Lubricant impacts on piston deposit formation in the Enterprise marine diesel research engine

Brian Kaul, Mike Kass, and Eric Nafziger – Oak Ridge National Laboratory
Willie Givens, Andrew Satterfield, Eric Senzer, and Min Chen – ExxonMobil

ABSTRACT

The impact of lubricant formulation on piston deposits was studied using the Enterprise, a reduced-scale, single-cylinder, two-stroke crosshead marine diesel research engine. The Enterprise engine was specially designed for marine diesel lubricant research, with a custom reduced-scale cylinder lubricant injection system and extensive instrumentation of thermal boundary conditions on both the liner and piston. Lubricant conditions typical of full-scale marine diesel engines are obtained by matching mean piston speed, liner temperature profile, and combustion metrics to realistic values.

Piston deposit thicknesses were measured after a set period of operation, with a focus on lubricant-based deposits on the lands and ring grooves, using both optical and contact-based measurement techniques. Engine operation for each lubricant was conducted according to a standardized protocol, with precise control of engine speed and load, cylinder lubricant injection rate, coolant temperatures, and system oil temperature; the liner and piston temperatures are continuously monitored during operation. After operation with each lubricant was completed, the engine was disassembled, and the piston and ring deposits were characterized. The piston was then thoroughly cleaned, and the lubricant system flushed, between each lubricant formulation being evaluated. The impacts on piston deposits of the lubricants being evaluated can thus be accurately quantified and are described herein.

1 INTRODUCTION

Since implementation of IMO 2020, compliant fuel typically referred to as VLSFO and MGO with a maximum sulfur content of ≤0.5 wt% has grown to approximately 80% of the bunker market. This significant reduction from a global IMO maximum limit of 3.5 wt% fuel sulfur has shifted the emphasis of the cylinder lubricant function from corrosion control to deposit control, thereby shifting the required cylinder oil total base number (TBN) lower. A BN level of 40 is considered by engine designers to be adequate for use with IMO 2020 compliant fuel.

As newer engines are designed for higher efficiency, operating temperatures and pressures continue to increase. Excessive deposit build-up in ring grooves and behind piston rings can cause malfunction of the rings and lead to catastrophic scuffing incidents [1, 2, 3]. Cylinder oils must therefore be designed to withstand and perform under higher stress conditions. The leading marine 2-stroke engine designer, MAN-ES, introduced new cylinder oil performance standards designated Category I and Category II with clearly differentiated piston cleanliness criteria [4]. Category II represents higher keep-clean performance recommended for newer engine designs (Mark 9 and newer). Similarly, WinGD, the other major 2-stroke engine builder introduced their new line of higher efficiency dual fuel "XDF" engines which operate at higher temperatures and pressures, especially when operating in gas mode [5, 6]. Given this trend, the Enterprise research engine, which is described in detail in a prior paper by the authors [7], is being used as a tool to evaluate the deposit control capacity of different lubricant formulations.

2 DESIGN OF DEPOSIT CONTROL EVALUATION PROTOCOL

A key objective of this study was to develop a lubricant test protocol that would closely simulate deposit control performance observed in the field. Four cylinder oil candidates were selected based on their documented differentiable deposit control performance in thousands of field trial and commercial operating hours. The selection of oils was also based on the broad range of cylinder lubricant total base number (Table 1). Bold values in Table 1 represent the best performing candidate in that laboratory test. This table shows that Oil A and Oil D were formulated with higher levels of antioxidant and/or dispersants as reflected in higher nitrogen levels. Laboratory bench tests were performed to validate higher oxidative stability and enhanced high-temperature deposit control according to the targeted performance profile. These products were designed to match the deposit control performance of conventionally formulated higher BN products. Successfully replicating the relative field performance ranking of the candidates in the Enterprise engine would form the basis for a meaningful and particularly relevant

Table 1. Typical properties of cylinder oil candidates

			Oil A	Oil B	Oil C	Oil D
Oil Description			Non-commercial BN20 with acceptable performance in 4000-hr DF Validation trial; very good deposit control in MAN-ES Licensee shop test	Commercial BN40 product with more than 12,000 hours of field experience showing acceptable "Cat I" performance	Commercial BN100 product with more than 20,000 hours of field experience and documented "Cat II" performance	Commercial BN40 product with more than 6,000 hours of field trial experience and documented "Cat II" performance
Overall Field Performance relative ranking			**+**	**=**	**++**	**++**
Chemical Properties			**BN20 HP (non-com)**	**BN40 Cat I (com)**	**BN100 Cat II (com)**	**BN40 Cat II (com)**
TBN of Petroleum Products	Base Number	mgKOH/g	19	40	100	40
ASTM D874	**Sulfated Ash**	**mass%**	**2.2**	5.1	13.4	5.2
	Calcium	ppm	8680	16400	41500	16500
ASTM D5185	Sulfur	ppm	8650	8500	12000	12000
	Nitrogen	ppm	**509**	209	152	327
Physical Properties			**BN20 HP (non-com)**	**BN40 Cat I (com)**	**BN100 Cat II (com)**	**BN40 Cat II (com)**
ASTM D445	Kinematic Viscosity, 40°C	mm^2/s	211	214	216	218
	Kinematic Viscosity, 100°C	mm^2/s	19.0	19.0	20.1	19.2
Viscosity Index			101	100	107	99
Calc. KV at High Temp.	at 250°C	mm^2/s	1.92	1.91	2.04	1.91
HTHS Tapered Bearing Simulator	Apparent Viscosity	cP	5.4	5.5	5.9	5.3
Laboratory Bench Screening			**BN20 HP (non-com)**	**BN40 Cat I (com)**	**BN100 Cat II (com)**	**BN40 Cat II (com)**
XOM Bulk Oxid. Used Oil	Kinematic Viscosity, 100°C	mm^2/s	25	35	27.3	26.2
XOM Bulk Oxid. Vis. Increase	**Viscosity Increase**	**%**	**29%**	82%	36%	37%
CEC L-85 Pressure Differential Scanning Calorimeter	**Oxidation Induction Time**	**min**	226	96	157	**>240**
ASTM 6186 mod.	**PDSC—OIT 210°C (3.5 MPa O_2)**	**min**	24.6	10.2	16.5	**24.9**
SOP 608/LOQUS	Hot Tube at 290°C, Deposit Rate	mg/h	**0.03**	0.57	0.25	0.20
	Hot Tube at 310°C, Deposit Rate	mg/h	1.05	6.08	**0.52**	0.67
	Hot Tube at 320°C, Deposit Rate	mg/h	5.1	8.97	2.82	**2.88**
	Hot Tube at 330°C, Deposit Rate	**mg/h**	10.2	12.5	11.6	**8.6**

screening tool to quickly assess the impact of cylinder lube formulations and formulation components on deposit control in a fired engine. This study was conducted with MGO (fuel S <0.1 wt%) only. However, there are plans to replicate this study with multiple other fuels such as VLSFO, LNG and ammonia.

Another objective was to establish a high-precision quantitative deposit measurement procedure to make assessment of the keep-clean performance of lubricants less subjective. While photographs of pistons provide a reasonable impression of performance, they are superficial relative to measuring the thickness of deposits on engine pistons, including within ring grooves. A laser profilometer is used in conjunction with a rotary stage to measure a continuous profile of the piston with deposits, and the measurement is repeated after cleaning the deposits from the piston. Algorithms for aligning the scans and determining the differential thickness allows continuous measurement of deposit thickness across the entire surface including lands and ring grooves as well as quantification of the volume of the deposits [8].

2.1 Operation and Instrumentation

For this study, the engine was operated steady state at a medium speed/load condition (400 rpm/9.8 bar BMEP) chosen to represent slow steaming operation, with a mean piston speed of 5.76 m/s. The Hans Jensen Lubricators cylinder lubrication system on the Enterprise engine comprises four lubricators which each supply 0.88 mg per injection. The lubrication system was operated in a “Skip 4” strategy for all operation, resulting in lubrication injections every fifth engine cycle, for an overall lubrication rate of 0.704 mg per cycle or 0.646 g/kWh.

Coolant and temperatures were maintained constant (± 1°C) at the engine outlet, resulting in a consistent liner temperature profile as shown in Figure 1. System and cylinder oil supply temperatures were also maintained constant (± 1°C). Pressures, temperatures, and flows of all fluid streams in and out of the engine are instrumented, and in-cylinder pressure is collected every 0.2° crank angle for combustion analysis, as described in detail in Kaul et al. [7]. Engine emissions were also monitored using nondispersive infrared CO and CO_2 analyzers, a paramagnetic O_2 analyzer, a flame ionization for total hydrocarbons, and a chemiluminescent detector for NO_x. An AVL MicroSoot Sensor was used to measure particulate mass concentration. Data files were collected every half-hour during operation to collect relevant engine performance parameters.

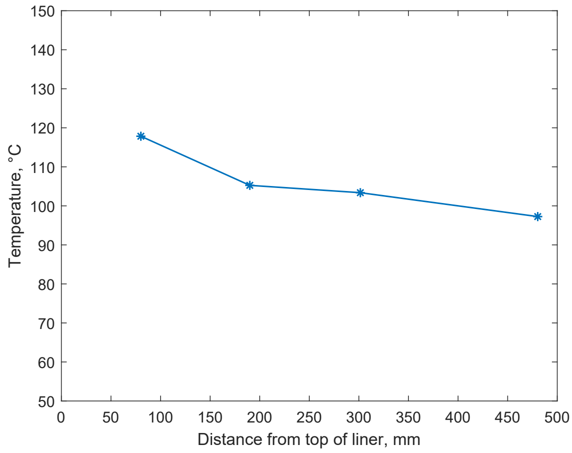

Figure 1. Liner temperature profile

Two telemetry pistons with eleven thermocouples positioned as shown in Figure 2 have also been instrumented by IR Telemetrics to monitor piston temperatures. These pistons use a radio telemetry system to broadcast piston temperatures in real time, with a sequential update rate of 0.5 seconds per channel; four additional channels not shown monitor electronics package temperatures, for a total of 15 channels each updating once every 7.5 seconds continuously during engine operation. The two telemetry pistons, P1 and P2, are nominally identical to allow pistons to be swapped during engine overhauls so that deposits on one piston can be evaluated offline while the engine is reassembled or operated using the other piston. These instrumented pistons are expected to provide insights into how temperature profiles impact deposit formation and behavior at key areas of the piston.

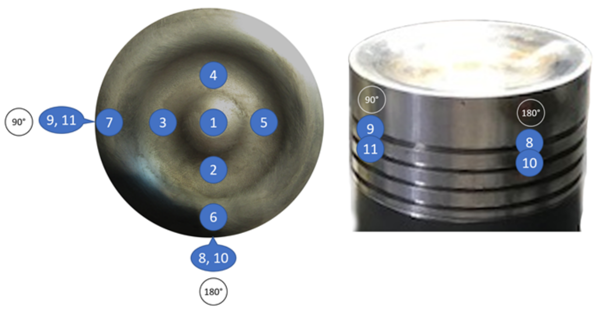

Figure 2. Locations of thermocouples on the instrumented pistons. Thermocouples 1–7 are installed below the piston crown; 8–9 are behind the top ring groove, and 10–11 are behind the second ring groove.

2.2 Procedure

The initial phase of this effort was to determine deposit formation as a function of time. This approach was taken because of the dynamic behavior of deposits which build up and dislodge over time until a steady state is reached where no significant increase in deposit build-up is occurring over time [6]. Deposit measurements were made through scavenge ports at roughly the same locations on the piston after six test hours per day for five days using an Elcometer 456 magnetic induction coating thickness meter with a T456CF1S straight probe. Oils A, B, C, and D were tested for a total of 30 hours each with Elcometer deposit thickness measurements at 6-hour intervals to determine if the deposit control performance ranking in field experience could be replicated in the Enterprise engine. Oils A, B, and C were chosen to evaluate the ability to rank between different TBN oils, and Oil D was added to determine whether the protocol was precise enough to discriminate between MAN-ES Category I and Category II 40 BN cylinder oils. Findings indicated that deposits tended to stabilize after 18 hours, as shown in Figure 3, and the deposit control performance of the candidates ranked as expected based on documented field experience. Table 2 shows the outline of test conditions and selected operating parameters.

At the end of the 30 test hours, the telemetry piston was removed and mounted on a turntable for optical scanning and deposit thickness measurements, which consist of determining the difference between scans of the piston with deposits in place and after they have been cleaned off. Details of the measurement technique for the laser profilometer method can be found in Kaul et al. [8]. As shown in Figure 4, the magnetic thickness meter and the profilometer results are in good agreement; variations are attributed to the imprecision of the location of the contact measurement for the magnetic meter relative to the variable-thickness deposits. The land and groove regions of the piston are labeled as shown in Figure 5. Results from measurements at the longitudinal center of the lands and grooves are herein termed "midline" deposit measurements and are used as typical values for each region to avoid distortion due to edge effects at the land/groove transitions. Statistics including mean, median, and maximum deposit thicknesses were calculated for both the midline measurements and the full scan for each region. The volume of deposits for each region was also calculated by integrating the deposit thickness around the circumference of the piston. The engine was reassembled with the second telemetry piston while measurements were conducted on the test piston to avoid prolonged engine downtime.

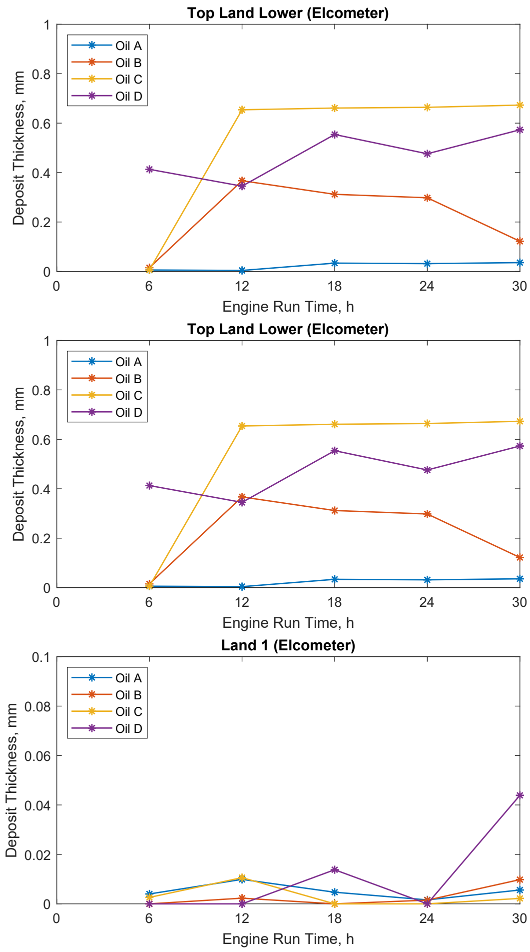

Figure 3. Deposit thickness progression over 30 hours of engine operation

The second phase of testing applied an 18-hour test duration over three days of engine operation to determine if the protocol could properly discriminate between two 40 BN products, Oil B (BN40 Cat I) and Oil D (BN40 Cat II). Results again showed generally good agreement with field observation.

Table 2. Test outline and operating parameters

Oil Code	Piston ID	Test Date	Hours of Operation	Piston Top Avg T, °C	Ring Groove 1 Avg T, °C	Ring Groove 2 Avg T, °C	Exhaust Avg T, °C
Oil A BN20	P1	3/25/2022	30	356	196	172	462
Oil B BN40 Cat I	P2	4/19/2022	30	313	184	162	499
Oil C BN100 Cat II	P1	4/28/2022	30	305	170	151	535
Oil D BN40 Cat II	P2	6/21/2022	30	336	193	165	535
Oil D BN40 Cat II	P1	7/21/2022	18	316	180	159	519
Oil B BN40 Cat I	P1	9/8/2022	18	311	186	164	522

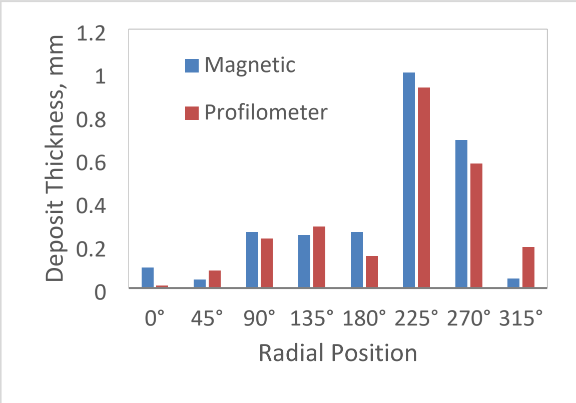

Figure 4. Comparison of upper top land magnetic coating meter measurement with mean value of upper half of profilometer scan cross-section for each angular position. From Kaul et al. [8].

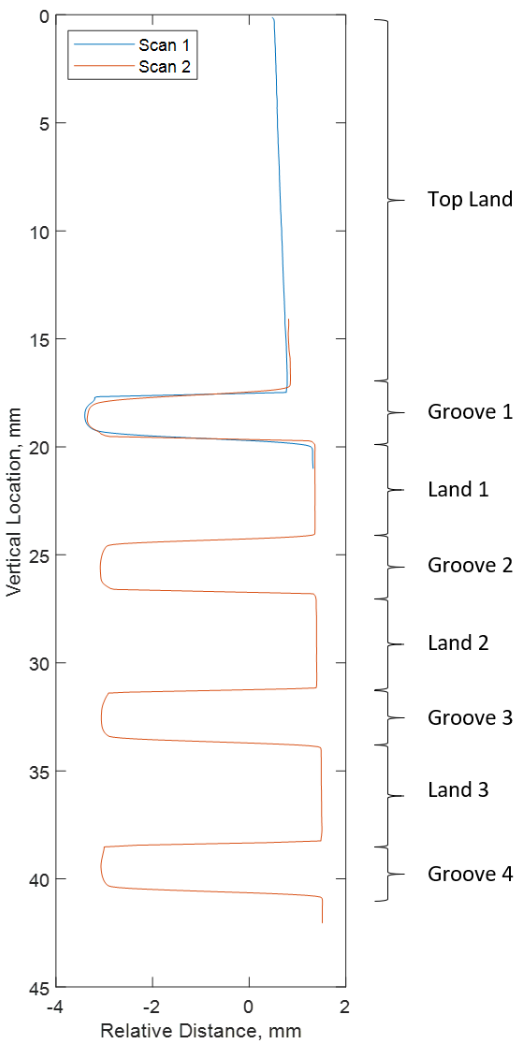

Figure 5. Laser profilometer scans of a clean piston with land and groove areas identified. Vertical and horizontal axes are not equally scaled. From Kaul et al. [8].

3 DISCUSSION OF RESULTS

3.1 Phase 1: 30-hour test protocol

At the end of each candidate oil test, the laser profilometer was used to measure deposits around the entire circumference of the piston. The mean deposit thickness at the midline position of each land and groove region was calculated, and these values are stacked in Figure 6 to visualize the relative magnitude of overall deposit thickness for each lubricant based on the height of the columns. The volume of deposits in each region was also calculated as described previously, and these are stacked in Figure 7.

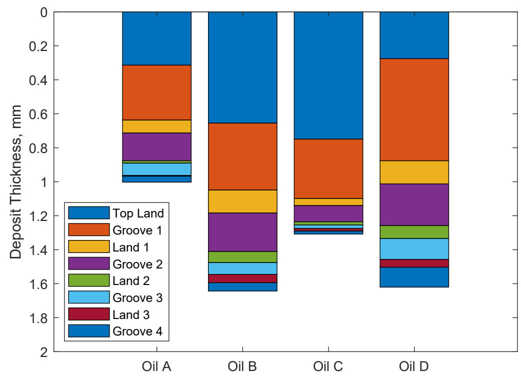

Figure 6. Deposit thickness at the midline height of each region for Oils A, B, C, and D after 30 hours of operation

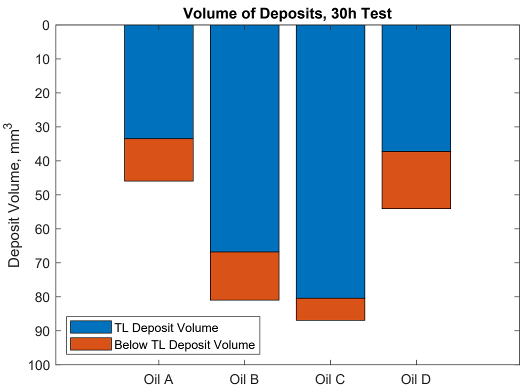

Figure 7. Volume of deposits, top land vs lower regions of piston, for Oils A, B, C, and D after 30 hours of operation

3.1.1 Relative performance of lubricants

The relative deposit control performance of the oils showed good agreement with field experience. Oil A (BN20) is a low (sulfated) ash formulation with enhanced high temperature stability. Oil A field experience is based on a completed 4000-hour WinGD DF validation trial which was assessed as close in performance to a fully validated Category I 40BN product. Oil A showed the lowest average deposit thickness and volume, consistent with much lower concentration of ash-forming calcium-based detergents (sulfonates, phenates—which can contain calcium carbonate for acid neutralization) compared to the higher BN candidates. Piston deposits in 2-stroke marine diesel application typically consist of high concentrations of Calcium (Ca) in the form of calcium sulfate and calcium carbonate [6].

As expected for the “Baseline” candidate, Oil B (BN40) showed relatively high deposit thickness over most areas of the piston. This is reflected in Figure 7 which shows the deposit volume to be similar to that of a much higher ash BN100 product. The piston photographs in Figure 9 show deposits at 135° and 180° positions.

Oil C (BN100) is a Category II product which has been used as the standard reference for Category II validation field trials of 40BN candidates. This oil showed the highest deposit thickness and volume on the piston Top Land (TL) and the lowest deposit thickness and volume on all areas below. Over 90% of the total deposit volume recorded for Oil C resides on the top land. This observation is consistent with early build-up of TL deposits which effectively insulates the rest of the lands and grooves from blowby gases and deposit precursors from the combustion process (Figure 3). The insulation concept is illustrated in Figure 8 by radial plots of the measured deposit thickness around the circumference of the piston for the top land and lower lands for Oil B and Oil C, which showed similar total deposit volumes. Oil C shows a more uniform thickness profile at all angles around the upper and lower areas of the top land; deposits on lower lands are comparatively insignificant. On the other hand, the top land deposits for Oil B and the other candidates (Oil A and Oil D) are not as uniform, and blowby gases and oxidized species from the combustion process can more easily travel to lower areas on the piston and be further distributed around the lands and grooves by constantly moving ring gaps.

The higher performance Category II BN40, Oil D showed general deposit thickness profile similar to that of the base line Oil B, but much lower deposit volume. This means that Oil D deposits that were of the same thickness as Oil B did not cover as much surface area. These results, although directionally indicative of better performance than the baseline (Oil B), were not as discriminating as expected based on field experience. A closer look at operating conditions showed that the piston temperature during Oil D test was significantly higher than those during testing of Oil B and Oil C (Table 2). Repeat testing of Oil C is warranted to investigate whether the observed TL deposit profile is a cause or an effect of the much lower piston temperatures recorded. It can be expected that higher piston temperature would be more severe in terms of promoting deposit formation. The next phase of testing using the optimized 18-hour protocol focused on rigorously controlling as many parameters as possible to ensure better discrimination could be realized between Category I and Category II BN40 products.

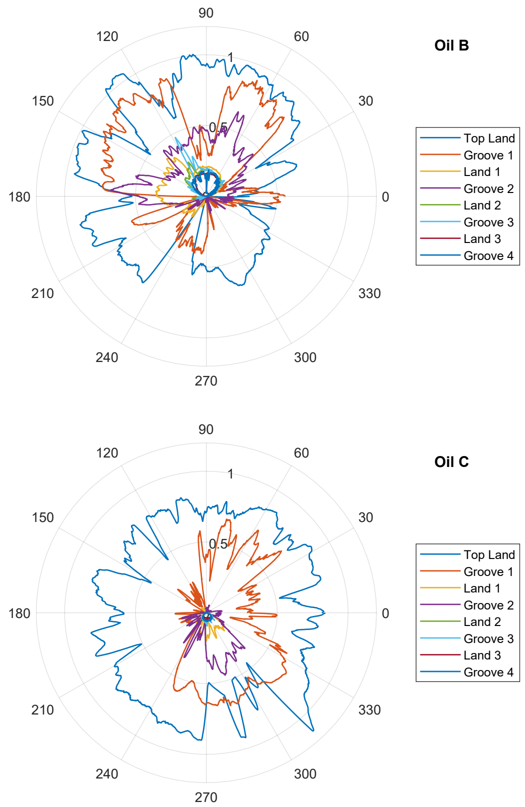

Figure 8. Deposit thickness profile around pistons for Oils B and C having similar volume but different distribution of deposits

3.2 Phase 2: 18-hour test protocol

The second phase of testing applied the 18-hour test duration to determine if the protocol could properly discriminate between two 40 BN products, Oil B (BN40 Cat I) and Oil D (BN40 Cat II). As seen in Table 2, these oils used the same telemetry piston (P1), and conditions were carefully controlled to minimize the potential variability of parameters such as average exhaust temperature, which would be indicative of significantly different thermal boundary conditions for the piston, particularly at the top land and crown areas that are exposed to combustion gases. Results are represented by the same parameters and in the same format as the Phase 1 30-hour results. Oil D showed overall lower deposit thickness (Figure 10) and lower volume of deposits (Figure 11). The optimized 18-hour protocol showed very good agreement with field experience and is consistent with the Category II performance profile.

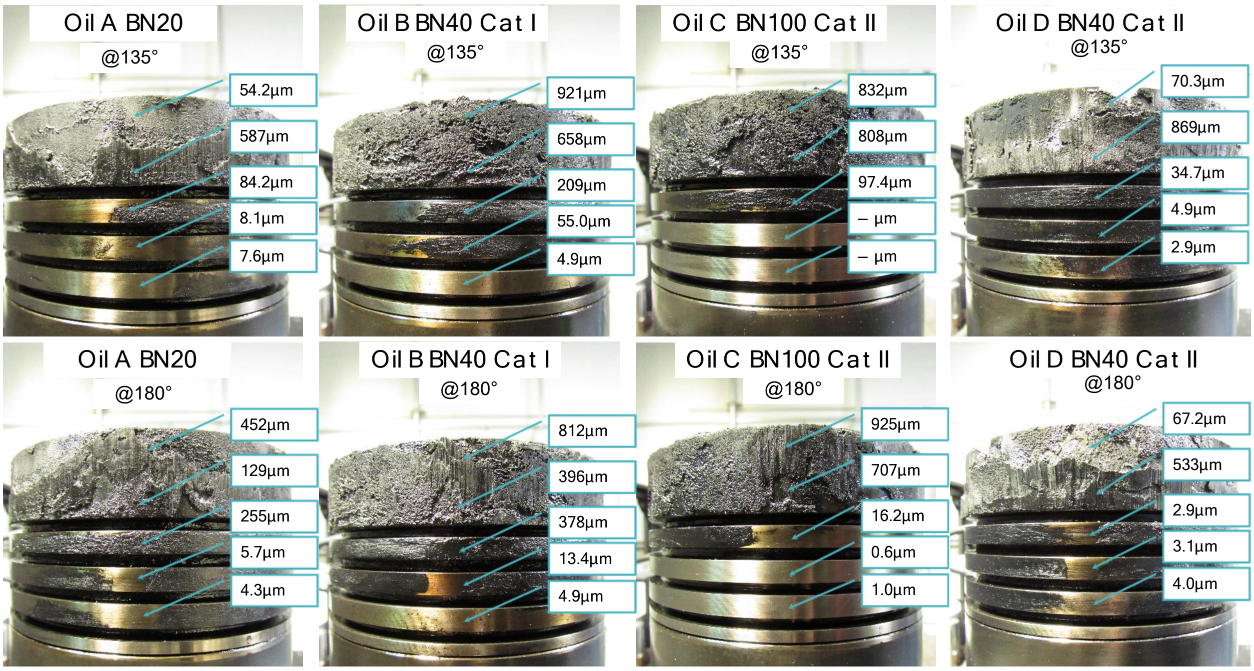

Figure 9. Photographs of pistons after 30-hour test showing deposit thickness

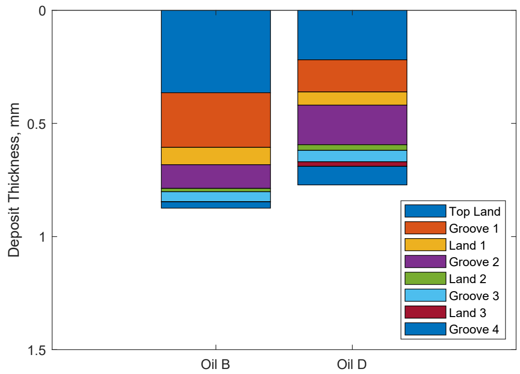

Figure 10. Deposit thickness at the midline height of each region for Oils B and D after 18 hours of operation

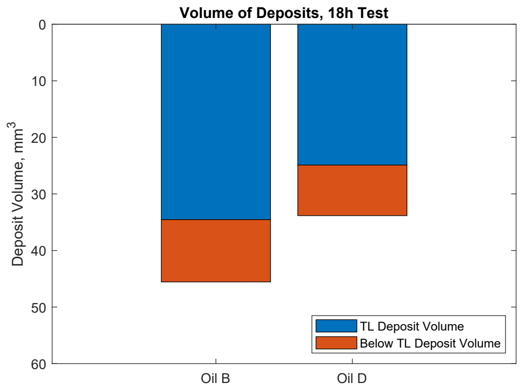

Figure 11. Volume of deposits, top land vs lower regions of piston for Oils B and D after 18 hours of operation

Photographs comparing Oil D and Oil B at multiple angles around the entire circumference of the pistons are shown in **Error! Reference source not found.**.

4 SUMMARY AND CONCLUSIONS

1. An effective test protocol was developed using the Enterprise research engine to assess the deposit control capacity of cylinder oils. The protocol was validated by utilizing a broad range of CLO candidates with well-known field performance. The test protocol ranked the "keep clean" performance of four oils in the same order as field experience.

2. Repeat testing of the reference cylinder oils will be integrated into test plans for other candidate CLO formulations as a way to establish test precision.

3. Laser profilometer scanning technology enabled extension of deposit measurements to volume calculations. The methodology provides an efficient mechanism to quantify and visualize deposits over the entire piston surface area directly exposed to cylinder lubricants.

4. Further examination of the impact of deposit distribution and location is warranted. Pinning piston ring is a

possible approach to exploring further, to deconflate the impact of varying ring

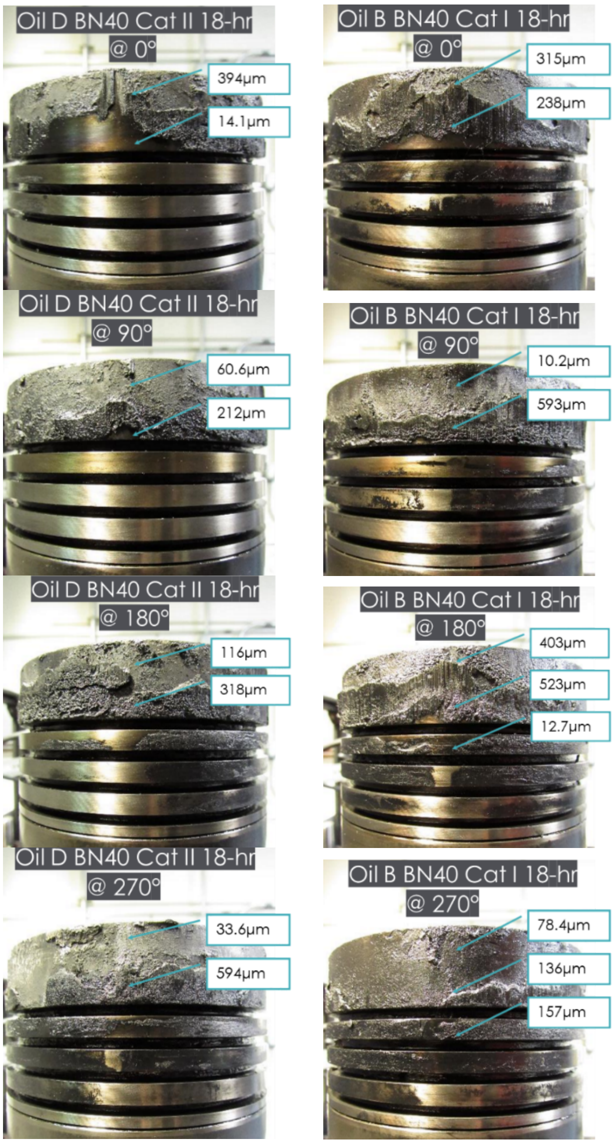

Figure 12. Photographs of pistons after 18-hour test showing deposit thickness for Oils B and D

position and gas flow. In the case of Oil C (BN100), higher TL deposits seemed beneficial to keeping lower lands and grooves cleaner, potentially reducing blowby flow of hot combustion products down to lower piston regions. These top land deposits are much harder and denser than the deposits in other regions, and it has been shown that the hardness of deposits correlates with damage including bore polishing and scuffing [9], but Piston Cleaning Rings (PCRs) are widely used to mitigate these effects. The liner used in this study did not have a PCR; repeat testing will be necessary when one is introduced to determine whether this protective effect is maintained.

5. The thermal and chemical boundary conditions of the test oil include both piston surface temperatures and combustion gas temperatures and composition. Both of these boundaries can be assumed to have a significant impact on the formation of deposits, particularly on the top land area where there is significant exposure to combustion gases. Exhaust temperature appears to be a good proxy for combustion gas temperature and should be carefully controlled to maintain consistent boundary conditions for evaluating deposit control performance.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

BMEP	Brake Mean Effective Pressure
BN	Base Number
Cat	Category
CLO	Cylinder Lube Oil
Com	Commercial
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MGO	Marine Gasoil
Non-com	Non-commercial
PCR	Piston Cleaning Ring
TBN	Total Base Number
TL	Top Land
VLSFO	Very Low Sulfur Fuel Oil

6 ACKNOWLEDGEMENTS

This manuscript has been authored in part by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

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8 CONTACT

ExxonMobil:
Willie Givens, willie.a.givens@exxonmobil.com

Oak Ridge National Laboratory:
Brian Kaul, kaulbc@ornl.gov