are vessel or engine operation, fuel sulfur level and oil formulation design. Figure 22 through Figure 24, to which OEM-specified abnormal and alert threshold values of Fe content in drip oils [13] are appended, have displayed the piston deposit rating and drip oil monitoring results of the three 70BN lower-viscosity cylinder oils which are tested back-to-back on the same vessel against one common 70BN fleet commercial reference oil of KV100 at upper end of SAE 50 viscosity grade. It is observed that:

- 70BN test oil of KV100 at lower end of SAE 50 (C9071) has demonstrated equivalent performance to the reference oil in total piston ring land rating but slightly higher total wear as rated by Fe content in drip oils. It is noted that Fe contents in drip oils for both test oil and reference oil have remained below the abnormal threshold till the end of the field testing where the Fe content in the last single drip sample of the test oil has risen to be double of the abnormal value.
- 70BN test oil of KV100 at upper end of SAE 40 (C9074) has witnessed deteriorated piston ring pack area cleanliness and increased ring-liner wear. In average, this test oil of further lower KV100 is performing slightly worse than the reference oil in both piston deposit control and ring-liner wear protection.
- 70BN test oil of KV100 at mid of SAE 40 (C9076) has performed slightly better in controlling piston ring land deposit and total wear than the reference oil in the same field testing. Interestingly, this test oil performs comparably to the test oil of KV100 at lower end of SAE 50 in terms of ring land deposit and total wear control even though it has the lowest KV100 and its field testing lasts the longest among the three low viscosity test oils. Since fuel sulfur level remains nearly the same throughout the back-to-back field testing, well-maintained engine and/or favorable vessel operating conditions may account for the observed good performances.

The above observations imply that some lowering of KV100 of marine cylinder oils, in order to cut down BS usage, may be acceptable in terms of piston deposit control and liner wear protection. However, proof of performances via field testing should be performed to decide how much KV100 could be lowered comfortably with fuel economy gain but without compromising deposit control and wear protection under given application scenarios which involve but are not limited to vessel operation, engine loading, fuel sulfur and oil formulation.

In OEM-governing MCL specifications, a drop of KV100 of MCL by one SAE viscosity grade from SAE50 to SAE40 may not be in prospect given the design and operation of modern slow-speed two-stroke marine engines. However, if KV100 could be manipulated to the lower end of SAE50 viscosity grade through maintaining piston cleanliness and ring/liner wear via assistance of MCL package chemistry design, an appreciable reduction of BS usage is not unlikely by formulating hand in hand with other thickening approaches presented above in this article.

7 CONCLUSIONS

Four MCL thickening pathways, based respectively on alternative thickener (AT), base oil thickener (BT), additive component thickener (CT) and de-thickener (DT), have been proposed, defined and explored via the hierarchical lubricant testing system – bench, engine and field – on selected thickener chemistries (AT, BT, CT) and physical route (DT). Extension and combination of these pathways are also under our investigations.

Each pathway or each route under a given pathway contributes in different thickening manners and at different thickening efficiencies to replace conventional bright stock or reduce its usage in MCLs, which results in different impacts on piston deposit formation and ring/liner wear prevention depending on MCL package chemistry, BN level, fuel type, engine design, operating severity, etc. Given these circumstances, all the thickening pathways are on different technological readiness levels, and no single thickening solution, or the most logical successor to traditional BS, is applicable nowadays to all operation scenarios; in other words, not all options to replace traditional BS are equally viable.

We have been proactively monitoring emerging thickeners and evaluating thickener options to seek the most cost-effective thickeners or thickening solutions for MCL formulating. From field testing performances of the thickener chemistries and physics covered in the article, we have observed:

- Polymeric hydrocarbyl alternative thickener of high molecular weight / Type I as a full BS replacement in a 70BN MCL in Gp II BO has helped gain a Category I NOL from MAN ES.

- Polymeric hydrocarbyl alternative thickener of high molecular weight / Type B as a full BS replacement in a 70BN MCL in Gp II BO has helped gain a Category I NOL from MAN ES.

- A 100BN MCL blended with API Group II EHC 340 MAX™ BO as a complete replacement of BS and API Group I BO delivers equivalent field performances in piston deposit and ring / liner wear control to Category II Reference 100BN MCL blended with conventional lower viscosity API Group II BO and BS.

- Dispersancy thickener, balanced with other MCL additive package components, can significantly reduce BS content in finished oil. An Oronite dispersancy thickener in a well-tailored MCL package enables nearly complete removal of conventional BS when being blended in API Group I BO. In field testing, this 40BN formula has reached MAN ES Category II performance level.

- Lowering viscosity can reduce BS usage in MCLs but with pros and cons. Piston deposit and ring / liner wear control by lower-viscosity MCLs depend on engine type, sulfur content in fuel oil and operating condition. In addition, the extent of KV100 reduction for MCL products needs OEMs endorsement.

- Field testing, instead of in-house low-end bench testing and prediction-deficient engine testing, shall remain the ultimate resort to proof-of-performance of thickening chemistries (AT, BT and CT) and physics (DT). However, pragmatic field testing programs for alternative thickener approval have yet to be stipulated by OEMs.

It is expected that individual AT, BT, CT or their combinations would help decouple BS or minimize BS dependence in future MCL formulation development when BS supplies continue to decline. DT may not be a feasible pathway in the short term because lower viscosity is coupled with both opportunity (fuel economy) and risk (tribological reliability).

8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AEO: Automotive engine oil

API: American Petroleum Institute

AT: Alternative thickeners

BN: Base number (based on ASTM D2896)

BO: Base oil

BS: Bright stock

BT: Base oil thickener

CT: Additive component thickener

DI: Detergents/dispersants and inhibitors

DT: De-thickener

FO: Finished oil

GHG: Greenhouse gas

HMw: High molecular weight

IMO: International Maritime Organization

KV100: Kinematic viscosity at 100°C

LMw: Low molecular weight

MCL: Marine cylinder lubricants

MERH: Main engine run hours

NOL: No-objection letter

OEM: Original Equipment Manufacturer

SAE: Society of American Engineers

VLSFO: Very low sulfur fuel oil

9 ACKNOWLEDGMENTS

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10 REFERENCES AND BIBLIOGRAPHY

[1] CIMAC Guideline: The causes of scuffing and actions to prevent scuffing in two-stroke engines, 2023-03 (1st edition).

[2] CIMAC Recommendation 31: The lubrication of two-stroke crosshead diesel engines 2017-05.

[3] MAN ES Service Letter SL2022-728. SL2022-728 Cylinder and system oils

[4] Lubricants for WinGD engines_v8. Issue 008 2021-04.

[5] Ole Christensen. Cylinder lubrication of two-stroke crosshead marine diesel engines. Wartsila Technical Journal 02.2010. Cylinder lubrication of two-stroke crosshead marine diesel engines

[6] Global Lubricant Basestocks: Market Analysis and Opportunities, Kline, July 2023.

[7] Anuj Kumar. The evolving global bright stock market. TLT Market Trends, June 2018. Market Trends

[8] 20 Minutes with Lee Hyeung Jin by Rachel Fowler, Publisher/Editor-in-Chief | TLT 20 Minutes, December 2022. 20 Minutes2

[9] EHC 340 MAX™. EHC MAX 340 - Group II/II+ | ExxonMobil Basestocks

[10] Kiovsky, T. E. et al. 1993. Lubrication Engineering, 50, 4, 307-312

[11] Bartz, W. J. 1998. Tribology, 1-23

[12] Andrew Satterfield, et al. CIMAC Paper 468, Vancouver, June 10-14, 2019

[13] MAN ES Service Letter SL2023-738/IKCA. June 2023