Technical Report Documentation Page

1. Report No. FHWA/TX-08/0-5532-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Solutions to the Engine Failures That Occurred Soon After Galveston Ferry Operations Began Using Texas Low Emissions Diesel Fuel		5. Report Date September 2007 6. Performing Organization Code
7. Author(s) Ron Matthews (CTR), Matt Hall (CTR), John Hedrick (Southwest Research Institute), and Clark Kibler (Kibler Technologies)		8. Performing Organization Report No. 0-5532-1
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-5532
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Technical Report January 2005–August 2007 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract

The research team found that the GFO engine failures were the result of three factors: 1) the poor ring pack design of these engines, which results in a high oil consumption rate, 2) the high ash content of the re-refined oil that was used in the ferries, and 3) the decreased flame temperature for TxLED relative to 2D on-road diesel.

The research team evaluated nine candidate oils as potential replacements for the re-refined oil that GFO was using as a result of a recommendation from a prior project that was conducted at a different university. These oils were evaluated based upon their effects on the oil consumption rate, engine wear, and in-cylinder calcium deposits. All of the candidate oils performed much better than the re-refined oil in all metrics. The research team recommends that GFO begin using Exxon Elite 20W50 in all of its ferries.

A hardware solution was also identified. Although the hardware solution is not essential (as the failure problems are solved via use of a different oil), the hardware solution results in significantly decreased oil consumption, and thus is worthwhile.

17. Key Words Diesel, engines, failures, oils	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	42	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Solutions to the Engine Failures that Occurred Soon After Galveston Ferry Operations Began Using Texas Low Emissions Diesel Fuel

Prof. Ron Matthews, Center for Transportation Research and Engines Research Program
Prof. Matt Hall, Center for Transportation Research and Engines Research Program
John Hedrick, Southwest Research Institute
Clark Kibler, Kibler Technologies

CTR Technical Report:	0-5532-1
Report Date:	September 14, 2007
Project:	0-5532
Project Title:	Galveston Ferry Operation (GFO) Engine TxLED Failure Assessment, Solution, and Implementation
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Center for Transportation Research
The University of Texas at Austin
3208 Red River
Austin, TX 78705

www.utexas.edu/research/ctr

Printed in the United States of America

Disclaimers

Author's Disclaimer: The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

Patent Disclaimer: There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Engineering Disclaimer

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

Project Engineer: Ronald D. Matthews
Professional Engineer License State and Number: Texas No. 52561
P. E. Designation: Research Supervisor

Acknowledgments

The authors express their appreciation to our TxDOT Project Director, Don Lewis, who is the fleet manager for all of TxDOT's vehicles, including the ferries. We also wish to thank Mark Rodriguez, Engineer and Maintenance Supervisor 1, and to Leonard Segura, Chief Engineer/Maintenance Coordinator, both of the TxDOT Houston District, Galveston Ferry Office.

Products

Product P1 is a list of the low-ash oils that the research team recommended for testing via sea trials. This product is Table 1 of this report. Product P2 is the research team's analysis of the root causes for the engine failures. This product is Section 2 of this report. Product P3 is a stand-alone report on the final round of oils tested. However, virtually all of the information in that report is included in Section 3.B of the present report.

Table of Contents

List of Figures

List of Tables

Executive Summary

Following the failures of all ten propulsion engines used at TxDOT's Galveston Ferry Operations (GFO) within months after switching from 2D on-road diesel fuel to an ultra-low sulfur diesel fuel (Texas Low Emissions Diesel, TxLED), the Center for Transportation Research (CTR) at the University of Texas was awarded a contract to determine the root cause of the engine failures and to develop a solution that allowed continued use of TxLED.

CTR used Southwest Research Institute and Kibler Technologies as subcontractors on this project. Professors Ron Matthews and Matt Hall, of the UT Engines Research Program, lead the CTR effort. John Hedrick lead the SwRI effort, which consisted of determining the root cause of the failures of the locomotive engines used for propulsion in the GFO ferries and seeking a hardware solution to overcome these failures. Clark Kibler, of Kibler Technologies, specified the oils that were subjected to testing and aided in the analyses of the results from the oil tests.

The research team found that the failures were the result of three factors: 1) the poor ring pack design of these engines, which results in a high oil consumption rate, 2) the high ash content of the re-refined oil that was used in the ferries, and 3) the decreased flame temperature for TxLED relative to 2D on-road diesel.

The research team evaluated nine candidate oils as potential replacements for the re-refined oil that GFO was using as a result of a recommendation from a prior project that was conducted at a different university. These oils were evaluated based upon their effects on the oil consumption rate, engine wear, and in-cylinder calcium deposits.

All of the candidate oils performed much better than the re-refined oil in all metrics. The research team recommends that Galveston Ferry Operations begin using Exxon Elite 20W50 in all of its ferries. Although this is an airplane piston engine oil, aircraft oils are necessarily designed to minimize wear due to the danger resulting from an engine failure at altitude. Thus, it was not surprising that this oil had the lowest rate of change of wear metals of all oils tested. Additionally, like all aviation piston engine oils, Exxon Elite has no ash whatsoever. Thus, it was also not surprising that Exxon Elite also had the lowest rate of accumulation of calcium deposits. Exxon Elite also had the second lowest oil consumption rate.

A hardware solution was also identified. A hardware solution is needed only if none of the candidate oils solve the problem of engine failures, which all of the candidate oils did. However, the hardware solution results in significantly decreased oil consumption, and thus is worthwhile. This hardware solution consists of a new and improved ring pack and cylinder liners with an improved finish. In addition to the improved rings and liners, the improved EMD 645 power cylinder assembly includes new and improved flat face valves and new valve rotators and springs

1. Introduction

Following the recommendations of Project 0-4576, the Texas Department of Transportation (TxDOT) began using an ultra-low sulfur diesel fuel, Texas Low Emission Diesel (TxLED), in all of its diesel engines in the fall of 2003, except for the ferries operated by TxDOT, which switched to TxLED in January 2004. No problems were encountered with any of these engines except that all ten propulsion engines used in the ferries operated by TxDOT's Galveston Ferry Operations (GFO) failed within about six months after switching to TxLED. TxDOT operates other ferries elsewhere, and none of the propulsion engines used in those ferries experienced any problems. Furthermore, each of the GFO ferries has two other diesel engines that are used for auxiliary power generation, and none of those diesel engines experienced any problems. Therefore, Project 0-5532 was awarded to the Center for Transportation Research (CTR) at The University of Texas at Austin (UT) to investigate, determine the root cause of the failures, and recommend solutions.

Professor Ron Matthews, who is Head of the General Motors Foundation Engines Research Labs at UT, was the Research Supervisor for Project 0-5532. He was assisted by Professor Matt Hall, Associate Head of the General Motors Foundation Engines Research Labs. Subcontractors on this project were Southwest Research Institute (SwRI) and Kibler Technologies. Leading the SwRI effort was John Hedrick, a research engineer in the Medium Speed Diesel Engine group of the Engine, Emissions, and Vehicle Research Division. His contributions were critical to this project because his group focuses on locomotive diesels, including the EMD 12-645E engines used for propulsion in the GFO ferries. SwRI's primary responsibilities on Project 0-5532 were to determine the root cause of the failures of the locomotive engines used for propulsion in the GFO ferries and to seek a hardware solution to overcome these failures. Clark Kibler, of Kibler Technologies, was essential to this project because he is an authority on engine failure analyses, especially those related to the engine lubricating oil. Kibler Technologies' primary responsibility on Project 0-5532 was to specify the oils that should be subjected to testing and to aid in the analyses of the results from the oil tests.

Figure 1. The M/V Dewitt C. Greer at the Galveston ferry terminal

Five ferries are operated by GFO between Galveston and Port Bolivar: the M/V Robert H. Dedman, the M/V Gib Gilchrest, the M/V Dewitt C. Greer, the M/V Robert C. Lanier, and the M/V Ray Stoker, Jr. The M/V Greer is shown in Figure 1. The Galveston–Bolivar ferry has been in operation since 1929. The fleet is currently operated by TxDOT and consists of five double-ended vessels, each 265 feet long and 66 feet wide. Each ferry can accommodate 500 passengers, 70 automotive vehicles, and 6 crewmembers. In addition, each ferry is capable of carrying six eighteen-wheel trucks weighing up to 80,000 lbs each. The Galveston–Bolivar ferry operates 24 hours a day, 7 days a week, and 365 days per year. The 2.7 mile trip averages about 15 minutes and crosses one of the busiest marine intersections in the world, composed of the Houston Ship Channel and the Texas Inter-Coastal Waterway. The Galveston–Bolivar ferry services over six million people annually.

Each GFO ferry has four diesel engines: two Electro-Motive Diesel (EMD) 12-645E propulsion engines and two Detroit Diesel Corporation (DDC) 8V-92NA diesel engines that provide 120V, 60 Hz AC power to satisfy the electrical energy needs of the boat.

The root cause for the failures of the GFO propulsion engines is discussed in Section 2. The tests performed to find a suitable lubricating oil to solve the failure problem are discussed in Section 3. Potential hardware solutions to this problem are discussed in Section 4. Section 5 is a summary of the work performed as part of this project and the conclusions that can be drawn as a result of TxDOT Project 0-5532.

2. Root Cause of the Engine Failures

The lubricating oil used in the GFO ferries at the time of the engine failures was a re-refined engine oil supplied by Safety-Kleen called America's Choice® Railroad Diesel Engine Oil. The oil is offered in both multi- and single viscosity and either a 13 or a 17 TBN. The specific version of Safety-Kleen used in the TxDOT GFO application was straight SAE 40 wt. oil with a TBN of 17.

The GFO propulsion engines failed when they were switched from use of on-road 2D diesel fuel to TxLED. The specific failure was that the engines would no longer start after operating on TxLED for several months. The EMD 12-645E diesels are 2-stroke diesels that have exhaust valves in the cylinder heads for "uniflow" scavenging. The sealing surfaces of many of the exhaust valves in the failed engines had been "torched," resulting in loss of compression of that cylinder. Relatively few cylinders of a 12-cylinder diesel must lose compression before the engine will no longer start.

Based on a detailed inspection of some of the failed exhaust valves and corresponding cylinder heads, SwRI determined that the EMD exhaust valve failures were caused by deposits in the combustion chamber that break loose and are caught between the exhaust valve and the exhaust valve seat during the valve closing event of the engine cycle. These loose deposits cause mechanical damage to the surface finish of the valve face and/or the valve seat, or simply hold the valve off the valve seat, preventing the valve from sealing normally. The combustion gases escape the combustion chamber and the high temperature and high pressure combustion gases simply "torch" the valve at the point of the combustion gas leak across the valve face.

It is believed that the deposits are formed due to the high engine oil consumption rate of the EMD 12-645E engines. This was determined by analyzing the composition of the deposits in the combustion chamber. These deposits are largely made up of ash and calcium, the primary dispersant additive in the oil. Calcium is found in oil additives and not found in the fuel.

Therefore, the GFO engine failures occurred due to the combination of three factors. First, the EMD 12-645E engines have a poor ring pack design that results in high oil consumption rates. Second, re-refined oil is used in these engines. Restoring adequate lubricating properties to an oil that has already been used once requires the use of additives, resulting in a high calcium concentration in the oil and, thereby, in the deposits. These deposits are “burned off” quickly enough when using 2D on-road diesel fuel that no problems were experienced. Also, the base stock for the re-refined oil results in carbon deposits, some of which can cause the piston rings to fail to seat on the bottoms of the ring grooves, leading to the high oil consumption rate noted as the first factor. The third contributing factor is the decreased flame temperature of TxLED relative to 2D on-road diesel. This allowed the deposits to build to a higher level. Occasionally, a deposit will flake off an in-cylinder surface. On rare occasions, a flake will get stuck between an exhaust valve and its seat as the valve is closing. On subsequent engine cycles, the partially open valve and its seat will get “torched” by the hot products of combustion. In turn, this results in the loss of compression in that cylinder. Once a cylinder loses compression, diesel combustion is no longer possible. Because starting a diesel engine is the most challenging operating condition, a diesel does not need to lose compression in many cylinders before it will no longer start.

In summary, the GFO engine failures were the result of the combination of three factors:

1) the high oil consumption rate of the EMD 12-645E engines (due to a poor ring pack design, but augmented by the use of re-refined oil),

2) the use of re-refined oil, which necessarily contains additives that cannot burn, especially calcium, and

3) the lower flame temperature of TxLED.

A solution to the engine failures can be attained via eliminating any of these three factors or a combination of them. However, because TxDOT is committed to doing its part to improve air quality, it will continue using TxLED in the GFO ferries. This leaves attack on the first two factors as potentially viable solutions. The effects of a variety of lubricating oils are discussed in Section 3. Hardware solutions are discussed in Section 4.

3. Lube Oil Tests

At the outset of Project 0-5532, five lube oils were selected for testing. One of the main criteria used in the selection of these oils was that all candidate oils had to be approved by EMD for use in their engines. One exception was made to this criterion so that an oil with a lower Total Base Number (TBN, a measure of the unburnable, or ash, content of the oil) could be examined. This exception contained a zinc-based additive, zinc dithiophosphate, which is a powerful anti-oxidant, and anti-wear additive. Near the initial termination date for this project, we found that the rationale for EMD’s specification that zinc-based oils were not approved for their engines did not, in fact, apply to the EMD 12-645E engines used by GFO. Specifically, some EMD engines have silver-coated bearings that are attacked by zinc. However, the EMD 12-645E engines do not have these bearings. Furthermore, none of the GFO engines are still under warranty. Therefore, the project team requested a project extension to allow us to examine additional oils. This extension was approved, resulting in a second round of oil tests.

The initial round of oil tests is discussed in Subsection 3.A. The second round of oil tests is discussed in Subsection 3.B. The conclusions from both rounds of oil tests are presented in Subsection 3.C.

3.A. Initial Round of Oil Tests

The research team on Project 0-5532 determined that changing the oil to a type that is more oxidatively stable with lower levels of calcium should provide an immediate low-cost solution.

In order to validate that changing the oil was an effective option, the research team established that a minimum of six months of sea trials of five candidate oils (a different oil for each ferry) should be conducted. Candidate oils were chosen on the basis of:

- Quality
- Availability
- EMD approval
- Lowest available TBN/ash level
- If possible, multi-viscosity grade

Table 1 lists the five oils that were selected for sea trials and for rapid screening tests conducted at UT. For comparison, the re-refined oil originally in use is included in Table 1 as well.

Table 1. Oils Selected for the Initial Round of Tests in Comparison to the Re-Refined Oil Used Previously

Oil	Viscosity Grade	TBN/% ash	Type	Ferry
Royal Purple Syn V EMD	40	13.0/0.33	synthetic	M/V Dedman
Citgo 943	40	13.5/1.40	mineral*	M/V Gilcrest
Mobilgard 450 NC	40	13.0/1.60	mineral	M/V Greer
Shell Caprinus XR 40	20W40	13.6/1.46	mineral	M/V Lanier
Texaco DEO 13	40	13.0/1.53	mineral	M/V Stoker
SafetyKleen	40	13.0**/1.30	re-refined	all

* Mineral oil is derived from crude oil.
** We were originally led to believe that the TBN for SafetyKleen was 17 rather than 13.

All of these oils had lower ash/TBN levels than the re-refined oil in use when the problems first surfaced after the ferries were switched to TxLED fuel. Also, they all are made from virgin base stocks of premium quality, and all are from major suppliers of finished lubricants. However, the Royal Purple Syn V EMD contains a zinc dithiophosphate package and, therefore does not have EMD approval. It was chosen to examine the effects of a synthetic oil with a relatively low TBN and a lower ash content compared to the re-refined oil and to the EMD-approved oils.

Tests were performed on oil samples from each of the boats after switching from the re-refined oil to one of the candidate oils. The goal of these tests was to ensure that the engines had been sufficiently flushed of re-refined oil and replaced with the candidate oil. This step was required because it is impossible to completely remove all of the oil from the engine without doing a complete engine overhaul. After it had been determined that the candidate oil was sufficiently pure in the crankcase, a similar procedure was required for the fuel. After all ten of the propulsion engines used for the ferries had failed, GFO had no choice but to switch back to 2D on-road diesel fuel. TxLED was not used until the candidate oils had been determined to be sufficiently pure. Then, it was necessary to ensure that the 2D on-road diesel fuel had been replaced by TxLED sufficiently that the contamination by 2D diesel was minimal. The purity of the fuel on each ferry was assessed via measurements of the sulfur concentration of the fuel, as TxLED contains <15 ppm sulfur while 2D on-road diesel contains ~500 ppm sulfur. The sea trials officially began on January 27, 2006.

Valero, the TxLED supplier, agreed to pay for tests of both the fuel samples and the oil samples during the first round of testing. Riverside Laboratories, in Tulsa, Oklahoma, performed the required testing of the fuel samples from each boat and the used oil samples from each engine during the first round of testing.

In addition to the sea trials of the candidate oils, “rapid screening” tests were also performed at UT. A single-cylinder Yanmar diesel engine was modified to produce a high oil consumption rate by increasing the piston ring end gaps. Additionally, this engine was operated under conditions that promote oil consumption: low speed and low load. The tests performed at UT were essential because of the extreme difficulty of obtaining accurate deposit data from the ferry engines. Additionally, as discussed later in detail, obtaining accurate oil consumption data from the sea trials was not possible either.

The candidate oils were assessed using three criteria: 1) the rate of accumulation of calcium deposits within the cylinder, 2) the rate of change of wear metals in the oil, and 3) the oil consumption rate.

The effects of the lube oil on the deposit accumulation rate are illustrated in Figure 2A. Figure 2B illustrates the effects of the oil on the deposit of primary concern: calcium. All five candidate oils are clearly superior to the re-refined oil from the calcium deposit perspective.

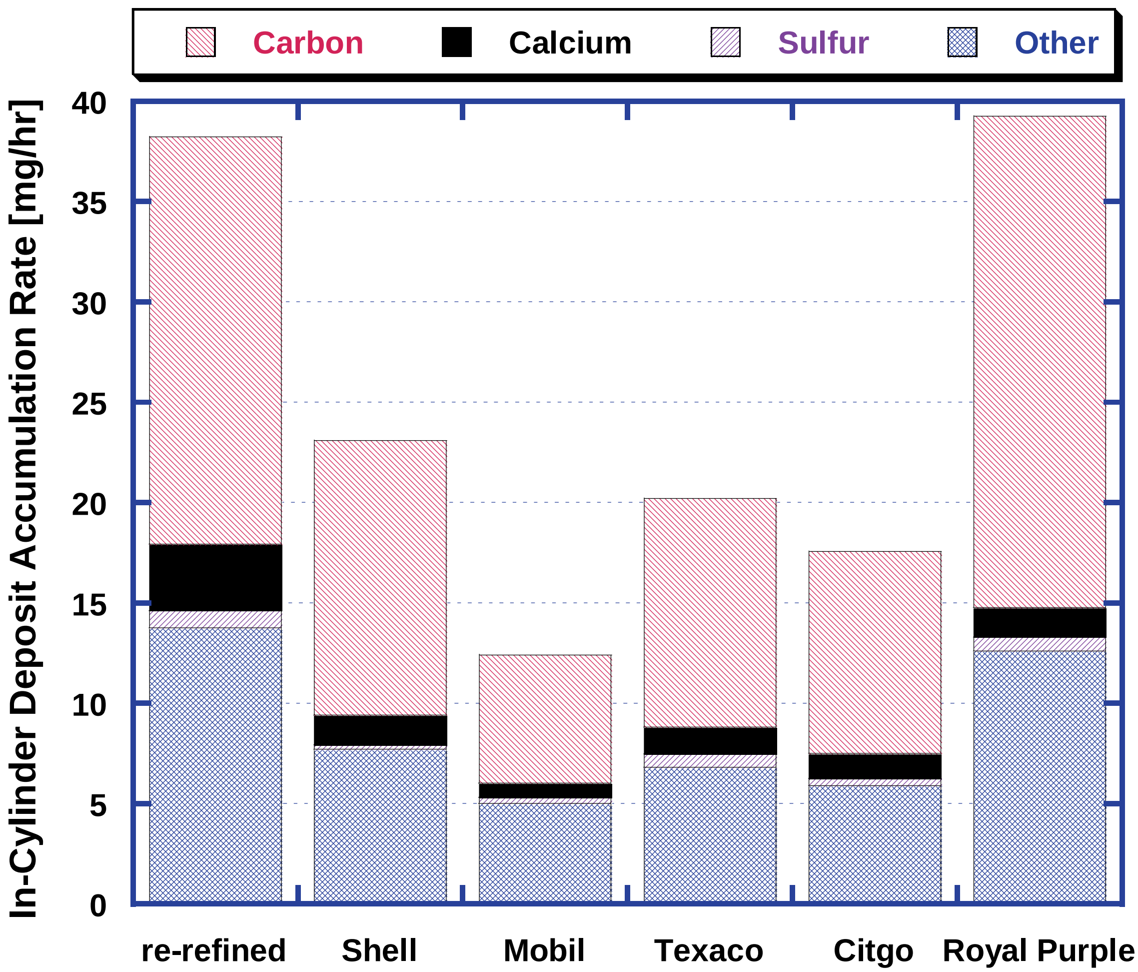


Figure 2A. Effect of lube oil formulation for the initial five candidate oils in comparison to re-refined oil on the rate of deposit accumulation within the cylinder

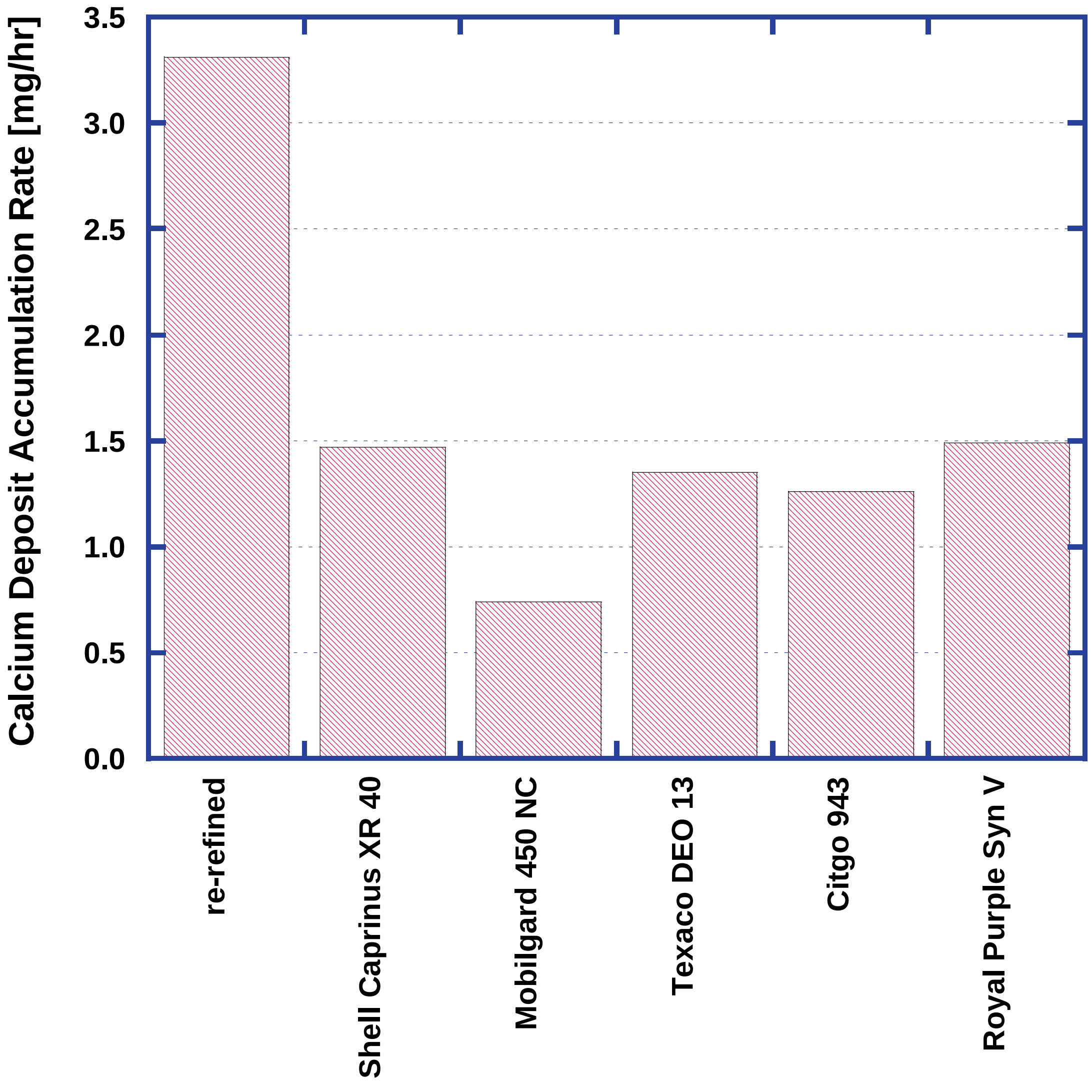


Figure 2B. Effect of lube oil formulation for the initial five candidate oils in comparison to re-refined oil on the rate of calcium deposit accumulation within the cylinder

Figure 3 illustrates the effects of the oil on the rate of change (in parts-per-billion per hour) of wear metals in the oil. The wear metals are iron, aluminum, lead, and copper. For these engines, the primary wear metal is copper that comes from a thrust bearing under the piston. During the first round of testing, the wear metals were quantified via periodic sampling and analysis of the oil from each engine during the sea trials.

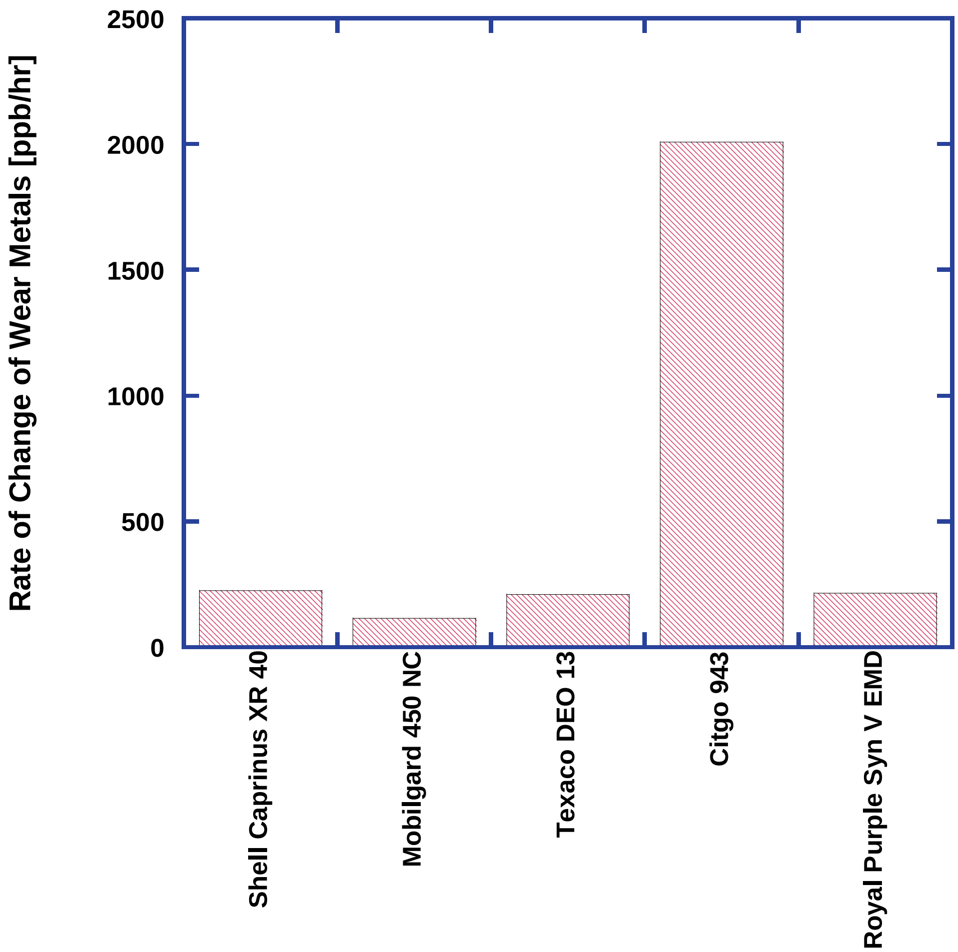


Figure 3. Effect of lube oil formulation for the initial five candidate oils on the rate of change of wear metals in the oil

As shown in Figure 3, four of the initial five candidate oils produced a very low rate of change of wear metals. The Citgo 943 oil was used in the M/V Gilchrest, which accumulated the fewest hours of operation of all the ferries, at only ~750 hours between the beginning of the sea trials and the final oil analyses, compared to 2,000–4,000 hours for the other boats/oils. Nevertheless, the wear metals in the Citgo 943 oil were much higher than for any other oil even at comparable hours of operation. However, it is possible that the engines in this ferry had not had many of these thrust bearings replaced recently while the engines in the other ferries had had significantly more of the thrust bearings replaced more recently. To account for and quantify this potential factor, we requested TxDOT's records for hours at which each of the thrust bearings in each of the ferry engines had been replaced, but these records were not available.

Figure 4 illustrates the effects of the oil on the oil consumption rate measured using the UT rapid screening tests. All of the initial five candidate oils are clearly superior to the re-refined oil from the perspective of oil consumption.

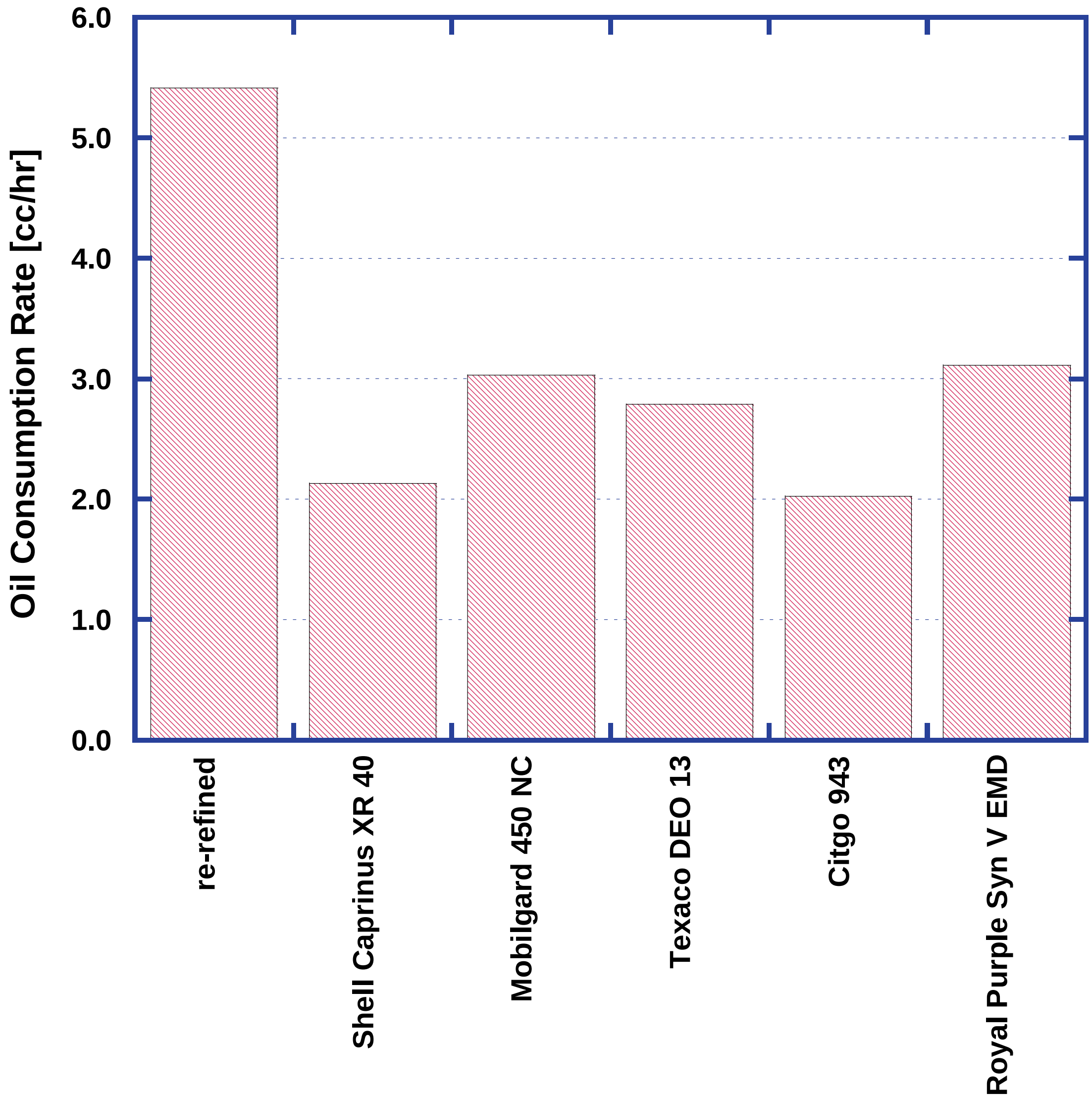


Figure 4. Effect of lube oil formulation for the initial five candidate oils in comparison to the re-refined oil on the oil consumption rate from the UT rapid screening tests

Figure 5 compares the oil consumption rates from the sea trials with those measured using the UT rapid screening tests. It is obvious that there is no correlation. This is due to the fact that the engines in the ferries are rebuilt one cylinder at a time on an as-needed basis. Thus, one of the ferries may have had, for example, 16 of the 24 cylinders rebuilt recently (due to the problems experienced after initially switching to TxLED) while another may have had only 5 of the 24 cylinders rebuilt recently. Because the UT tests involved testing all of the oils in the same engine, the UT tests are clearly the better measure of the effects of the oil on oil consumption.

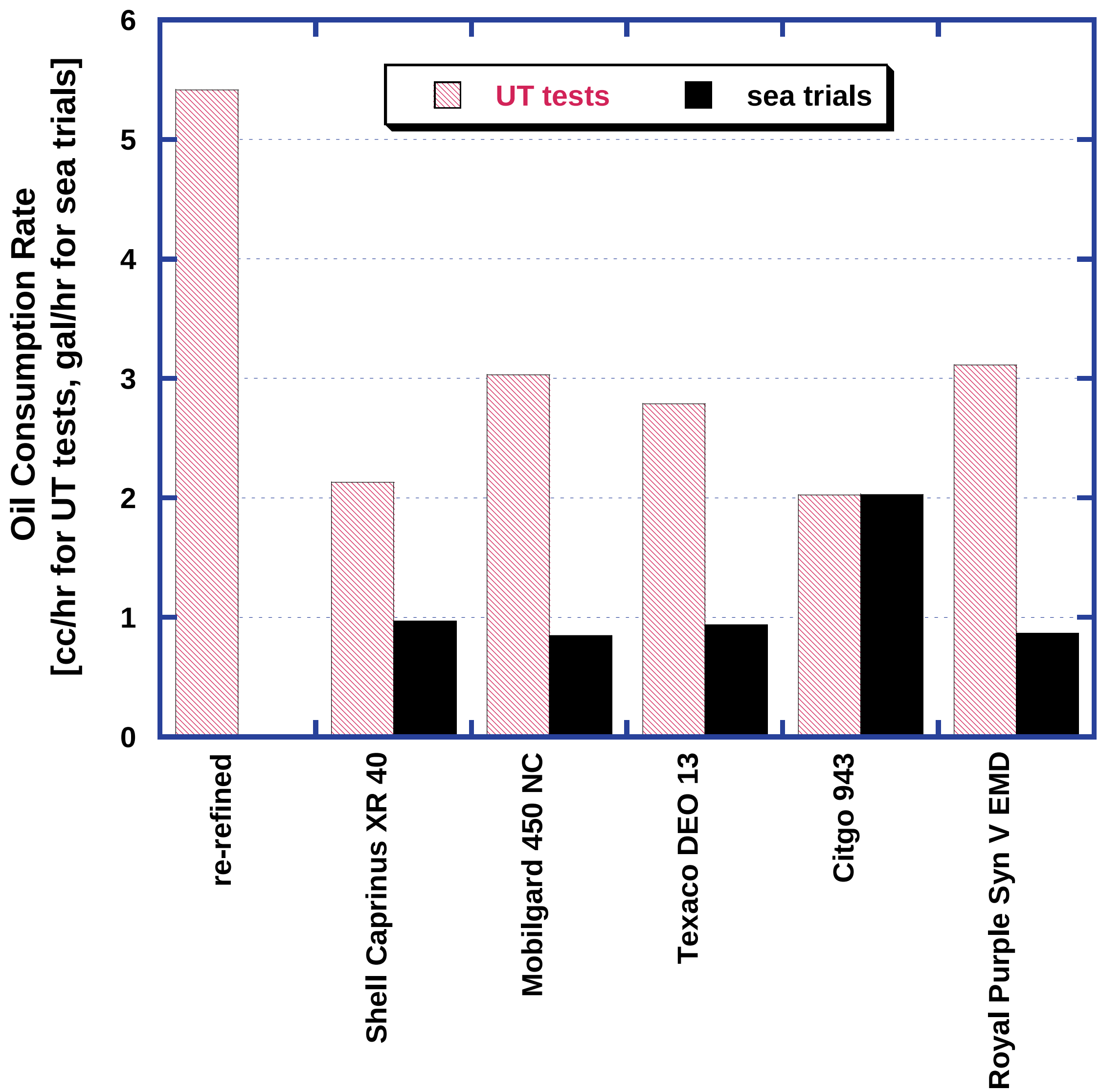


Figure 5. Comparison of the oil consumption rates from the UT tests to those measured during the sea trials

All five of the initial oil candidates were better than the re-refined Safety-Kleen from the perspective of all of the metrics used: oil consumption, calcium deposits, and wear metals in the oil. Of these, the calcium deposit accumulation rate is the most important criterion and the oil consumption rate is the second most important criterion. Mobilgard 450 NC had the lowest rate of accumulation of calcium deposits and also the lowest wear metals. Citgo 943 produced the lowest oil consumption rate (but the highest wear metals), but Shell Caprinus XR 40 was a very close second.

From the tests of the first five candidate oils, it can be concluded that major-branded engine oils for EMD engines will provide better engine life than the re-refined oil, when TxLED ultra-low sulfur diesel fuel is used. One cylinder-head problem surfaced during the ten months that the sea trials were conducted. That problem was most likely due to residual damage and/or carry-over deposits from the re-refined oil used prior to the sea trials.

Here, it is important to note that the candidate oils from the first round of tests performed much better than the re-refined oil in all metrics, but—with the exception of the synthetic oil—the TBN and ash content were not significantly lower than for the re-refined oil. Specifically, why does the re-refined oil result in more deposits, when the conventionally refined oils with similar TBN and ash content do not? There are two reasons for this initially unexpected result. First, additives can vary in makeup even though the ash levels are the same. Some calcium salts (used for dispersant/detergent properties as well as possible anti-wear properties) will be very stable at a given temperature; some will be less stable. Magnesium is used in a similar way, and often combined with calcium to obtain a synergistic result. It is probable that the type of detergent/dispersant used in the re-refined oil is less stable than that used in the other oils. These additive/base oil variations partially explain the better performance with the premium conventionally refined oils. Second, re-refined base oils have been proven to be less stable from an oxidation standpoint even when additized. These less stable molecules will more readily form carbon deposits. Carbon deposits within the cylinder of a diesel engine rarely result in problems. However, the less stable base oil can also produce deposits between the piston rings and the bottoms of the ring grooves, and this can interfere with piston ring sealing. This contributes to increased oil consumption, which then contributes to a faster rate of in-cylinder deposit build-up. The same faster build-up also affects the exhaust valve seat, which leads to the torching problem that resulted in the GFO engine failures. That is, the most important factor may be the effect of the oil formulation on oil consumption and the consequent in-cylinder deposits.

3.B. Final Round of Oil Tests

One of the oils selected for the initial round of tests contained zinc dithiophophate (ZDP) and, thus, was not approved by EMD. However, the EMD 12-645E engines do not have silver-coated bearings, so there is no scientific rationale for not approving oils with this important additive. Additionally, none of the GFO engines is still under warranty. Also, the Royal Purple Syn V EMD oil tested during the initial round of testing did not cause any problems, and this oil contains ZDP. For these reasons, it was decided that a second round of oil tests should be performed to include oils that may not be EMD approved but that have properties that could make them beneficial for the GFO application. Table 2 lists the five oils that were selected for the second round of testing.

Table 2. Oils Selected for the Second Round of Tests*

Oil	Viscosity Grade	TBN/%ash	Comments
Chevron DELO 400	15W40	10.2/1.35	2007+ diesel truck oil
Exxon XD-3	15W40	10.0/1.10	2007+ diesel truck oil
Exxon Elite	20W50	13.5/~0	aviation piston engine oil
Mobil Pegasus 710	40	6.5/0.94	stationary natural gas compressor engine oil**
Shell Caprinus XR 40	20W40	13.6/1.46	repeat oil from 1st round

*All are mineral oils, and none are EMD-approved except the Shell Caprinus XR 40
**Used in large stationary natural gas engines, the vast majority of which are used to power compressors on natural gas pipelines

New commercial diesel engine oil formulations have been introduced to reduce volatility, reduce zinc levels (for catalytic converter life), and enhance oxidation stability. Additionally, many of these new oils are multi-grade, such as 10W30 and 15W40, and have been identified as ones that will lower oil consumption rates. They also contain ZDP, but at lower levels than was previously common. These oils are lower in ash (to increase the life of diesel particulate filters used on trucks that must meet 2007+ heavy-duty emissions standards) and could result in lower rates of deposit formation. Therefore, two of the oils chosen for the second round of testing were oils that are approved for 2007+ heavy-duty diesel trucks: Chevron DELO 400 and Exxon XD-3. The third oil chosen for the second round of testing was an ashless multi-grade aircraft piston engine oil: Exxon Elite 20W50. Aircraft piston engine oil is designed to generate minimum ash in combustion chambers and on exhaust valves while still providing protection of internal engine parts and maintaining cleanliness. The final oil selected for the final round of tests was a single viscosity grade premium natural gas compressor engine oil: Mobil Pegasus 710. This oil has a low ash content and is commonly used in 4-stroke stationary natural gas engines. Finally, it was decided to examine Shell Caprinus XR 40 again to serve as a control for the second round of tests.

Due to the problems discussed in Subsection 3A regarding obtaining accurate data from the sea trials, all of the second round testing was performed via the UT rapid screening tests and the oil analyses were performed at Southwest Research Institute.

By this point in the project, TxDOT had switched from the refined TxLED produced by Valero to a fuel that produces equivalent NOx emissions but via a splash blending process rather than via a change in the refining process. Thus, splash-blended TxLED was used for the second round of tests instead of the refined TxLED that was used in the first round of tests. Tests were performed at UT using the Yanmar diesel, as modified to produce a high oil consumption rate, operating under the low load, low speed conditions used to acquire the data provided in this report. It was found that the NOx emissions when using refined TxLED were, indeed, equivalent within the experimental uncertainty of the tests. This provided some evidence, but not absolute certainty, that the flame temperatures are essentially the same for the two versions of TxLED. This is important because the decreased flame temperature for refined TxLED was one of the three factors that contributed to the GFO engine failures.

The cylinder deposits for all oils tested are illustrated in Figure 6A, and Figure 6B (discussed later) shows this comparison for just the calcium deposits. With the exception of the Royal Purple synthetic oil, all of the candidate oils have a much lower total deposit rate than the re-refined oil.

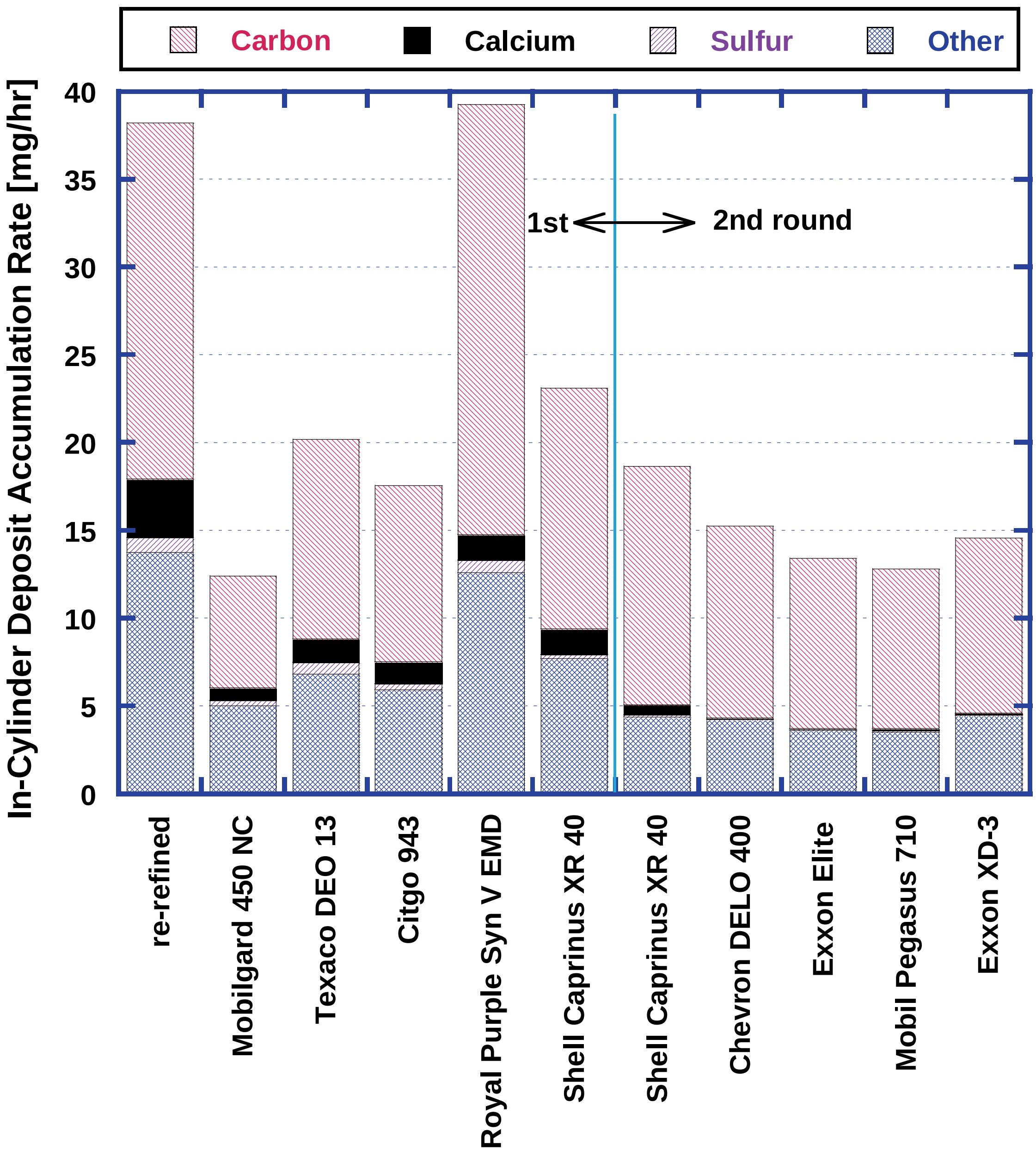


Figure 6A. Effect of lube oil formulation for all of the candidate oils in comparison to re-refined oil on the rate of deposit accumulation within the cylinder

Figure 6B compares only the calcium deposits for all oils examined. All of the candidate oils have a much lower rate of accumulation of calcium deposits, and the four new oils selected for the second round of tests have a much lower rate of calcium deposit accumulation than the oils examined during the first round of tests.

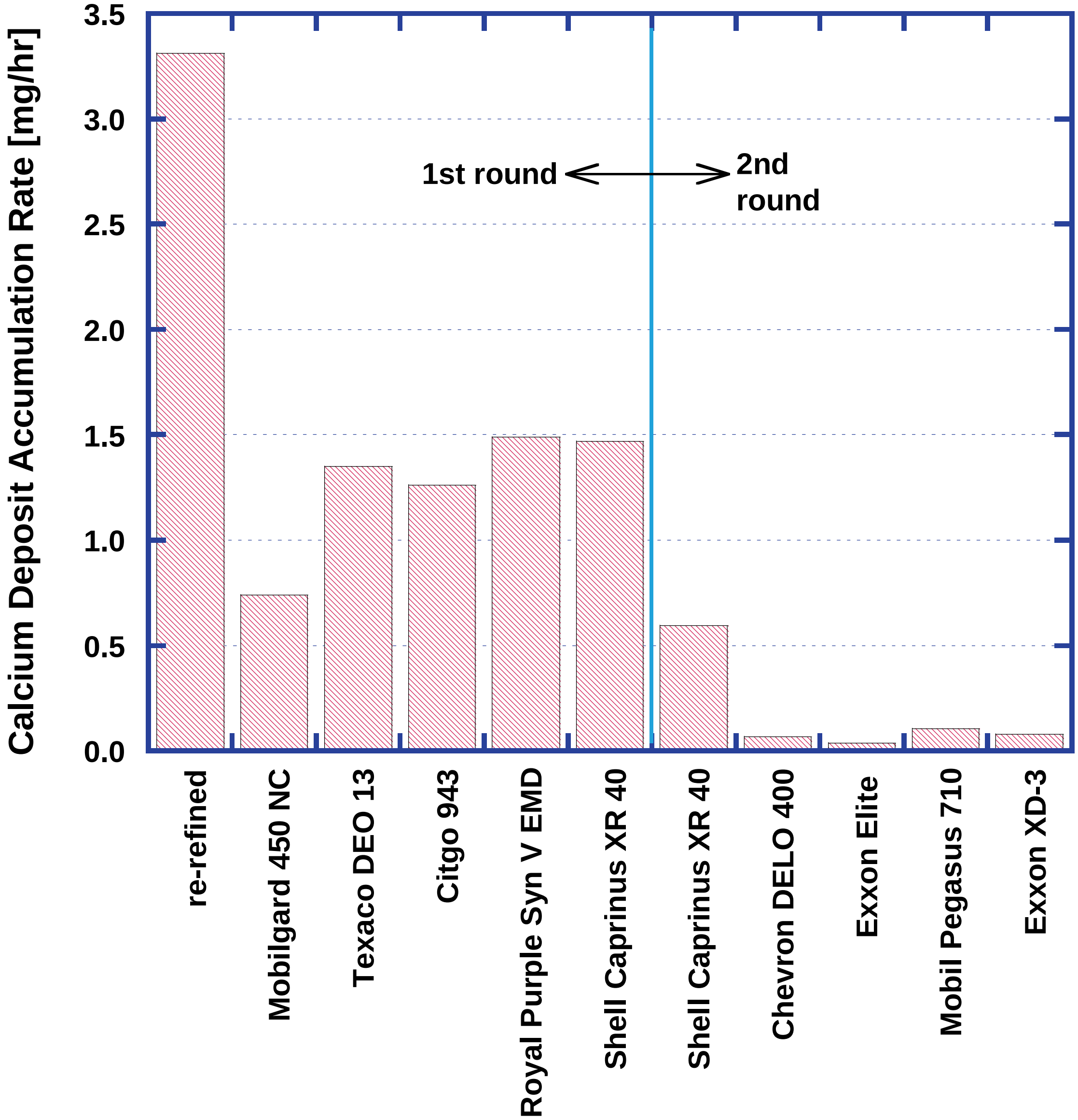


Figure 6B. Effect of lube oil formulation for all of the candidate oils in comparison to re-refined oil on the rate of calcium deposit accumulation within the cylinder

Figure 7 illustrates the effects of the oil on the wear metals in the oil. Two of the oils selected for the second round of testing are comparable or better than all but the best oil in the first round from this perspective. However, it must again be noted that the wear metals during the first round were determined from the sea trials, which engendered some uncertainty in the results for the reasons discussed in Subsection 3.A. Due to this difficulty, the very high rate of change of wear metals determined for one of the oils in the first round, which might have been an artifact of not testing the wear metals for all oils in the same engine and with identical operating conditions, serves to minimize differences in the wear metals for the remaining oils.

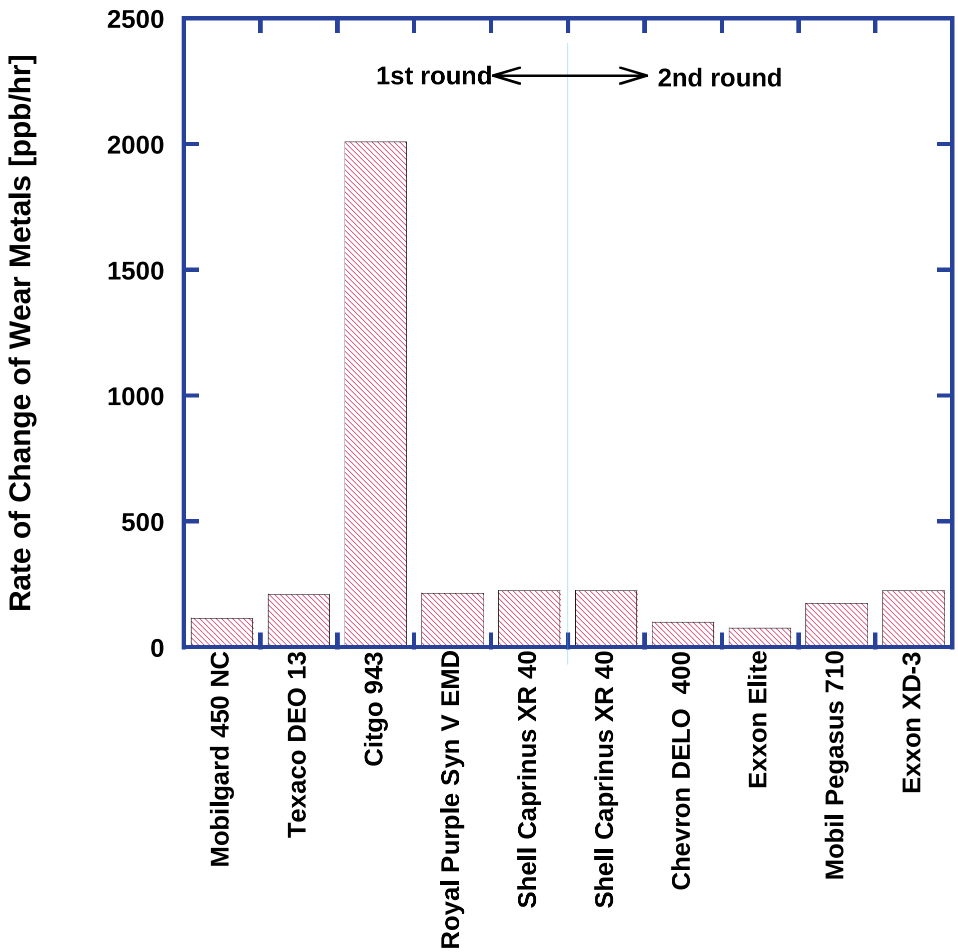


Figure 7. Effect of lube oil formulation for all of the candidate oils on the rate of change of wear metals in the oil

The effect on oil consumption is illustrated in Figure 8. All of the candidate oils from both rounds of testing are clearly superior to the re-refined oil. Two of the four new oils selected for the second round (Exxon Elite and Mobil Pegasus 710) are equivalent to the best two oils from the first round (Citgo 943 and Shell Caprinus XR 40), and a third oil from the second round (Exxon XD-3) is superior to all of the other candidate oils from the perspective of oil consumption.

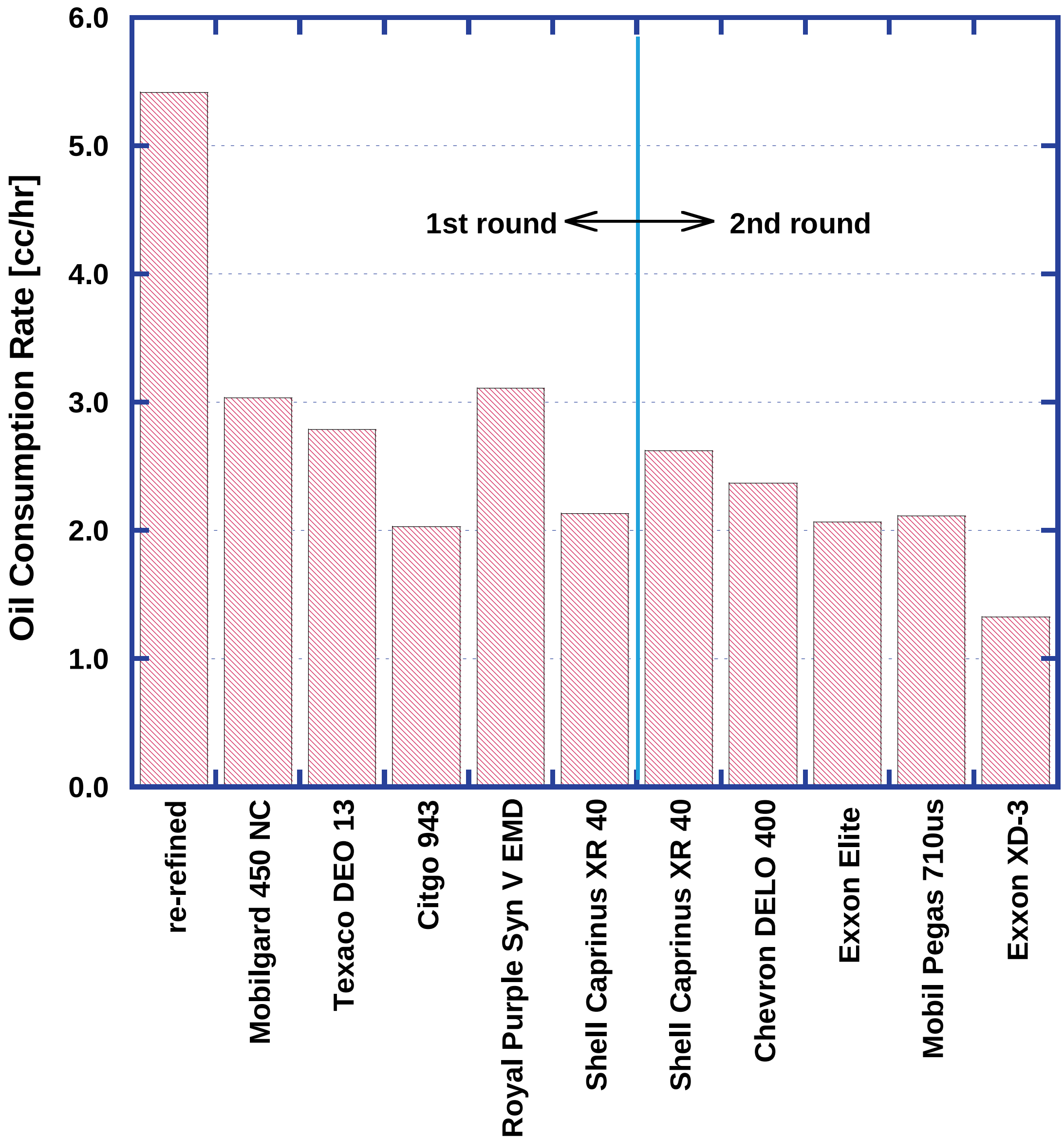


Figure 8. Effect of lube oil formulation for all of the candidate oils in comparison to re-refined oil on the oil consumption rate

A rating scale is used to simplify the comparisons between the oils in the following subsection.

3.C. Conclusions from the Oil Tests

Shell Caprinus XR 40 was tested during both the initial and the final round of testing. While one of the performance metrics was very repeatable (wear metals), the others were not as repeatable as initially expected. Therefore, at the end of the final round of testing, this oil was tested a third time so that the test-to-test repeatability could be quantified via statistical analysis of the results. Because it was impractical to test all ten oils three or more times, it was assumed that the Coefficient of Variance (the standard deviation normalized by the mean) was the same for the other oils as the measured value for the Shell Caprinus XR 40. Given this assumption, it was possible to determine the 95% confidence intervals for all three performance metrics (oil consumption rate, rate of accumulation of calcium deposits, and rate of change of wear metals in the oil) for all oils. If the confidence intervals for any performance metric for any two oils overlap, then it cannot be said that these two oils are statistically different from the perspective of that particular performance metric.

Each performance metric was examined independently. The oil that performed worst (e.g., highest oil consumption) was assigned a rank of 10 and the oil that performed best was assigned a rank of 1. The other oils were ranked linearly between these two extremes via:

$$R_x = \frac{M_x - M_{worst}}{M_{best} - M_{worst}}\left[R_{best} - R_{worst}\right] + R_{worst} = \frac{M_x - M_{worst}}{M_{best} - M_{worst}}\left[1 - 10\right] + 10 \qquad \text{(Equation 1)}$$

where, for this specific performance metric, R_x is the rank (numerical score) for “Oil X”, R_{best} is the rank for the best oil (R_{best}=1), R_{worst} is the rank for the worst oil (R_{worst}=10), M_x is the measure of this performance metric (e.g., the measured oil consumption rate in cc/hr) for “Oil X”, M_{best} is this measure for the best oil, and M_{worst} is this measure for the worst oil.

Figure 9 shows the rankings of the candidate oils from the perspective of oil consumption. The Exxon XD-3, engineered for heavy-duty trucks that must meet 2007-2010 emissions standards, was clearly the best oil from the perspective of oil consumption. Although this oil is not EMD approved, this is not significant because none of these engines is still under warranty and the EMD 12-645E engines used in the ferries do not have silver coated thrust bearings, so there is no scientific rationale for not approving oils that use a ZDP additive..

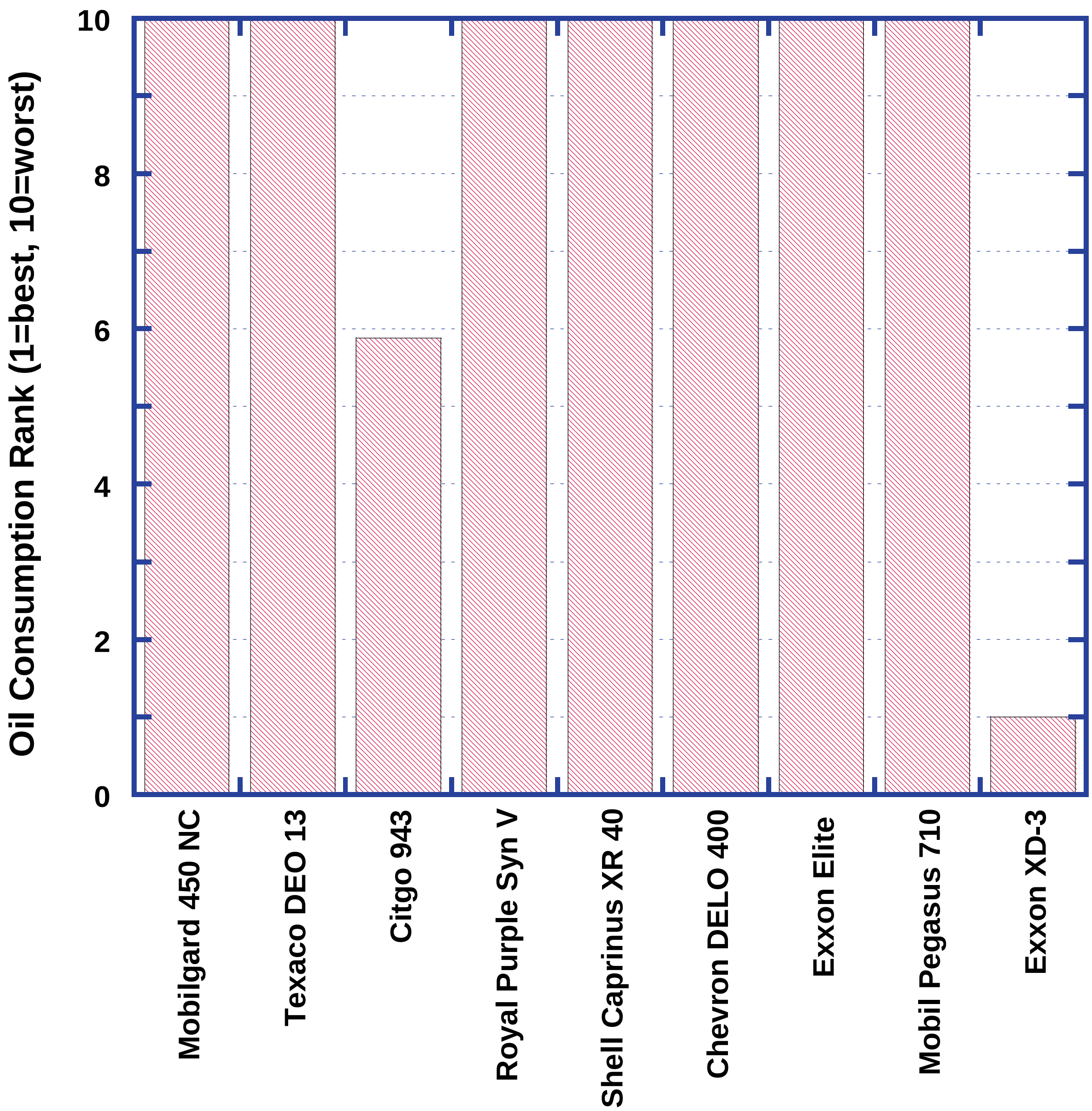


Figure 9. Ranking of the candidate oils regarding oil consumption

Figure 10 provides the ranks for the candidate oils from the perspective of wear metals. Due to the uncertainties associated with the quantification of the wear metals from the sea trials during the first round (discussed in Subsection 3.A), the rank for the Citgo oil was adjusted via assuming that the very high rate of change of wear metals for this oil was an artifact of the engines' rebuild history. To compensate for this, it was assumed that the rate of change of wear metals for this oil was equivalent to that of the next worse oil, then determining the scores for the various oils. Failure to make this adjustment in the wear metals would result in all oils other than the Citgo having almost the same rank—de-emphasizing differences in wear metals for all other oils. With or without this adjustment, the Exxon Elite is the best oil from the wear metals perspective, followed by Chevron DELO 400 and Mobilgard 450 NC. Compensating for the uncertainty in the reason for the high rate of change of wear metals for the Citgo sea trials is important to the overall ranking of the oils, which is discussed with respect to Figure 12.

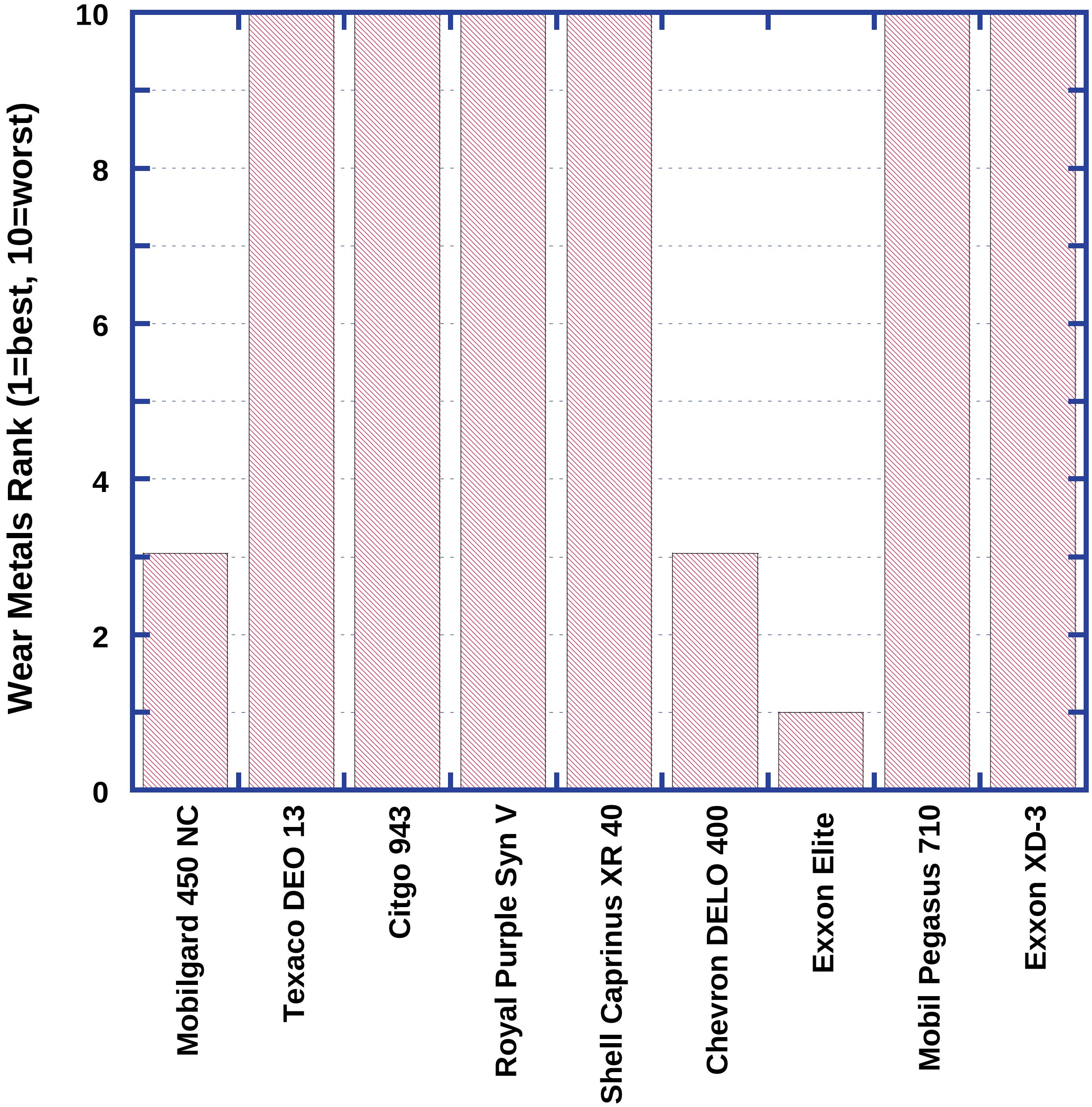


Figure 10. Ranking of the candidate oils regarding the wear metals

Presented in Figure 11 are the rankings of the candidate oils with respect to calcium deposits left in the cylinder. All four of the oils selected for the second round of tests are clearly superior to the oils selected for the first round, all of which are EMD approved except for the synthetic oil. Exxon Elite was the best oil from the calcium deposit perspective, followed closely by Chevron DELO 400 and Exxon XD-3, then Mobil Pegasus 710.

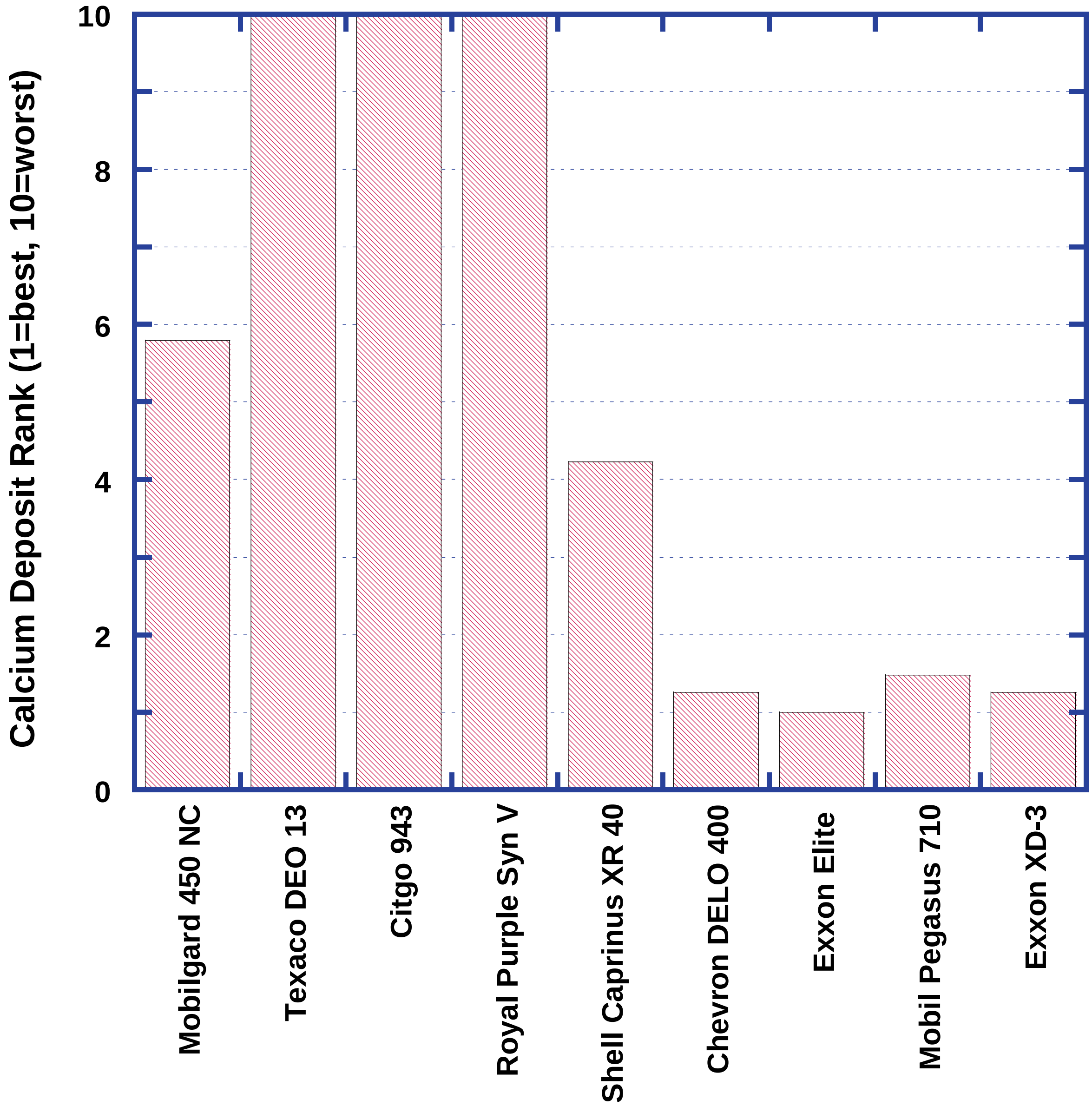


Figure 11. Ranking of the candidate oils regarding calcium deposits

The overall rankings of the oils are presented in Figure 12. These overall rankings were calculated by summing the rankings (scores) for each oil over the three performance metrics, then assigning an overall rank of 1 to the oil with the lowest total score, an overall rank of 10 to the oil with the highest score, and using Equation 1 to calculate the overall scores for the remaining candidate oils. From this overall perspective, three of the four new oils selected for the second round of tests, none of which are EMD-approved, are clearly superior to the oils initially selected for testing—all of which were EMD approved except for the synthetic. Again, EMD approval is not required because none of the GFO engines are still under warranty, and EMD's requirement for a zinc-free oil should never have been applied to the EMD 12-645E engines used in the GFO ferries because they do not have any silver-coated bearings. The new oils selected for the second round of testing (not including one that was tested a second time as a control) were all superior to both the re-refined oil and to the oils selected for the first round of testing except that the Mobil oil selected for the second round was not quite as good as the Mobil oil examined during the first round of tests. The new oils during the second round were Exxon XD-3, Exxon Elite, Mobil Pegasus 710, and Chevron DELO 400. Any of these four oils would be clearly superior to the re-refined oil used in the GFO ferries when the engine failures occurred. Of all of the oils tested, the Top 5 oils were Exxon Elite (20W50) with an overall score of 1.0, followed by Exxon XD-3 (15W40) with an overall score of 1.13, Chevron DELO 400 (15W40) with an overall score of 2.15, Mobilgard 450 NC (a straight 40 "weight" oil) with an overall score of 4.42, Mobil Pegasus 710 (another straight 40 "weight" oil) with an overall score of 5.74, and Shell Caprinus XR 40 (20W40) with an overall score of 7.11, all on a 0-10 point scale.

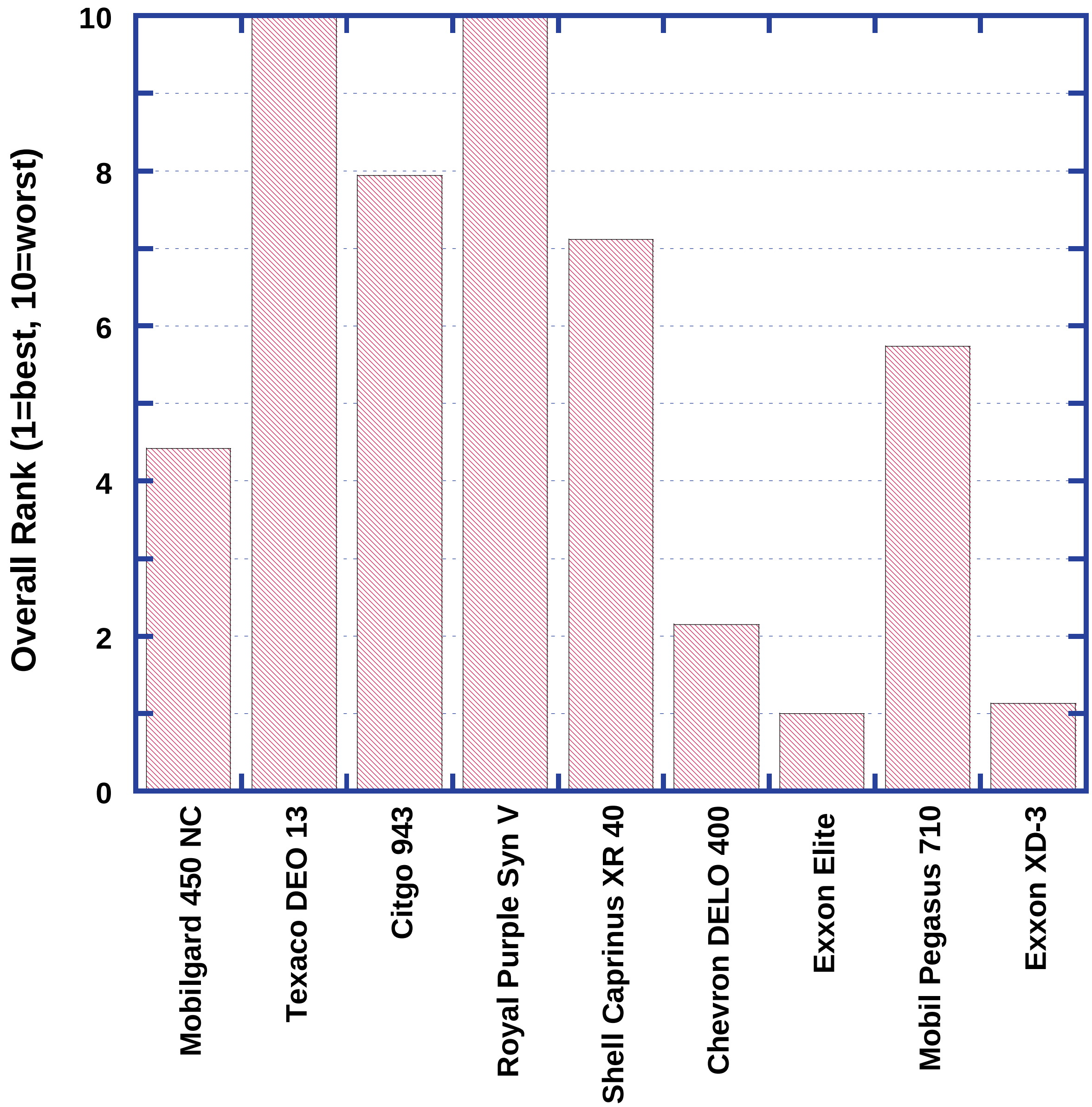


Figure 12. Overall ranking of the candidate oils

4. Hardware Solutions

SwRI was tasked with identifying a mechanical solution to reducing or eliminating the deposits. In practice this can be done only by reducing oil consumption in the engine. Oil consumption can be reduced by utilizing:

- **Option 1:** Ring and liner kits that have been specially developed by EMD to reduce oil consumption.
- **Option 2:** Operating the engine with high engine oil temperatures (high oil temperature yields lower oil viscosity and less oil consumption).
- **Option 3:** Changing the oil formulation, such as from a single grade (SAE 40) to a multi-grade (SAE 20W40). Note that this oil needs to be approved by EMD for this engine application.

Option 2, changing the engine operating conditions, is not practical. Option 3, changing to an oil other than the re-refined oil in use when the engine failures occurred, was the subject of Section 3. Before the hardware solution (Option 1) can be used, the hardware must be approved by EMD for Power, Marine, and Industrial (PM&I) applications, due to the critical nature of these engine applications.

In our attempt to identify sources of low oil consumption components, SwRI contacted EMD, Marine Systems, Inc. (MSI), and Stewart & Stevenson (S&S). EMD is the original equipment manufacturer for this engine and is the preferred source of all components for the application. Both MSI and S&S are EMD component suppliers. MSI provides components for both the railroad industry and PM&I applications. S&S supplies components only for PM&I applications.

MSI has advertised a new low oil consumption piston ring set for 645 engines in PM&I applications. The brochure provided by MSI states that their new ring set "has been proven to reduce oil consumption, of up to 50% in comparison to other ring designs" (PN 40082478). In a discussion this with Mr. Ray Sykes of MSI, he stated that the benefits of this ring pack design would be minimal due to the light loading of this application. Apparently this ring pack provides significant oil consumption reductions only on high power output engine applications.

MSI did state that the GFO application is similar to some drilling rig generator sets that mostly run at 900 RPM and light load. MSI has had good success in reducing the lubricating oil consumption on these by running the engines at the upper end of the allowable operating jacket water temperature. This was done by adjusting the jacket water temperature controller, typically using an AMOT valve, to 195° F jacket water outlet temperature. SwRI checked with Mr. Mark Rodriguez of GFO and learned that the AMOT system on the main engine jacket water system is already operating at 190° F. The increase of the jacket water temperature by 5° F, to 195° F, would not appreciably improve the oil consumption rate.

S&S stated that they were having reasonable success with a new ring set (PN 40082478) in reducing oil consumption in EMD 645 turbocharged engines operating as prime movers in generator applications on offshore drilling rigs. S&S stated that this ring set is most effective when the engine is turbocharged and operating under heavy load conditions. Because the engines used by GFO are roots-blown rather than turbocharged, and typically lightly loaded, the benefits of the ring pack would be reduced. S&S also suggested increasing the jacket water temperature to 195° F to minimize the oil consumption. These recommendations matched those of MSI.

The benefits of using multi-grade engine oil, approved for this application, should not be overlooked. It has been demonstrated that multi-grade engine oils (SAE 20W-40) can reduce the oil consumption, compared to straight weight oil (SAE 40). It is possible that the multi-grade oil could provide a fuel consumption improvement. However, the benefits of using a multi-grade oil in this application are unknown and need to be documented.

In 2005, EMD published a brochure (provided in Appendix A) that discussed some engine components that have been upgraded for PM&I applications. These new components that might benefit the GFO include:

1) A new cylinder head design with induction-hardened valve seats
2) New exhaust valves designed with a flat face
3) Valve rotators and valve spring system

These components will not necessarily help reduce the oil consumption rate of the engine, but should help reduce the valve failures for those deposits that do break loose and are caught between the valve and the valve seat.

The induction-hardened valve seats in the new cylinder heads would reduce the risk of damage to the valve seat in the event that a deposit becomes trapped between the valve face and valve seat. Additionally, the new flat face exhaust valve design (illustrated in Figure 13) has less surface area exposed to combustion gases and therefore operates at cooler temperatures. These cooler operating temperatures affect the material hardness when the engine is under a load, which in turn affects the valve's ability to survive an impact of a loose deposit lodging between the valve face and valve seat.

Figure 13. New valve face for PM&I applications

The new cylinder heads are also fitted with valve rotators and special springs (note the green color on the springs in Figure 14 to designate the different design) to accommodate the valve rotators. The valve rotators could also be valuable in reducing the valve failures by allowing the valve to rotate and change the location at which the valve and valve seat contact at the closure of the valve. This rotation also allows the valve and valve seat some relative motion that could help crush the deposits between the two surfaces, thus allowing for better sealing if a deposit is caught between the valve and valve seat.

Figure 14. New valve rotators and springs for EMD PM&I applications

In 2006, EMD developed improved cylinder liner and piston ring components for their 645 locomotive engines. This liner and ring combination decreases the oil consumption rate by (typically) 50%, and up to 80% if done in conjunction with a complete overhaul. If applied to the GFO ferry engines, these components could produce a significant reduction in the deposits in the EMD engines. In addition to the improved rings and liners, the improved power cylinder assembly includes the flat face valves depicted in Figure 13 and the new valve rotators and springs shown in Figure 14.

In conclusion, a hardware solution has been identified to reduce the oil consumption of this engine. This hardware solution would be a combination of a new ring pack and liner finish. A hardware solution is needed only if none of the candidate oils, identified by others working on this project, solve the problem of engine deposits building up in the combustion chambers.

5. Summary and Conclusions

Following the failures of all ten propulsion engines used at TxDOT's Galveston Ferry Operations within months after switching from 2D on-road diesel fuel to an ultra-low sulfur diesel fuel (Texas Low Emissions Diesel, TxLED), the Center for Transportation Research (CTR) at the University of Texas was awarded a contract to determine the root cause of the engine failures and to develop a solution that allowed continued use of TxLED. CTR used Southwest Research Institute and Kibler Technologies as subcontractors on this project. It was found that the failures were the result of three factors: 1) the poor ring pack design of these engines, which results in a high oil consumption rate, 2) the high ash content of the re-refined oil that was used in the ferries, and 3) the decreased flame temperature for TxLED relative to 2D on-road diesel.

The research team consisted of investigators from the UT Center for Transportation Research, Southwest Research Institute, and Kibler Technologies. Professors Ron Matthews and Matt Hall, of the UT Engines Research Program, lead the CTR effort. John Hedrick lead the SwRI effort, which consisted of determining the root cause of the failures of the locomotive engines used for propulsion in the GFO ferries and seeking a hardware solution to overcome these failures. Clark Kibler, of Kibler Technologies, specified the oils for testing and aided in the analyses of the results from the oil tests.

The research team evaluated nine candidate oils as potential replacements for the re-refined oil that GFO was using as a result of a recommendation from a prior project that was conducted at a different university. These oils were evaluated based upon their effects on the oil consumption rate, engine wear, and in-cylinder calcium deposits. We also analyzed the oils for evidence of oxidation, nitration, and sulfation, but found no evidence of any of these from either the sea trials or the UT engine tests.

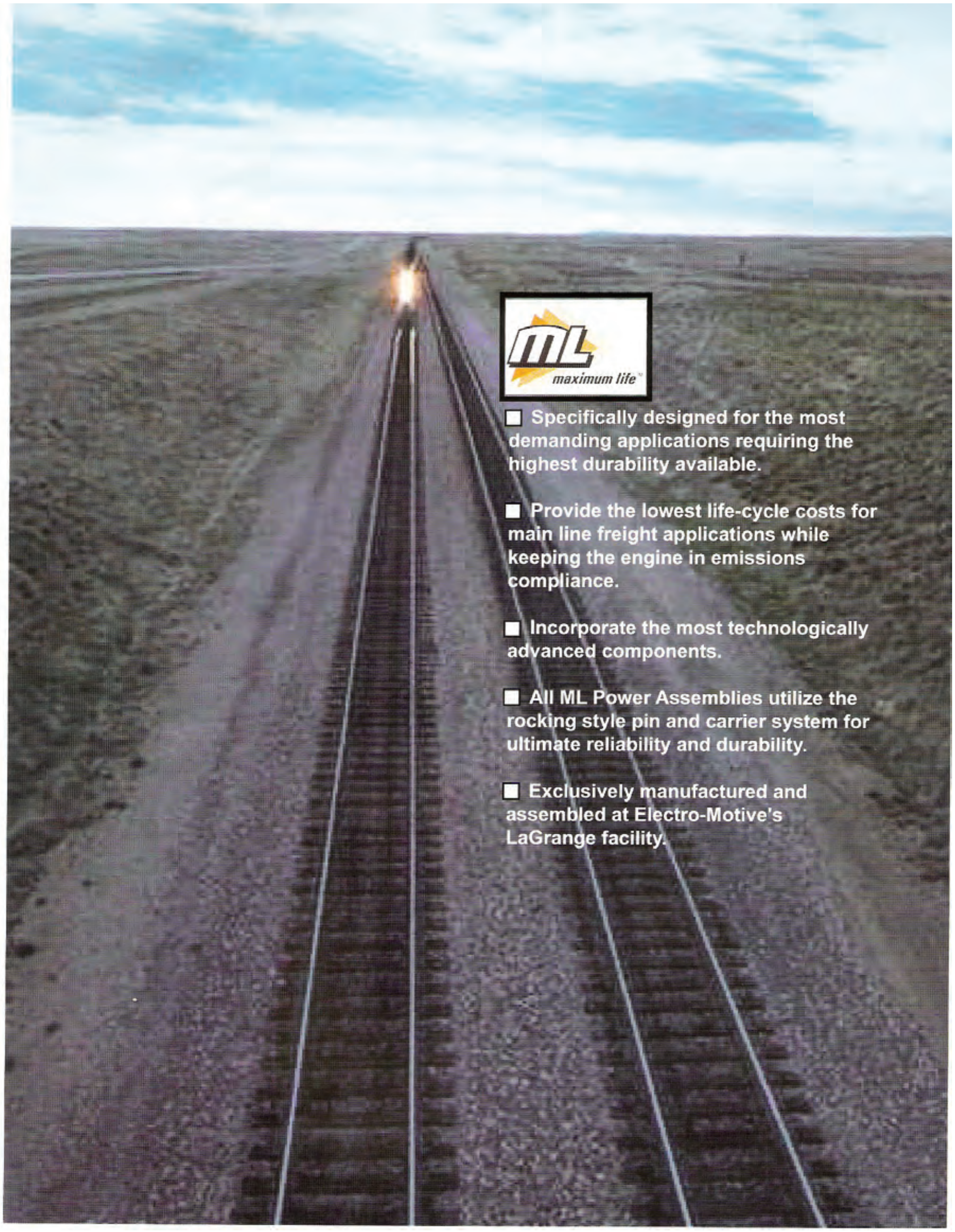
Here, it is important to note that all of the candidate oils performed much better than the re-refined oil in all metrics, but—with the exception of the synthetic oil evaluated in the first round of testing and most of the oils from the second round of testing—the TBN and ash content were not significantly lower than for the re-refined oil. This poses the logical question: why does the re-refined oil result in more deposits, when the conventionally refined oils with similar TBN and ash content do not? The most important factor may be the effect of the oil formulation on oil consumption and the consequent in-cylinder deposits.

Of all the oils tested, the Top 5 oils were Exxon Elite (overall score = 1.0), followed by Exxon XD-3 (overall score = 1.13), Chevron DELO 400 (overall score = 2.15), Mobilgard 450 NC (overall score = 4.42) and Mobil Pegasus 710 (overall score of 5.74), all on a 0-10 point scale.

The research team recommends that Galveston Ferry Operations begin using Exxon Elite 20W50 in all of its ferries. Although this is an airplane piston engine oil, aircraft oils are necessarily designed to minimize wear due to the danger resulting from an engine failure at altitude. Thus, it was not surprising that this oil had the lowest rate of change of wear metals of all of the oils tested. Additionally, like all aviation piston engine oils, Exxon Elite has no ash whatsoever. Thus, it was also not surprising that Exxon Elite also had the lowest rate of accumulation of calcium deposits. Exxon Elite also had the second lowest oil consumption rate.

A hardware solution was also identified. A hardware solution is needed only if none of the candidate oils solves the problem of engine failures, which most of the candidate oils did. However, the hardware solution results in significantly decreased oil consumption, and thus is worthwhile even though an oil has been recommended for use by GFO. This hardware solution consists of a new and improved ring pack and liners with an improved finish. In addition to the improved rings and liners, the improved EMD 645 power cylinder assembly includes new and improved flat face valves and new valve rotators and springs

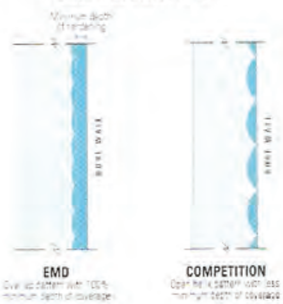
Appendix A: EMD Brochure Provided by MSI


ML
maximum life
Specifically designed for the most demanding applications requiring the highest durability available.
Provide the lowest life-cycle costs for main line freight applications while keeping the engine in emissions compliance.
Incorporate the most technologically advanced components.
All ML Power Assemblies utilize the rocking style pin and carrier system for ultimate reliability and durability.
Exclusively manufactured and assembled at Electro-Motive's LaGrange facility.

Blade Rod – The EMD blade rod has been redefined with improved slipper surface processing. Through machining optimization, EMD has improved the loading surface resulting in improved bearing life and increased durability. Through continuous improvements EMD has led the industry in connecting rod technology.

Tapered Thrust Washer – With the latest design improvement in thrust wear, EMD has developed a thrust washer with improved wear characteristics that have resulted in improved durability and reliability. Through several years of testing, the new design has proven to reduce thrust washer wear, especially into the carrier platform relief groove. Cracked thrust washers are virtually eliminated with the use of the tapered thrust washer.

Cylinder Liner – The hardened upper bore (HUB) liner is the industry standard when it comes to cylinder liners and the EMD liner has always set the benchmark in reliability and durability. With an improved ground bore there are no liners straighter in the industry. Combine that with the only 100% hardened upper bore available and you have a liner that has no equal, no matter what anyone may claim. Just ask the competition for their details.



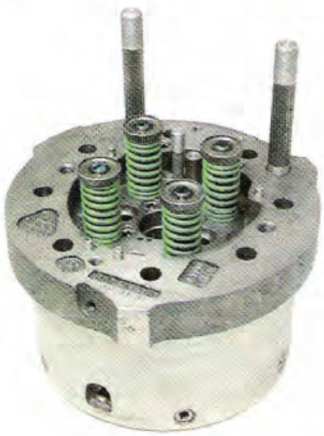
With the improved straightness of the EMD liner and the 100% hardened upper bore, the benchmark has once again been raised for all the competition. As horsepower demands continue to increase, only the EMD HUB liner will be able to provide the performance, durability, and reliability that customers have come to expect.

Rocking Style Pin and Carrier System – There is no system more robust than the rocking style system pin and carrier. Specifically designed for the higher horsepower range, this system provides the ultimate durability. For that reason every Maximum Life power assembly utilizes it. From the early 645E to the current 710 engine, the rocking style system results in unmatched performance, reliability, and durability.

Pistons – The pistons utilized in the Maximum Life power assemblies are none other than the Tin Plated Hardened Ring Groove Pistons. These pistons, like the EMD HUB liner, have become the industry standard in every application. Tin plating has proven to be the best break-in and operational coating available and provides unsurpassed protection against any type of scuffing.

The hardened #1 ring groove is another EMD innovation that has provided the industry with the ability to exceed the million-mile threshold between overhauls. It is no surprise that the Maximum Life power assemblies would include this feature.

Cylinder Head – The ML cylinder head utilizes the industry leading Diamond 6 Tangent Flow design. With newly added features, the ML cylinder head provides additional reliability and durability. This results in the best cylinder head available for the most demanding service.



New features include:

- Induction Hardened Valve Seats
- Flat Head Valves
- Valve Rotators with matched Valve Springs
- New Design Valve Locks

Diamond 6 Tangent Flow Head Casting –
The industry has yet to see a more robust cylinder head design. With the patented Tangent Flow feature, EMD has eliminated fire-face cracking and increased the retained equity in every head. Currently, customers typically re-use the EMD cylinder head for up to 5 service lives. There is nothing that defines Maximum Life more than the EMD cylinder head.

Induction Hardened Valve Seats –
The hardened valve seat offers the most durable valve sealing surface available in the market. With the increased hardness of the valve seat, uneven wear is virtually eliminated resulting in improved performance. Utilizing an exclusive patented induction hardening process, EMD has been able to eliminate surface micro-cracks that are common when trying to induction harden valve seats.

Flat Head Exhaust Valve – The new design, that eliminates the cup in the valve head, reduces the surface area resulting in less heat absorption that improves thermal fatigue life. A reduction in valve head deflection yields a 50% reduction in stresses and reduces the valve seat wear on the cylinder head. The design also includes a hardened stem tip that extends below the contact area of the keepers. This will reduce the chance of dropped valves.

New Valve Lock – Also known as the keeper, the new valve lock design is improved by increasing the amount of clamp load that is distributed onto the stem of the valve. With the increased grip on the valve stem, spun valves are a thing of the past. The new locks are black in color as compared to the metal gray of the old design.

Valve Rotators – Electro-Motive has applied valve rotators to the cylinder head in order to introduce a controlled spin on the valve. By spinning the valve there is less chance of developing uneven wear on the valve or the valve seat itself. This will result in improved valve sealing over time and reduces the occurrence of hard starting. The rotators are designed to accept the new black valve locks as well.

Due to the increased height of the rotator, in comparison to the old retainer, a new valve spring was designed to maintain the proper spring load on the valve system. For ease of identification, the new spring is green in color and is to be used only when the rotators are applied.

Improved Valve Guide – For marine applications, EMD has an improved valve guide design that utilizes a new material and hardening process. The new design has been extensively tested resulting in the highest resistance to corrosive wear found in marine applications. The corrosive resistance has been improved 18 times in comparison to the current design. Use of this new valve guide will eliminate crankcase over pressure due to leaking valve guides.

The new design can be identified by a circumferential groove on the outside of the valve guide collar.

Controlled Deflection Fork Rod – The "CD" Rod, is the latest design in connecting rods. This rod was designed utilizing analytical modeling to optimize the stiffness of the rod at the fork end. The reduced deflection of the fork rod basket area results in longer bearing life.

New features include:

- Increased cross sectional area of U-Slot region
- Increased rib size on the back side of the basket halves
- Optimized material location reducing basket deflection by 50%

Ring Sets - Electro-Motive continues to be the industry leader in piston ring technology. With the development of the industry-leading performance ring package, EMD continues work to reduce oil consumption. The added pressure of emissions regulations has forced the focus of ring development to shift from performance to oil control.

P/N 40033365 - The pre-stressed stainless steel ring set is the industry leader when it comes to engine performance. For locomotive applications, this ring set has become the standard to which everything else is compared. For that reason the Maximum Life power assemblies designed for locomotive applications will contain this ring set.

P/N 40082478 - This ring set has been specifically designed for the Power, Marine and Industrial (PM&I) applications that have experienced increased lube oil consumption. With a change in the material of the #2 and #3 combustion rings, this ring set offers a combination which has proven to reduce lube oil consumption, in PM&I applications, of up to 50% in comparison to other ring designs. In PM&I applications, the Maximum Life power assemblies will contain this ring set.

ELECTRO-MOTIVE

ml maximum life

Certified Genuine
OEM Product

The Maximum Life "ML" power assemblies offer all the latest technology in one complete package. Designed to give the customer the longest life, highest value, and complete confidence in the performance, durability, and reliability of their engine. Be assured that as EMD continues to deliver new designs and technology to the industry, such improvements will be incorporated into the Maximum Life power assemblies.

To guarantee that you receive what you ordered, every EMD Maximum Life power assembly is built at EMD and bears a certification tag with the trademarked logo of the Maximum Life series.

When good enough just doesn't cut it anymore, talk to your Electro-Motive sales representative and let us help you to specify the Maximum Life power assembly that fits your application.