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# Engine Durability, Emissions and Fuel Economy Studies with Special Boundary Lubricant Chemistry

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## ABSTRACT

A unique combination of boundary lubricant and surfactant chemistries has produced significant benefits in ring and bearing wear control. This chemistry is added as an engine treatment to current quality engine lubricants. Microscopic wear studies employing radioactive tracer and metal surface analysis techniques have helped define optimum chemistry for enhanced bearing and ring wear control in a running engine. These studies have also served to further our understanding of the wear protection mechanism. Results from macroscopic engine wear studies, carried out in Sequence IIIE engines/stands using modified ASTM IIIE protocols, paralleled data obtained from the radioactive wear studies. They confirmed the positive wear protection benefits of this unique chemistry. Vehicle emission evaluations using the Federal Test Procedure (FTP) for light duty vehicles with this unique chemistry showed no detrimental effects either as added pollutants or catalyst degradation. Initial fuel economy data have also indicated a substantial benefit for this chemistry, especially under engine conditions emphasizing boundary lubrication. The paper will describe and discuss the test methods employed in evaluating this unique chemistry and the relevance of the resulting data to improved engine durability, emissions and fuel economy.

## I. BACKGROUND AND INTRODUCTION

It has long been recognized that a substantial amount of engine wear occurs during the first few seconds after engine start.<sup>(1,2,3)\*</sup> This has been attributed to an increase in boundary (metal-to-metal) contact of engine parts after extended engine shutdown. This is especially true after overnight shutdown where oil drainback from critical engine parts (such as the piston/cylinder/ring area) to the sump has occurred.

However, certain engine parts, because of their position and function in the engine, almost always operate under boundary conditions of lubrication. Examples are top and second piston rings, especially at top and bottom dead center of the piston

stroke, and in the engine's valve train.<sup>(4)</sup> These parts normally show the greatest progression in wear with miles driven. The rod bearings (especially top rod bearings) and the rocker arms operate under a mixed boundary/hydrodynamic regime weighted towards the boundary. The rod bearings, because of their position in the engine and the great pressure gradients they are subject to, spend a very substantial part of their time under boundary conditions. The rocker arms experience considerable metal-to-metal contact because of their position at the top of the engine. The rod bearings and rocker arms show progressive wear with miles driven, but not to the same extent as the piston rings. Main bearings are, in contrast, designed to operate with a definite protective oil film between the bearing and the spinning crankshaft, i.e. under hydrodynamic lubrication, minimizing progressive wear in this part of the automotive engine.<sup>(5)</sup> Wear results from extensive testing in Sequence IIIE engines/stands using modified ASTM IIIE protocols (at an industry approved test laboratory) have demonstrated the boundary lubrication/progressive wear relationship described above. Moreover, data from these tests have shown that a unique combination of boundary lubricant chemistries can be quite effective in helping to control the extent of progressive wear in engine parts which operate primarily under boundary lubrication conditions. These test protocols and the resulting data will be described and discussed more extensively in the experimental and discussion parts of this paper.

In addition, microscopic wear studies employing a unique radioactive tracer technique for simultaneous measurement of both ring and bearing wear in a running engine have been carried out and will be discussed in the experimental and discussion sections of the current paper. These studies have helped define optimum chemistry for enhanced ring and connecting rod bearing wear control in a running engine, confirmed the positive wear protection benefits of the unique boundary chemistry (UBC) and have helped to achieve a better understanding of the wear protection mechanisms involved. A more detailed description of the unique tracer technique used in the current studies is described in a separate SAE Paper #941982 to be presented at the same SAE session as this paper.

Because of emission concerns associated with any "new" chemistry added to the lubrication system of an automotive engine, extensive emissions testing was carried out. These tests

\*Raised numbers in parenthesis are references listed on page 18 of this paper.

compared emissions with and without the unique boundary chemistry described in this paper. The testing included (1) a two stroke engine test, (2) an engine-driven ATF Cycling Test and (3) an on-the-road 80,500 km (50,000 miles) vehicle test. No measurable levels of fluorine (F) or fluoride compounds were found in the exhaust samples from the vehicles involved in these tests. The ability to detect F in the form of HF or other volatile fluorides was essential, since the unique boundary chemistry described in this paper contains colloidal PTFE particles as part of its five component chemical makeup. The emissions testing also included evaluation of catalytic converters to determine emission reduction efficiency. There was no deterioration in catalytic converter performance due to the unique boundary chemistry. A more detailed discussion and summary of these studies and results will be included in the experimental and discussion sections of this paper.

A limited number of ASTM Sequence VI fuel economy tests have been run with the UBC Engine Treatment. These tests have shown additional fuel economy benefits, especially at 135°C(275°F) oil temperature, over a leading API SG/ECII oil and over an API SH/ILSAC GF-1 oil. Work is in progress to more precisely define and optimize the benefits of the UBC relative to ECII oils of today.

## II. EXPERIMENTAL

A. SEQUENCE IIID WEAR SCREENER TESTS – This method<sup>(6)</sup> is a modified version of the ASTM Sequence IIID wear test which has been used by some industry members as a tool to evaluate cam and lifter scuffing and wear. The test consists of a four-hour break-in and an eight-hour test period (12 hours total). Prior to testing, the engine is disassembled and cleaned with standard solvent and compressed air. New camshaft, lifters and rocker arm pads and pivots are installed for each test. These same parts are removed and inspected for scuffing and wear upon test completion.

B. MODIFIED PROTOCOL ASTM SEQUENCE IIIE TESTS – In order to evaluate the true potential for the unique boundary chemistry (UBC) described in this paper to protect engine parts from progressive wear, two distinctly different engine operating protocols were carried out in the ASTM Sequence IIIE test/stands at a leading independent industry test laboratory from June, 1990 through April, 1992. These tests were designed following the recommendations of the National Advertising Division (NAD) Council of Better Business Bureaus, Inc.<sup>(7)</sup> NAD recommended that, “any quantitative claims be explicitly limited to those tests that used currently available oils and measured wear in the period after the replacement of the UBC Engine Treatment/oil mixture.” These protocols included (1) a series of “Stop/Start” tests and (2) a series of “Continuous Run” or “Extended IIIE” tests. In the case of the Stop/Start tests, wear in six engines was evaluated; three of these were treated with the UBC and three were not. These engines were “broken-in”, drained and then put through 500 cycles of starting, revving and stopping. In the continuous run tests, three engines (two treated with the UBC chemistry, one untreated) ran for 96 hours, one engine (untreated) ran for 128 hours, three (one treated, two untreated) ran for 480 hours and one (treated) ran for 736 hours. A more detailed description of each of these test protocols is summarized as follows:

Start/Stop Tests – A summary of the start/stop test's protocol is as follows:

(1) Three test engines were charged with 80 percent of an SAE 5W-30 API SG oil and 20 percent UBC Engine Treatment and three control engines were charged with 100 percent SAE 5W-30 API SG oil.

(2) The standard IIIE four-hour break-in was performed. The following sequence was then performed on each engine 330 times: (a) start engine, (b) idle operate for ten seconds, (c) ramp up to 2300 rpm, level-road load in less than one minute and operate at that rpm for ten minutes, (d) shut down, (e) pause for five minutes, and (f) restart.

(3) After 330 engine cycles, the oil was drained from all engines and replaced with 100 percent of SAE 5W-30 API SG oil and the engines were operated for four hours. The oil was then drained and the oil system purged of oil.

(4) Each engine was then started 500 times without oil. Engine speed was increased to 1000 rpm, and then the engine was stopped. There was a one minute pause between each cycle.

(5) Following completion of the test, all engine parts were remeasured and rated as specified in the Sequence IIIE procedure. Rings and main and connecting rod bearings and rocker arms were weighed.

Extended ASTM Sequence IIIE (Continuous Run) Tests – During the period June, 1991 through April, 1992, a series of Extended Sequence IIIE tests (“continuous run” tests) were conducted at a leading independent industry test laboratory. These tests were designed to evaluate the effect of UBC Engine Treatment on an engine that was run for extended periods through 3, 4, 15 and 23 oil drain intervals. Sequence IIIE tests operate under severe engine conditions which correspond to ~225 km (140 miles) for each hour of Sequence IIIE operation.<sup>(8)</sup> A summary of the test protocol for the extended IIIE test is as follows:

(1) Four test engines were charged with 80 percent SAE 5W-30 API SG oil and 20 percent UBC Engine Treatment and four test engines were charged with 100 percent SAE 5W-30 API SG oil.

(2) The standard IIIE four-hour break-in was performed. After an additional 32 hours of operation (36 hours total), and every 32 hours thereafter, the engines were drained and charged with 100 percent SAE 5W-30 API SG oil.

(3) After the requisite number of test hours for each of the continuous run tests described earlier, all engine parts were measured and rated as specified in the IIIE procedure. Rings, main and connecting rod bearings, and rocker arms were weighed.

C. RADIOACTIVE TRACER ENGINE WEAR STUDIES  
RADIOTRACER ENGINE TEST PROCEDURES – Tables 1 and 2 list the test procedures (I and II) used to evaluate piston ring and connecting rod bearing wear in the radiotracer wear studies. (Note that prior to testing, the engine was operated 7 hours under conditions ranging from no-load to full power to break-in the engine (see Appendix A). As shown, the test parameters covered a wide range of operating conditions including cold and hot starts and relatively mild to severe speed/load conditions. The rapid read-out of the wear happenings facilitated by the radiotracer technique allowed assessment of the importance of these operating conditions and observance of transient effects when changing test conditions. Total wear during the first 5.78 hours of the test was used to compare differences between oils. A 3-3-3 testing sequence was employed – three 5.78-hour tests on the reference oil, three on the test oil and again, three on

Table 1

**RADIOTRACER ENGINE WEAR TEST PROCEDURE I**

(A) Charge New Oil

(B) Operating Conditions

Test Conditions			Time/Step (min)	Cumulative (hrs)	Comments	
Torque (N·m)	Speed (rpm)	Coolant Out (°C)				
a) No Load	1500	Ambient	2	0.03	Cold Start	
b) 43	1600	85	90	1.53		
c) 47	2400	85	60	2.53		
d) 87	1600	104	90	4.03		
e) 95	2400	104	60	5.03		
f) 140	3200	104	45	5.78		
g) --	0		10	5.95		Down Period Hot Start
h) No Load	1500	85+	2	5.98		
i) 43	1600	85	15	6.23		
j) At test completion while engine is hot, immediately drain oil and flush with next oil to be tested. Immediately drain flush oil and allow engine to stand for 14+ hours before starting the next test.						

Table 2

**RADIOTRACER ENGINE WEAR TEST PROCEDURE II**

(A) Charge New Oil

(B) Operating Conditions

Test Conditions			Time/Step (min)	Cumulative (hrs)	Comments	
Torque (N·m)	Speed (rpm)	Coolant Out (°C)				
a) No Load	1500	Ambient	2	1.03	Cold Start	
b) 43	1600	85	90	1.53		
c) 47	2400	85	60	2.53		
d) 87	1600	104	90	4.03		
e) 95	2400	104	60	5.03		
f) 140	3200	104	20	5.36		
g) 140	3200	104	10	5.53		Drain 10% of Oil Charge Add 10% Additive Concentrate
h) 140	3200	104	15	5.78		
i) --			10	5.95		
j) No Load	1500	85+	2	5.98	Down Period Hot Start	
k) 43	1600	85	15	6.23		
l) Stop engine. While engine is hot, immediately drain oil and fill with next next oil to be tested. Immediately drain flush oil and allow engine to stand for 14+ hours before starting the next test.						

the reference oil. This method of testing was used to get a reading on test repeatability and to assess the importance of any carry-over effects from the preceding test(s).

At the completion of each 6.23-hour test the hot oil was drained and the engine flushed with the next oil to be used. The engine was allowed to stand for a minimum 14 hours prior to charging the next oil and starting the test.

Test Procedures I and II only differ in that at stage G of the test [140N·m/3200 rpm (103 ft-lb/3200 rpm)], while the engine was running, 10% of the oil charge is drained, and an equal amount of additive concentrate is added. This 10% addition

produced an oil composition which was identical to the next oil to be tested. The intent of this step was to observe any instantaneous wear benefits.

Two reference oils (see Table 3) were employed in the program. Reference Oil A was a blend of a modified API SH/CD detergent/inhibitor (DI) package in 150 solvent refined neutral. The DI package was modified to have one-half of the normal zinc dithiophosphate antiwear additive level. Also, no viscosity index improver was used in order to negate any wear effects relating to shear degradation of the VI improver. The resulting oil is an SAE 20 having a 6.7 cSt viscosity at 100°C and a 0.054 mass % phosphorous content.

Table 3  
Reference Oil Properties

	Reference Oil	
	A	B
Viscosity, mm <sup>2</sup> /sec (cSt)		
@ 40°C	43.2	58.9
@ 100°C	6.7	10.2
Metals Content, ppm		
Zn	680	1260
P	540	1120
Ca	70	1480
Mg	1640	330
API STATUS	—	SH/GF-1

Reference Oil B is an API licensed, commercial SAE 5W-30 API SH/ILSAC GF-1 engine oil.

D. EXHAUST EMISSION TESTS – Two series of exhaust emission tests were carried out in 4 cycle automotive engines comparing emissions with and without the UBC Engine Treatment described in this paper. The first evaluation involved four test cars, operated in convoy, preconditioned on a test track for 80,500 km (50,000 miles); the second evaluation, four engines in the Dexron® ATF Cycling Test<sup>TM</sup> operated for the equivalent of 80,500 km (50,000 miles).

On the Road Tests – The principal objective of this study was to identify semi-volatile, fluorine-containing compounds, if present, in exhaust samples of four vehicles equipped with 5.0 L engines. In addition, regulated emissions of HC, CO, and NO<sub>x</sub> were also measured. The vehicles were delivered to the test emissions laboratory after 6,400 km (4,000 miles) and again after 80,500 km (50,000 miles) of durability. The vehicles were provided in a "to-be-tested" condition. Two of the vehicles at 6,400 km (4,000 miles) contained a commercial SAE 5W-30 API SG/ECII engine oil treated with the UBC Engine Treatment for the evaluation. The other two cars contained the same, commercially available non-treated oil. There was no disclosure to the test laboratory concerning the identity of the two vehicles with the UBC treatment. The two treated and two untreated engines were tested for exhaust emissions using the Federal Test Procedure (FTP). All the catalytic converters were individually evaluated after the on-vehicle tests, using the procedure as outlined in Appendix B.

Table 4  
FTP Driving Schedule Summary

Segment	Duration, sec.	Distance, km	Average Speed, km/hr
Transient Phase	505	5.79	41.4
Stabilized Phase	867	6.28	26.1
UDDS	1372	12.1	31.7

The recommendation from the test laboratory's Chemistry and Chemical Engineering Division was that any fluorine compounds emitted would be in a semi-volatile form, not gaseous nor as an inorganic ash. Therefore, the decision to investigate only the semi-volatile fluorine and fluoride compounds was made before testing was begun. Regulated gaseous emissions (hydrocarbons, carbon monoxide, and nitrogen oxides) and carbon dioxide were measured on a raw, volume-fraction basis.

(1) Federal Test Procedure Emissions Test – The four vehicles with the 5.0 L engines were evaluated using the Federal Test Procedure (FTP) for light-duty vehicles. It uses the Urban Dynamometer Driving Schedule (UDDS), which is 1372 seconds in duration. The UDDS is divided into two segments: the first consisting of 505 seconds and the second consisting of 867 seconds. A complete FTP is composed of a cold-transient 505 and a cold-stabilized 867 portion, followed by a ten-minute soak and then a hot-transient 505. A summary of the cycle duration, driving distance, and average speed is given in Table 4. Tail pipe exhaust samples were collected in three Tedlar bags. Bag 1 collected emissions from the cold-transient phase. This segment contains the majority of the regulated emissions produced by the test vehicle. Bag 2 collected emissions from the cold-stabilized phase. In this phase, the converter has achieved continuous catalytic activity. Bag 3 contains a sample of the exhaust from the hot-transient phase. The FTP driving schedule with the cold- and hot-transient test segments identified is given in Figure 1.

(2) Converter Efficiency Performance Tests – After the vehicles had been tested, both underbody catalytic converters were removed. Each individual converter was evaluated to determine its emissions reduction efficiency. The performance test procedure consists of a light-off test and three air/fuel ratio sweeps with A/F perturbations. The light-off test is a measure of the time necessary for the catalyst to achieve a 50% reduction in the individual emission level. Conditions for the light-off test are a steady-state A/F ratio and a catalyst inlet temperature of 399°C (750° F). Exhaust gas is diverted around the catalytic

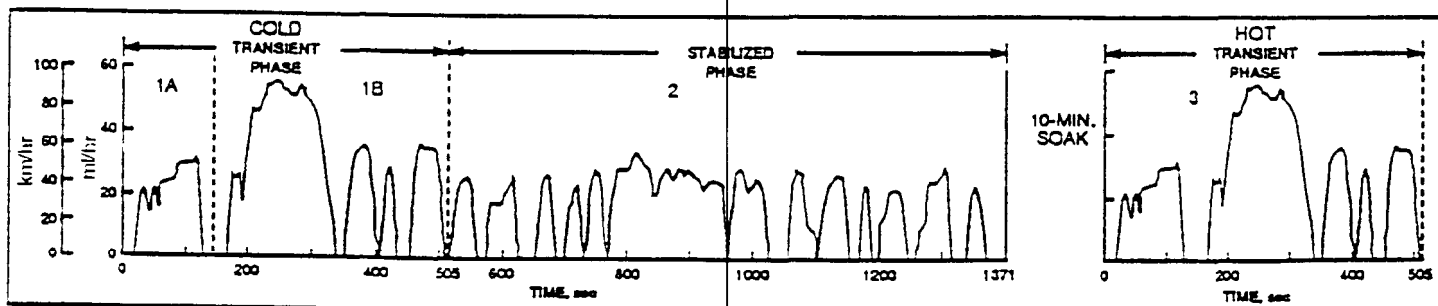


Figure 1. FTP Driving Schedule Showing Test Segments

converter until the proper conditions are achieved. The performance test procedure is given in Reference 10, Appendix A.

The performance testing portion of the test was conducted using a 5735cc (350 CID) engine. This engine is equipped with special fuel injection hardware and an Intelligent Controls Model #5160 fuel control.

(3) Fluorine Sampling and Analysis Techniques – The absorbent polyurethane foam (PUF)/XAD-2 resin, was extracted with 300 mL of dichloromethane (DCM) for 18 hours using a Soxhlet extractor. The DCM extract was then concentrated to 1.0 mL.

A 2.0  $\mu$ L portion of the final extract was then injected into a gas chromatograph/mass spectrometer (GC/MS) to generate a chromatogram. Each distinguishable peak on the chromatogram containing the mass spectrum was compared with the 45,000 spectra in the National Bureau of Standards (NBS) library. The spectrum of the peak and the best three matches of the library spectra were plotted for manual comparison.

Dexron® ATF Cycling Test – The objective of this project was to identify semi-volatile, fluorine-containing compounds in periodic exhaust samples from four 5.7 L engines. Two treated and two untreated engines were operated for 135,000 test cycles (1,503 hours) in the Dexron® transmission cycling test<sup>9</sup> which would be equivalent to operating a vehicle for 80,500 km (50,000 miles) under the same conditions.

In this study, volatile fluorine and fluoride compounds were investigated when the semi-volatile analysis did not reveal any known compounds. Regulated gaseous emissions (hydrocarbons, carbon monoxide, and nitrogen oxides) and carbon dioxide were measured on a raw, volume-fraction basis.

(1) Engine Operation – The Dexron® transmission cycling test utilizes a 5.7 L engine (GM SPO Part No. 10168440) as a "mule" to drive the transmission containing the test transmission fluid. The test procedure is described in detail in Reference 9. For this project, four engines of this type were specially built. The engine measurement, building, treatment, sampling, and maintenance were conducted under a separate project at the same leading independent industry test laboratory. Four test engines/stands were employed in the test program. Two engines (PET 1 and PET 6) ran the full 135,000 cycles on a commercial SAE 5W-30 API SG engine oil. The other two engines (PET 3 and PET 4) ran the first drain interval using this same engine oil with added UBC and thereafter, using the untreated commercial API SG engine oil. In all tests, the oil was changed at 8,100 cycles [4,830 km (3,000 mile) intervals]. Test operation was always contingent on transmission fluid tests. The 65 day tests of each engine began in September 1992 and were completed in December 1992. Test fuel was "super unleaded" gasoline.

(2) Sampling and Analysis Techniques – The terms volatile and semi-volatile in this study refer to the methods used for analysis of the samples. Compounds that are more conveniently analyzed by gas chromatograph are classified as volatile compounds. Sample requirements are different for volatile and semi-volatile analysis techniques. The volatile technique requires an evacuated cylinder for samples and a gas chromatograph for analysis. The semi-volatile approach utilizes a specially-prepared polyurethane foam (PUF) trap and a high-resolution mass spectrometer. For more information on the canister and gas chromatograph techniques, please refer to Reference 11. Fluoride, a negative ion, was sampled with an aqueous impinger and analyzed by ion chromatography. A schematic of the sampling system is shown in Figure 2.

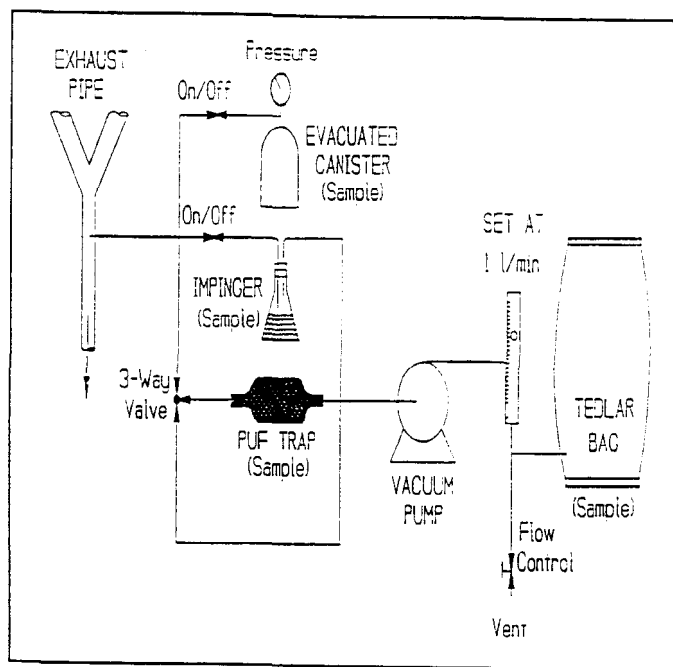


Figure 2. Schematic of Sampling System

E) FUEL ECONOMY TESTS – As indicated in the Background and Introduction section of this paper, a commercial SAE 10W-30 API SH/ILSAC GF-1 oil treated with the UBC was compared to the same commercial SAE 10W-30 oil in standard ASTM Sequence VI Tests.<sup>(12)</sup> The tests involved evaluating 0.9463 L (1 quart) of the UBC with 3.785 L (4 quarts) of an API SH/ILSAC GF-1 oil as the candidate test oil. The results of this latter test were compared to a second Sequence VI Test run with 4.731 L (5 quarts) of the same API SH/ILSAC GF-1 as test oil. In addition, a back-to-back fuel economy comparison of the UBC chemistry 0.9463 L (1 quart) and an SAE 5W-30 API SG/ ECII oil 3.785 L (4 quarts) versus 4.731 L (5 quarts) of the same SAE 5W-30 API SG/ECII oil was carried out on the same test stand using a modified Sequence VI procedure as follows:

Test Procedure/Sequence: – 1) Double flush with "detergent" oil to remove any carry-over from previous testing and to condition the working surfaces. Drain used oil.

2) Charge HR reference oil; age for 2-1/2 hours of engine operation at 135°C (275°F) oil temperature and conduct repetitive fuel consumption measurements at 66°C (150°F), 107°C (225°F) and 135°C (275°F) oil sump temperatures.

3) Change to the API SG/ECII motor oil; age 6 hours at 107°C (225°F) and conduct repetitive fuel consumption measurements.

4) Change to 20% UBC/80% API SG/ECII oil; age 6 hours at 107°C (225°F) and conduct repetitive fuel consumption measurements.

5) Change to 100% API SG/ECII oil; age 6 hours at 107°C (225°F) and conduct repetitive fuel consumption measurements.

6) Again change to the API SG/ECII oil; age 6 hours at 107°C (225°F) and conduct repetitive fuel consumption measurements.

All test parameters not noted above were set and maintained in accordance with the standard Sequence VI procedure.

### III. RESULTS AND DISCUSSION

A. SEQUENCE IIID WEAR SCREENER TESTS – Among the tests indicating the UBC Engine Treatment's ability to reduce engine

wear are two Sequence IIID Wear Screener Evaluations conducted by the independent industry test laboratory in May 1990.<sup>(6)</sup>

The Sequence IIID Wear Screener evaluations are modified versions of the Sequence IIID Wear tests which were commonly used in the testing industry to evaluate cam and lifter wear.

The May 1990, Sequence IIID Wear Screener Evaluations compared wear with 20 percent UBC Engine Treatment and 80 percent SAE 5W-30 SG oil to wear with 100 percent SAE 5W-30 SG oil. In these tests, maximum cam-plus-lifter wear with UBC Engine Treatment and the SAE 5W-30 SG oil was 0.0635 mm (0.0025 inches) as compared to 0.1778 mm (0.0070 inches) for the SAE 5W-30 oil alone — a reduction of 64 percent. Average cam-plus-lifter wear with UBC Engine Treatment and the SAE 5W-30 oil was 0.0381 mm (0.0015 inches) versus 0.0762 mm (0.0030 inches) for the SAE 5W-30 — a reduction of 50 percent.

The May 1990 tests were preceded by a March 1989 test which compared results obtained with 25 percent UBC Engine Treatment and 75 percent SAE 10W-40 reference oil to results with the reference oil alone.<sup>(13)</sup> Maximum cam plus lifter wear with UBC Engine Treatment and the reference oil was 0.2413 mm (0.0095 inches) versus 0.6147 mm (0.0242 inches) with the reference oil alone — a reduction of 61 percent. Average cam-plus-lifter wear with UBC Engine Treatment and the reference oil was 0.1372 mm (0.0054 inches) versus 0.3175 mm (0.0125 inches) with the reference oil alone — a reduction of 57%. These positive results indicated the UBC Engine Treatment's potential for reducing engine wear.

This positive antiwear effect has subsequently been confirmed statistically in a series of additional studies which showed a consistent pattern of wear reduction for the oil containing the UBC Engine Treatment chemistry. Results from these additional studies also help demonstrate that the UBC Engine Treatment has a positive antiwear effect on the metal engine parts that outlasts the presence of the original UBC Treatment in the engine. The results of these "Modified Protocol ASTM Sequence IIIE Tests" are summarized and discussed as follows:

**B. MODIFIED PROTOCOL ASTM SEQUENCE IIIE TESTS**

**Start/Stop Tests** – The start/stop tests evaluated wear in six (6) engines: three (3) treated with the UBC Engine Treatment and three (3) untreated. The engines were broken in, drained and then put through 500 cycles of starting, revving and stopping (see Experimental section for full test protocol details).

Again, a consistent pattern of wear reduction was observed for the UBC treated engines relative to the untreated engines. This is summarized in Table 5 below.

Table 5

**Start/Stop Tests**

Part	Mean Wear (grams)		% Mean Reduction Total Wear	Significant Differences @ Confidence Level
	Treated	Untreated		
Top Ring	0.0237	0.0352	33	.98
2nd Ring	0.0158	0.0306	48	.99
Top Rod Bearings	0.0475	0.0638	25	.86
Bottom Rod Bearings	0.0098	0.0095	--	--
Rocker Arms	0.0045	0.0058	22	--

\* See Table 9, Appendix E. If outlier data for Engine 10 were included, the mean wear for the untreated engines would be much larger.

As noted, the top and second rings of the UBC treated engines exhibited less wear than the controls. For the top rings, the mean reduction in total wear was 33 percent; for the second rings, the mean reduction in total wear was 48 percent. The results for the top and second rings were statistically significant at the 98 and 99% confidence levels, respectively. Significance was determined by using a SYSTAT module MGLH to perform a nested analysis of variance (ANOVA).

For the top rod bearings, the treated engines showed less average bearing wear (0.0475 grams) than the untreated engines (0.0638 grams). This difference was significant at the 86% confidence level. There was very little bottom rod bearing wear observed in these tests, and any difference between treated and untreated engines was insignificant.

**Extended ASTM Sequence IIIE (Continuous Run) Tests**

In the Extended IIIE test, engines are run continuously, except for oil changes. This test permits the examination of progressive wear over a long period of engine operation. If progressive wear does occur, different test lengths should produce different levels of wear. For example, Figure 3 plots the combined wear of the first and second piston ring against the length of the test for the eight engines tested. Here one sees a clear positive relationship; that is, the longer the engine runs, the greater the piston ring wear. Thus, progressive wear appears to occur.

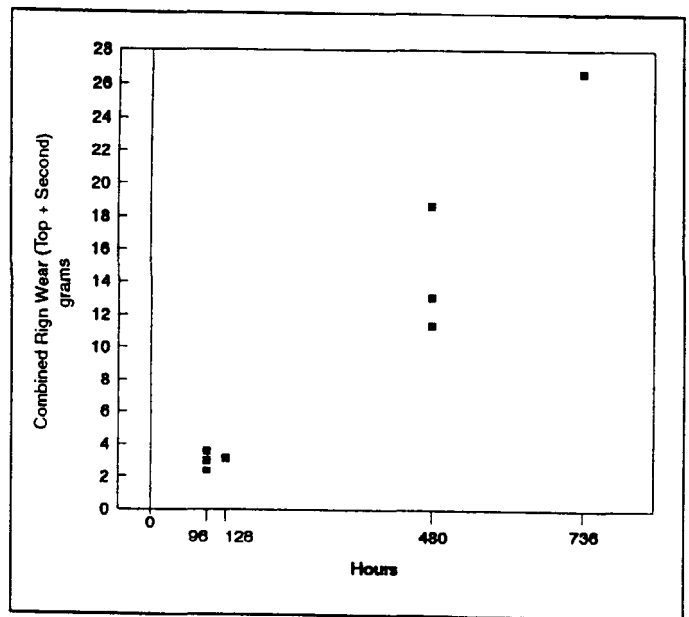


Figure 3. Combined piston ring wear for extended Sequence IIIE Test

In all tests, measured wear will include both progressive and break-in wear. For shorter tests, such as those of 96 or 128 hours in length, the measured wear will include a larger percentage of break-in wear because there is relatively little opportunity for progressive wear to occur. Thus, when testing for the effect of UBC treatment on progressive wear, it is most appropriate to examine the longer running engines because more of the measured wear in these engines is progressive wear. For these reasons, in testing for the effect of UBC treatment, the three engines running 480 hours (one treated, two control) were examined.

The data show that the treated 480 hour engine had lower measured wear than the average of the two controls. The percentage reduction in wear by part is given below (Table 6).

Table 6

Part	Reduction (%)
Top Rod Bearing	41
Bottom Rod Bearing	26
Top Piston Ring	17
Second Piston Ring	3
Rocker Arms	27

Rod bearings, piston rings, and rocker arms all show reductions in wear. Parametric tests of significance are not presented in this paper because the sample contains only one treated engine. Therefore, the non-parametric approach was appropriate.

Boundary Lubrication and Progressive Wear – Engine parts that are subject primarily to boundary lubrication conditions should show more progressive wear than those engine parts operating mostly under hydrodynamic conditions of lubrication. This is so because boundary lubrication involves some metal-to-metal contact while engine parts operating under hydrodynamic lubrication “hydroplane” on a film of oil much like car tires on a flooded road, thus minimizing metal-to-metal contact. The data from the Extended IIIIE Continuous Run Tests support this conclusion.

Table 7

#### Evidence of Progressive Wear by Part: Continuous Run Tests

	Total Wear_grams 96 Hour Tests	Total Wear_grams 480 Hour Tests	Ratio 480/96 (x100) Hrs Wear (%)
Piston Rings (Combined)	0.884	4.305	487
Rod Bearings (Combined)	1.417	2.971	210
Rocker Arms	0.122	0.244	200
Main Bearings (Combined)	1.390	1.306	94

As shown in Table 7, of the parts for which wear was measured gravimetrically, only main bearings do not show a progressive wear pattern over length of test. This is consistent with the understanding that main bearings receive primarily hydrodynamic lubrication during engine operation.

Also, piston rings, which are primarily boundary lubricated, show the greatest progression in wear, while rod bearings and rocker arms, which receive a mix of lubrications, show progressive wear, but not to the same extent as do piston rings.

All this implies that because the UBC is designed to reduce boundary contact, one should expect it to impact on the progressive wear of top and second piston rings, rod bearings, and rocker arms, but not that of main bearings. To test this hypothesis, a non-parametric (RANK) analysis of the Stop/Start Test data for piston ring, rod bearing and rocker arm wear, but not main bearing wear, was carried out. The summed wear data combining data from each of the referred to boundary lubricated parts are given in Table 8:

Table 8

#### Stop/Start Tests: Sums of Rod Bearing, Piston Ring and Rocker Arm Wear

Engine #	Treated?	Summed Wear* (grams)	Rank
11	Yes	0.434	1
13	Yes	0.771	3
15	Yes	0.684	2
10 <sup>1</sup>	No	0.958	6
12	No	0.855	4
14 <sup>2</sup>	No	0.914	5

Notes: 1. For rod bearings, both top and bottom, cylinder #4 of engine #10 is considered an outlier, so the wear for this cylinder for these parts was imputed using the average wear of the other five cylinders for the corresponding parts. Including the outlier does not change the rank order of the engines.

2. One top piston ring in this engine was destroyed during testing, so its weight was imputed using the average weight of the other five top piston rings for this engine.

\*3. Individual wear for each part in the six test engines (11,13,15,10,12,14) is shown in Table 9, Appendix E.

In the column furthest to the right in the above table, the engines have been ranked in terms of summed wear (lowest wear = rank 1, highest wear = rank 6). As shown, the three UBC treated engines occupy ranks 1, 2 and 3 while the untreated engines rank 4, 5 and 6. This is consistent with the premise that UBC Engine Treatment reduces boundary contact wear.

But what is the probability of this result occurring by chance? This probability is easy to calculate. It is equivalent to the well known textbook problem of (i) putting 3 black and 3 white marbles in an urn, and then (ii) drawing the 3 white ones out in 3 successive blind picks. This is known as sampling without replacement, and the probability of picking 3 white marbles in 3 picks is obtained by multiplying three fractions together. The numerator of each fraction is the number of white marbles left in the urn for that pick, the denominator is the number of all marbles left in the urn on that pick. It works out as follows:

Pick #1	Pick #2	Pick 3	Probability
(3 White/6 total)	X (2 white/5 total)	X (1 white/4 total)	= 1/20

Therefore, the probability of obtaining the engine wear rankings as shown above entirely by chance is 1/20 or 5%. In other words, if the UBC Engine Treatment did not reduce engine wear, one could be 95% sure that the ranking of the engines as summarized above would not have been obtained. This is consistent with rejecting a null hypothesis of no reduction in wear at the 95% confidence level.

This rank order test is a non-parametric test; it makes no assumptions about the population distribution of engine wear. This hypothesis was also tested parametrically using the t-test. Significance for the data ranking was also found using this parametric approach. As a check on the sensitivity of these results, this same procedure has been carried out by first normalizing the

part wear data so that each of the five parts has equal weight in the summed wear, and the same result holds: the treated engines occupy ranks 1, 2, and 3.

To sum up, the data show that for the stop/start tests, the UBC reduces engine wear, when engine wear is measured on those parts which show the progressive wear consistent with boundary lubrication. A non-parametric test, which makes no distributional assumptions about the data, indicates that we can project this reduction at the 95% confidence level.

480 Hour Continuous Run Test: A Non-parametric (RANK) Analysis – Three engines were run for 480 hours in an extended III E test. One can perform a similar analysis for them. The “summed-wear” for these three engines is presented in Table 10:

Table 10

**Continuous Run Tests: Sums of Rod Bearing, Piston Ring and Rocker Arm Wear**

Engine #	Treated?	Summed Wear* grams	Rank
16	Yes	2.110	1
17	No	2.189	2
19	No	3.220	3

\*Note: Individual wear for each part in the three test engines (16,17,19) is shown in Table 11, Appendix E.

This table shows that the one treated engine had the lowest summed wear and that the untreated engines occupy ranks 2 and 3. Again, this is consistent with the premise that the UBC Engine Treatment reduces wear in boundary lubricated areas of the engine.

Despite this consistency, however, one cannot make much of a statistical inference from this result because of the small number of engines in this test. The probability that the treated engine would occupy the lowest of three ranks purely by chance is simply 1/3 or 33%. Thus, one can only project this result at the 100 - 33 = 67% confidence level.

Combining Tests: A Non-parametric (RANK) Analysis – The preceding two sections have shown that the rank orders of treated versus untreated engines are completely consistent with the hypothesis that UBC Engine Treatment reduces engine wear in boundary lubricated areas of the engine. Put simply: in both tests, the treated engines occupy the lowest possible ranks.

However, what is the probability of this completely consistent result occurring entirely by chance across both tests? Since the stop/start and continuous tests are independent of each other, the probability of both tests together being completely consistent is simply the product of the chance probabilities for each test individually. That is, if there were no reduction effect from the UBC, the probability of obtaining these consistent rank orderings in both tests together would be  $(1/20) \times (1/3) = 1/60$ , or about 1.7%. The fact that these completely consistent results have been obtained across both tests allows one to reject a null hypothesis of no reduction at the  $100 - 1.7 = 98.3\%$  confidence level.

Therefore, to sum up, this boundary lubrication and progressive wear analysis has: (i) identified those engine parts with measured gravimetric wear that are subject to boundary lubrication, and (ii)

tested for any effect of UBC Engine Treatment on wear summed across those parts. Sample results have been completely consistent with a hypothesis of engine wear reduction, and non-parametric tests have shown that, for stop/start tests and both tests combined, these wear reductions can be projected with high confidence.

Valve Train Wear – The engine’s valve train also operates primarily under boundary lubrication.<sup>(5)</sup> However, wear in the valve train area of the automotive engine is not normally measured gravimetrically, but rather by changes in part length. Therefore, analysis of the effect, if any, on valve train wear by the UBC Engine Treatment cannot be included with the other (piston rings, rod bearings, rocker arms) boundary lubricated areas of the engine and will be dealt with separately here.

The following analysis and discussion includes lifter wear data from the “continuous run” modified protocol Sequence III E tests previously described in this paper.

A total of 8 tests were performed: 3 for 96 hours, 1 for 128 hours, 3 for 480 hours, and 1 for 736 hours. In all tests, lifter wear was measured after 36 hours (4-hour break-in + 32 hours on test – see Experimental section, page 2), then in 64-hour increments (96, 160, 224, 288 hours, etc.) for the length of the test.

The first 36 hours in a test of this type includes a 4-hour “break-in” period, where the lifters and camlobes – if they do not mesh closely – can sustain much wear in a little time. Beyond 36 hours one can expect lower, more gradual wear. Further, the full effect of the UBC Engine Treatment should begin to show up after, but not during the first 36 hours and be most pronounced long after the 96-hour period as suggested by the ring, top rod bearing and rocker arm wear data discussed earlier. Thus, in the analysis that follow, all wear is measured after the first 32 hours of the test (after 4-hour break-in).

Wear From 32 to 96 Test Hours – All 8 engines were run for 96 hours or more, so there are 8 engines where it is possible to measure the lifter wear from 32 to 96 hours. Of these, 4 were treated with UBC Engine Treatment and 4 were not. Each engine has 12 lifters, so there are a total of 96 parts, 48 treated and 48 untreated. On average, the 48 lifters from the treated engines wore 25% less than those from the untreated engines. Thus, within the sample, UBC Engine Treatment does show a reduction in lifter wear over the range from 32 to 96 hours.

The next question to consider is whether the sample results can be projected to the populations of engines and parts from which the sample was drawn. This raises several issues concerning inferential populations, statistical power, and independence among engine parts. To account for the fact that individual lifters are nested within engines, and that individual engines are nested into either the treatment or control side of the test, a SYSTAT module MGLH was employed to perform a nested analysis of variance (ANOVA).

The results of this nested ANOVA indicate that the reduction in wear observed in the sample cannot be projected to the population at a significant confidence level. See individual Engine Total Lifter Wear data from 32-96 test hours in Appendix E, Table 12.

Also, it appears that generally the amount of lifter wear over this 64-hour period was minimal and within the measurement error of the test process. This is evident in that some of the individual lifter wear measurements are negative (that is, the measured length of the lifter increased during the 64 hours of running).

To sum up, therefore, from 32 to 96 hours, the data indicate that treated engines have less lifter wear than untreated engines,

but an analysis of variance indicates no statistical significance to the data.

**Wear From 96 to 480 Test Hours** – There are 4 engines in the test that ran for 480 hours or more; 2 of these were treated with UBC and 2 were not. On average, the 24 lifters in the treated engines wore 31% less than the 24 lifters in untreated engines. Thus, within the sample, the UBC showed a reduction in wear over the interval from 96 to 480 hours (see Table 13 below).

Table 13

**Total Lifter Wear by Engine from 96 to 480 hours**

Engine	Treated	Wear (mm)	Wear (in.)	Relative Wear (%)
16	yes	.0635	.0025	} 69
18	yes	.0584	.0023	
17	no	.0914	.0036	} 100
19	no	.0864	.0034	

The question of projecting sample results to the population arises again. A nested ANOVA, similar to the one described above, for the lifter wear from these engines was again carried out. The observed reduction in wear is projectable at more than the 99% confidence level. Also, a visual inspection of the engine averages showed little engine-to-engine variation within either the treated or untreated engines. This stability in engine-to-engine results, which may be due to the longer duration of the test (480 - 96 = 384 hours versus 64 hours in the test described above), is the reason why a reduction of comparable magnitude (31% versus 25% in the test above) can be projected to the population with greater confidence.

Therefore, to sum up, the test data show that the UBC Engine Treatment reduces lifter wear. In the test of longer duration (from 96 to 480 hours), this reduction is statistically significant at the 99% confidence level; in the shorter test, there is a directional benefit but without statistical significance. In both, test reductions of comparable magnitude were obtained.

**C. RADIOACTIVE TRACER ENGINE WEAR STUDIES**

A brief description of the radioactive engine test procedures (both break-in and test), along with the test oil sequence, protocol and the two reference oil compositions, are given in the experimental section of this paper. A more detailed description of the unique tracer technique used in the current studies, the results of which will be summarized below, is described in a second SAE Paper # 941982 to be presented at the same SAE session as this paper. Some pertinent findings from these radioactive wear studies, which simultaneously measure piston ring and connecting rod bearing wear as it occurs, are summarized as follows:

**Piston Ring Wear** – As shown in Figure 4, there appears to be very little antiwear benefit in adding PTFE to the 0.05 mass % P, SAE 20 Reference Oil A under the test conditions employed. In contrast, (Figure 5), the UBC chemistry (which contains PTFE plus 4 additional chemistries to optimize PTFE effectiveness), shows a more dramatic improvement in wear control when added to the 0.05 mass % P, SAE 20 Reference Oil A, especially as boundary conditions (test severity in terms of increasing load, speed, coolant temperatures) are increased

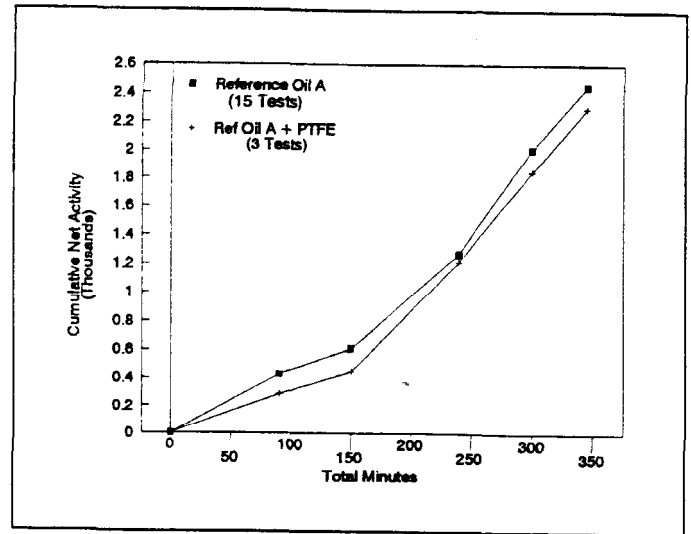


Figure 4. Ring wear for Reference Oil A and Reference Oil A with PTFE

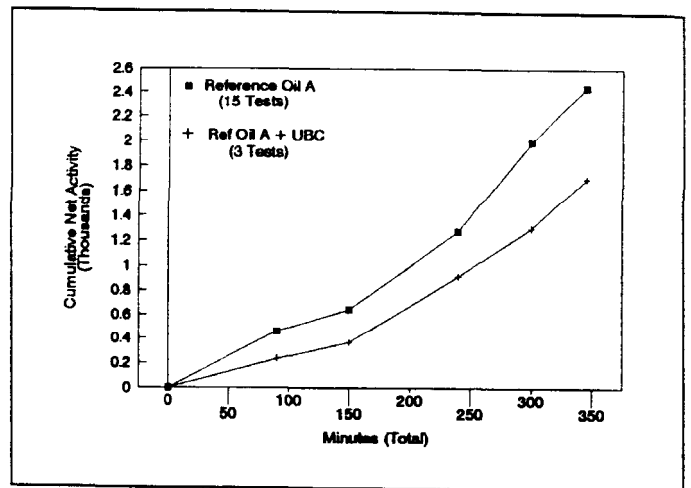


Figure 5. Ring wear for Reference Oil A and Reference Oil A with UBC

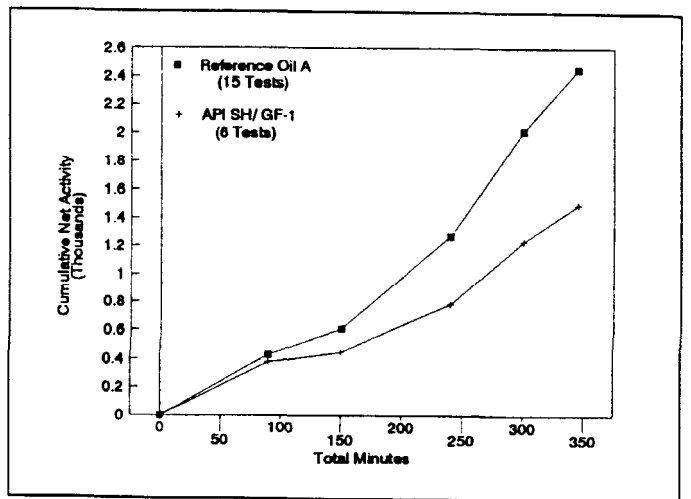


Figure 6. Ring wear for Reference Oil A and the API SH/GF-1 oil

in the engine (Conditions D, E and F, Procedures I and II, Tables 1 & 2, Page 3). Figure 6 shows the same relative wear protection advantage for a leading API SH/ILSAC GF-1 quality oil over the 0.05 mass % P SAE 20 Reference Oil A as the Reference Oil A with UBC chemistry (Figure 5). This is more directly

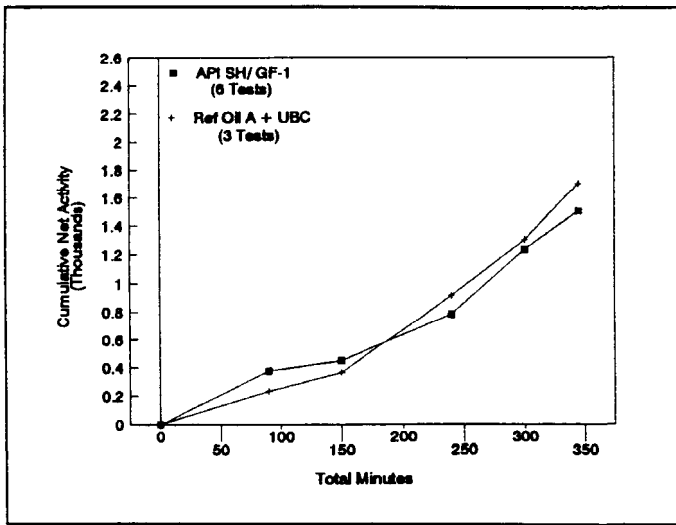


Figure 7. Ring wear for the API SH/GF-1 oil and Reference Oil A with UBC

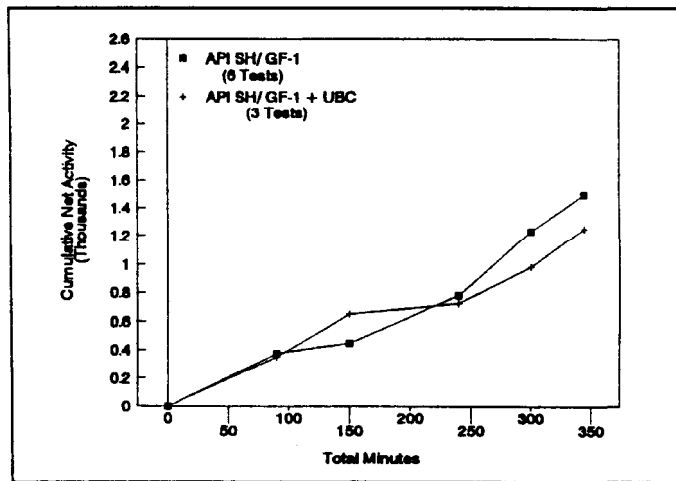


Figure 8. Ring wear for the API SH/ GF-1 oil and the same oil with UBC

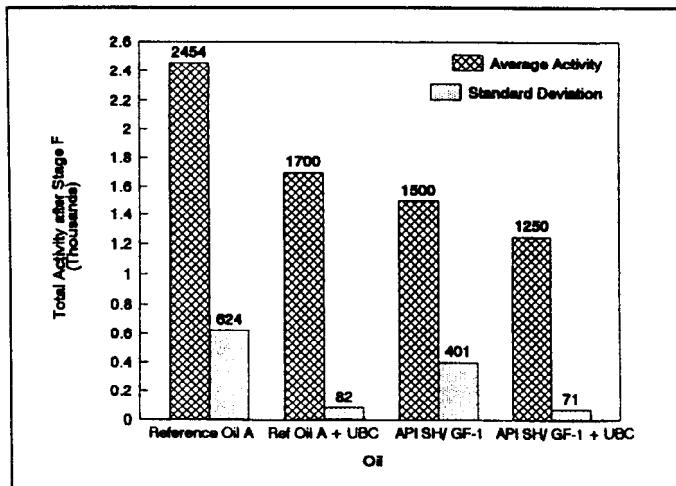


Figure 9. Piston ring average activities and standard deviations for several oils

seen in Figure 7 where the API SH/GF-1 oil and the Reference Oil A with UBC are directly compared. Moreover, addition of the UBC chemistry to the API SH/GF-1 oil appears to further increase the antiwear effectiveness of the SH quality oil (Figure 8). This additional piston ring antiwear benefit is even more

pronounced as test severity (boundary conditions) is increased. This is precisely where and when the UBC chemistry should be most effective, as discussed earlier in this paper.

The comparisons described here have been in terms of total downstream activity associated with activated wear particles ( $\gamma$  rays) specific to a given preactivated engine part. There is a direct relationship between activity as shown in the figures and gravimetric wear. This relationship is: Ring Wear =  $3.8153y^{0.9688}$ ,  $\mu\text{g}$  (per  $y$  cpm); where cpm = counts per minute (see SAE Paper # 941982).

In Figure 9 are summarized the ring wear (average activity) and standard deviations(S) respectively, associated with four (4) of the pertinent test oils evaluated in this radioactive engine wear program. The first item of note is that both the ring wear (average activity = 2454) and the standard deviation ( $S = 624$ ) for the 0.05 % P SAE 20 Reference Oil A are quite large over the 15 runs represented by the shown data. This 0.05 % P Reference Oil A is quite borderline in antiwear performance containing ~ 50% of the usual (.10 % P) ZDDP antiwear and no VI Improver. The data suggest that this reference oil's antiwear performance can be greatly affected by (1) small, difficult to control, variations in engine operating conditions and (2) by strong, antiwear carryover effects associated with other antiwear chemistries being evaluated in this program. This excessive variability at high wear levels makes it very difficult, if not impossible, to demonstrate statistically significant wear benefits for other oils versus the 0.05 % P SAE 20 Reference Oil A. However, the second item of note is that the addition of the UBC Engine Treatment chemistry to said poor Reference Oil A (0.05 % P SAE20) substantially reduces both the level of ring wear (1700) and the variability ( $S = 82$ ) in the data. A similar trend is noted with the addition of the UBC to the API SH oil (average activity = 1250 and  $S = 71$ ).

Connecting Rod Bearing Wear - Turning now to the connecting rod bearing wear data, Figure 10 shows that the addition of suspended PTFE only to the poor 0.05 % P Reference Oil A actually worsens the wear performance of the poor reference oil. However (Figure 11), addition of the full UBC Engine Treatment to the reference oil greatly improves its anti bearing wear performance just as in the case of piston ring wear. The antiwear benefits of the API SH oil relative to the borderline reference oil appear to show up only after the more severe boundary conditions (conditions D, E and F in Tables 1 & 2, Page 3) are reached (Figure 12). This is in contrast to the ring wear data reported earlier in which differences started showing up during condition B of the test procedure. One explanation may be that piston rings almost always operate under boundary conditions, but rod bearings operate under mixed boundary/hydrodynamic conditions. The UBC (perhaps a stronger boundary lubricant than the chemistry in the API SH oil) plus borderline reference oil does however show antiwear benefits relative to the API SH oil beginning with the early stages (B and C) of the test procedure (Figure 13). Again, the addition of UBC to the API SH oil gives substantial anti bearing wear benefits relative to the API SH oil (Figure 13), paralleling data obtained with the piston rings.

As in the case of piston ring wear, both the average activity (wear) and the standard deviations (S) associated with four (4) of the pertinent test oils are summarized in Figure 14. Again, the bearing wear and S for the borderline 0.05 % P reference oil were excessive and left little room for establishing statistical significance for other oils relative to the borderline reference oil.

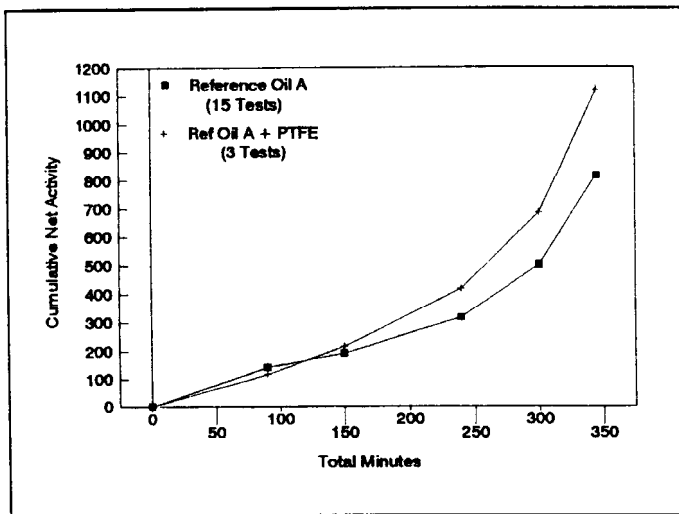


Figure 10. Bearing wear for Reference Oil A and Reference Oil A with PTFE

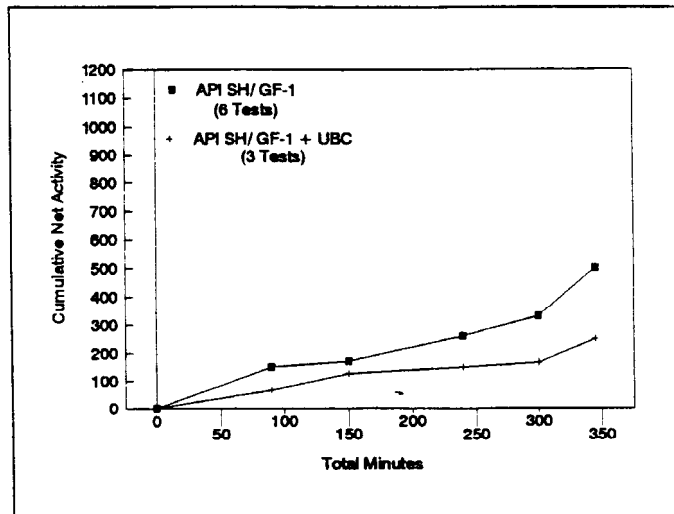


Figure 13. Bearing wear for the API SH/GF-1 oil and the same oil with UBC

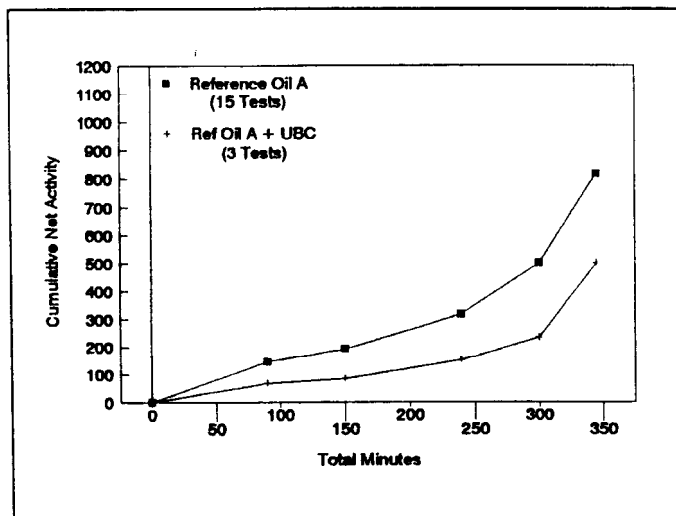


Figure 11. Bearing wear for Reference Oil A and Reference Oil A with UBC

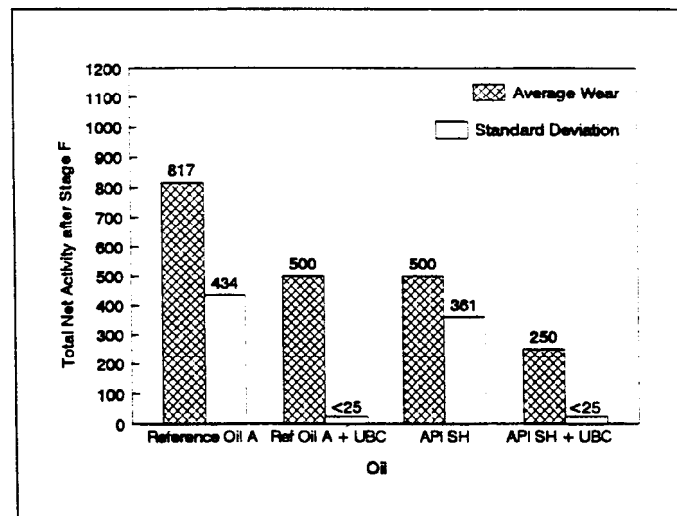


Figure 14. Bearing average activities and standard deviations for several oils

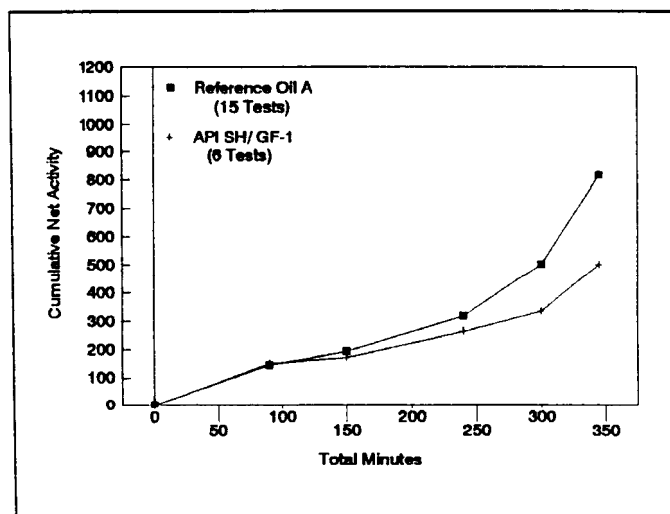


Figure 12. Bearing wear for Reference Oil A and the API/SH GF-1 oil

However, as in the case of piston rings wear data, the addition of the UBC Engine Treatment chemistry to both the borderline Reference Oil A and the API SH oil, respectively, reduces both

the average wear and the standard deviation of the wear data substantially.

To sum up, therefore, UBC Engine Treatment appears to provide antiwear benefits, both in the piston rings and the connecting rod bearings, when added to either the borderline Reference Oil A or to the API SH/ILSAC GF-1 oil. This is evident both from the substantially reduced level of wear observed and the much reduced variability in the wear data.

Again there is a direct relationship between bearing wear in grams and counting activity. This relationship is: Bearing Wear =  $79.5657y^{0.889}$ ,  $\mu\text{g}$  (per  $y$  cpm); where cpm = counts per minute (see SAE Paper # 941982.)

D. EXHAUST EMISSION TESTS – Two series of exhaust emission tests were carried out in automotive engines comparing emissions with and without the UBC Engine Treatment described in this paper. The first evaluation involved four engines operated on the road for 80,500 km (50,000 miles); the second evaluation, four engines in the Dexron® ATF Cycling Test.

On the Road Tests – The principal objective of this project was to identify semi-volatile, fluorine-containing compounds in exhaust samples of four vehicles with 5.0 L engines. In addition, regulated emissions of HC, CO, and NO<sub>x</sub> were also measured. The full

details of the test program are described in the experimental section of this paper and the results of the exhaust emission studies are summarized as follows:

**A. Fluorinated Compounds** – Since the objective was to identify fluorine-containing compounds in the exhaust, twice the level of PTFE was used in this evaluation. Fluorine products of combustion were researched. The combustion products of fluorinated hydrocarbons could include tetrafluoroethylene, carbon tetrafluoride, tetrafluoroethylene oxide, perfluorocyclobutane, hexafluoropropylene, and perfluoroisobutylene, as well as several other compounds.

The sample gas chromatograph (GC) traces were compared to the GC traces of known compounds using the GC/MS computer reverse library search. In addition, standard chemical samples of hexafluoropropylene and tetrafluoroethylene, considered the most likely products of combustion, were also compared against exhaust samples. None of the fluorine containing compounds listed in the NBS library were found among the semi-volatile (PUF) samples. The detection limit was approximately 2 µg per compound, per sample [0.4 µg/km (0.6 µg/mile) for Bags 1 and 3, 0.3 µg/km (0.5 µg/mile) for Bag 2].

**B. Gaseous Emissions** – The normal, regulated gaseous exhaust emissions were sampled throughout the FTP vehicle cycle and during the catalyst evaluations. Tedlar® sample bags were filled with dilute vehicle exhaust during the cold-transient (Bag 1), the cold-stabilized (Bag 2), and the hot-transient (Bag 3) of the FTP. These bags were analyzed immediately afterward.

Computer printouts obtained from all of the vehicles for hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>) and carbon dioxide (CO<sub>2</sub>) are located in Reference 10, Appendix B. A summary of the FTP emissions is given in Table 14. Vehicles 1 and 4 used the UBC Engine Treatment; vehicles 2 and 3 did not. Comparison graphs of individual vehicles at the 6,440 km (4,000 mile) point and the 80,500 km (50,000 mile) point are located in Reference 10, Appendix C.

The individual catalyst evaluation information for the 6,440 km (4,000 mile) accumulation point is located in Reference 10, Appendix D. Graphs and data sheets for the individual catalysts at the 80,500 km (50,000 mile) point are in Reference 10, Appendix E. Comparison graphs for each particular catalytic converter can be found in Reference 10, Appendix F.

Therefore, to sum up, no measurable levels of fluorine or fluoride compounds were found in the exhaust samples from any of the four 1992 5.0 L engine vehicles during any of the emissions tests, within the detection limits of the procedures and instrumentation used. All vehicles showed a similar increase in gaseous emissions during the FTP driving cycle between the 6,440 and 80,500 km (4,000 and 50,000 mile) data, both those using the UBC treatment and those not using it. The increase is most probably due to normal catalyst deterioration.

**Dexron® ATF Cycling Test** – The full details of the test program are described in the experimental section of this paper and the results of the exhaust emission studies are summarized as follows:

**A. Fluorinated Compounds** – Since the objective was to identify fluorine-containing compounds in the exhaust, fluorine products of combustion were researched. The combustion products of fluorinated carbon could include tetrafluoroethylene, carbon tetrafluoride, tetrafluoroethylene oxide, perfluorocyclobutane, hexafluoropropylene, and perfluoroisobutylene, as well as several other compounds.

hexafluoropropylene, and perfluoroisobutylene, as well as several other compounds.

The gas chromatograph (GC) traces of each sample were compared to the GC traces of known compounds using the GC/MS computer reverse library search. In addition, standard chemical samples of hexafluoropropylene and tetrafluoroethylene, considered the most likely products for combustion, were also compared against exhaust samples. Only one sample, taken from a treated engine at 20,000 cycles, revealed a trace amount of a fluorinated compound: hexafluoropropylene at 77 ppb. No compounds were found among the semi-volatile (PUF) samples.

**B. Fluoride Measurements** – Fluoride can be trapped in an aqueous impinger if it is present in the exhaust in the form of hydrogen fluoride. Using this approach, very low levels of fluoride ions were found in the aqueous impinger samples (Table 15). Statistical outlier analysis were applied to the fluoride data to investigate the anomalous point measured on engine PET 3 at 100,000 cycles: 99 mg/L. This point was considered an outlier on the high end with a 90% confidence level. The outlier analysis are included as Appendix C of Reference 14. The fluoride levels were considered to be nominal. There was no significant difference between treated and non-treated engines. Furthermore, background (laboratory air) fluoride was at a similar level (0.002 ppm).

**C. Gaseous Emissions** – The normal, regulated gaseous exhaust emissions were also sampled. Tedlar® sample bags were filled with exhaust over a 30-minute period, so that the effects of any single cycle would be reduced in the average. The bags were analyzed immediately afterward. Data obtained from all engines for hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), and carbon dioxide (CO<sub>2</sub>) are plotted over time as shown in Figure 15. These data were then separated according to treated engines (PET 3 and PET 4) and untreated engines (PET 1 and PET 6) to investigate differences (Table 15). Although the average hydrocarbons for treated engines appeared higher than for untreated engines, a statistical test ("student's T") indicated no significant difference at a 95% confidence level.

There is an additional observation about the hydrocarbon data. Three out of four engines exhibited the highest levels at the 20,000-cycle sample point. The untreated engines both emitted over 16,000 ppm at that time (Figure 15). To check the effect of fuel injector plugging, one of the test engines (PET 4) was sampled before and after its injectors were cleaned (cleaning was periodically performed throughout the tests). In this limited experiment, the hydrocarbons were reduced only 10 percent. The phenomenon would require further work to investigate, but appears to be unrelated to the UBC treatment and does not affect the conclusion of this work.

Therefore, to sum up, no significant levels of fluorine or fluoride compounds were found in the exhaust of the 5.7 L engines treated with the UBC additive system. Gaseous emissions showed some possible influence of the additive. The hydrocarbon levels were higher and the nitrogen oxides were lower on the average for treated engines, but the differences were not statistically significant.

#### E. FUEL ECONOMY TESTS

**Modified Protocol Sequence VI Test** – As outlined in the experimental section of this paper, a modified protocol Sequence VI Test was carried out to determine (1) the extent to which UBC Engine Treatment improves the fuel efficiency

Table 14

## 3-Bag Composite FTP Emissions after 6,400 km (4,000 mi)

Vehicle Number	Catalysts Installed	Date	Mileage (km)	Mileage (mi)	Test Number	Emissions (g/km)			Emissions (g/mi)			Fuel Economy (km/L)	Fuel Economy (mpg)
						HC	CO	NOx	HC	CO	NOx		
1	yes	8/3/92	6452	4009	1-C-1	.083	.34	.350	.133	.55	.563	6.80	16.0
1	yes	8/4/92	6473	4022	1-C-2	.073	.30	.355	.118	.48	.572	6.89	16.2
1	yes	8/5/92	6494	4035	1-C-3	.074	.32	.375	.119	.52	.604	6.76	15.9
1	no	8/6/92	6526	4055	1-B-1	.156	1.73	.406	.251	2.78	.654	6.72	15.8
1	no	8/7/92	6547	4068	1-B-2	.144	1.50	.301	.231	2.41	.484	7.01	16.5
2	yes	8/3/92	6478	4025	2-C-1	.086	.31	.305	.138	.50	.491	6.84	16.1
2	yes	8/4/92	6502	4040	2-C-2	.075	.28	.344	.121	.45	.554	6.93	16.3
2	yes	8/5/92	6523	4053	2-C-3	.075	.28	.328	.120	.45	.528	6.93	16.3
2	no	8/6/92	6555	4073	2-B-1	.182	1.71	.304	.293	2.75	.490	6.93	16.3
2	no	8/7/92	6576	4086	2-B-2	.181	1.63	.309	.292	2.62	.498	7.01	16.5
3	yes	8/3/92	6450	4008	3-C-1	.098	.35	.301	.158	.57	.485	6.84	16.1
3	yes	8/4/92	6470	4020	3-C-2	.095	.46	.298	.153	.74	.480	6.97	16.4
3	yes	8/5/92	6492	4034	3-C-3	.083	.34	.295	.134	.54	.475	7.01	16.5
3	no	8/6/92	6526	4055	3-B-1	.191	1.89	.298	.307	3.04	.480	6.97	16.4
3	no	8/7/92	6544	4066	3-B-2	.190	1.97	.281	.306	3.17	.453	6.89	16.2
4	yes	8/4/92	6450	4008	4-C-1	.144	.85	.315	.232	1.37	.507	6.84	16.1
4	yes	8/5/92	6468	4019	4-C-2	.137	.89	.316	.220	1.44	.508	6.89	16.2
4	yes	8/6/92	6486	4030	4-C-3	.143	1.06	.298	.230	1.70	.479	6.80	16.0
4	no	8/7/92	6518	4050	4-B-1	.232	2.27	.283	.373	3.65	.456	7.01	16.5
4	no	8/11/92	6550	4070	4-B-2	.245	2.74	.304	.394	4.41	.490	6.89	16.2

## 3-Bag Composite FTP Emissions after 80,500 km (50,000 mi)

Vehicle Number	Catalysts Installed	Date	Mileage (km)	Mileage (mi)	Test Number	Emissions (g/km)			Emissions (g/mi)			Fuel Economy (km/L)	Fuel Economy (mpg)
						HC	CO	NOx	HC	CO	NOx		
1	yes	10/27/92	80480	50008	1-50-C-1	.158	.80	.395	.254	.96	.636	7.27	17.1
1	yes	10/28/92	80500	50020	1-50-C-2	.154	.58	.401	.248	.94	.646	7.23	17.0
1	yes	10/29/92	80521	50033	1-50-C-3	.153	.57	.423	.246	.92	.680	7.23	17.0
1	no	10/30/92	80558	50056	1-50-B-1	.341	2.93	.400	.549	4.71	.644	7.18	16.9
1	no	11/02/92	80590	50076	1-50-B-2	.368	3.41	.390	.593	5.48	.627	7.23	17.0
2	yes	10/27/92	80480	50008	2-50-C-1	.143	.48	.375	.230	.77	.603	7.18	16.9
2	yes	10/28/92	80503	50022	2-50-C-2	.142	.58	.400	.229	.94	.643	7.06	16.6
2	yes	10/29/92	80522	50034	2-50-C-3	.145	.52	.420	.234	.84	.676	7.10	16.7
2	no	10/30/92	80544	50054	2-50-B-1	.341	3.22	.419	.548	5.19	.675	6.84	16.1
2	no	11/02/92	80595	50079	2-50-B-2	.353	3.36	.381	.568	5.40	.613	7.14	16.8
3	yes	10/27/92	80480	50008	3-50-C-1	.163	.70	.649	.263	1.13	1.045	7.01	16.5
3	yes	10/28/92	80500	50020	3-50-C-2	.179	.67	.432	.288	1.08	.696	7.10	16.7
3	yes	10/29/92	80522	50034	3-50-C-3	.194	.66	.472	.313	1.07	.759	7.10	16.7
3	no	10/30/92	80554	50054	3-50-B-1	.409	3.23	.415	.659	5.20	.668	7.10	16.7
3	no	11/02/92	80587	50074	3-50-B-2	.382	3.04	.448	.615	4.89	.721	7.06	16.6
4	yes	10/27/92	80480	50008	4-50-C-1	.250	1.34	.447	.403	2.15	.720	7.18	16.9
4	yes	10/28/92	80496	50019	4-50-C-2	.269	1.40	.422	.433	2.25	.679	7.18	16.9
4	yes	10/29/92	80516	50030	4-50-C-3	.249	1.47	.409	.401	2.37	.658	7.23	17.0
4	no	10/30/92	80545	50048	4-50-B-1	.433	4.18	.408	.703	6.72	.657	7.10	16.7
4	no	11/02/92	80574	50066	4-50-B-2	.422	4.15	.406	.679	6.68	.654	7.18	16.9

Table 15

file: petrosort

## PETROLON

## TRANSMISSION CYCLING TEST ENGINE EMISSIONS

SAMPLE CODE	ENGINE CYCLES /1000	IMPINGE	PUF TRAP	CANISTER		GASEOUS				Impinger Sample Vol. Liters of Exhaust	Fluoride In Exhaust, ppm
		(aqueous) F. mg/L	Fluorinated Compounds ppb	HC ppmc	CO ppm	NOx ppm	CO2 %				
PET1	5	0.32	0	0	5366	11091	780	12.1	17.445	0.005	
PET1	10	0.21	0	0	5167	9930	778	11.8	27.273	0.002	
PET1	20	0.47	0	0	over rang	11223	658	12.7	26.905	0.004	
PET1	40	0.23	0	NM	2554	9811	835	10.4	18.408	0.003	
PET1	60	<DL	0	NM	998	12033	947	13.4	40.272	0.000	
PET1	80					invalid Sample - Leak Suspected				NM	
PET1	100	<DL	0	0	750	11801	812	12.58	17.332	0.000	
PET1	120	0.081	0	0	791	11156	970	11.65	19.088	0.001	
PET1	140		0	0	921	13597	929	12.07	16.794	0.000	
PET6	10	0.37	NM	0		not sampled			18.295	0.004	
PET6	20	0.29	0	0	16379	14555	953	13.4	24.044	0.004	
PET6	40	0.39	0	NM	2404	13684	1232	13.5	21.637	0.006	
PET6	60	0.54	0	NM	1496	13455	1060	12.9	21.269	0.002	
PET6	80	0.198	NM	0	1097	9622	787	9.5	19.824	0.004	
PET6	80	0.353	NM	0	968	12403	990	11.92	17.247	0.000	
PET6	100	<DL	0	0	1247	11540	868	12.3	16.936	0.002	
PET6	120	0.104	0	0	947	14525	1518	13.48	16.709	0.000	
PET6	140		0	0	928	14716	1077	12.96			
avg		0.237067			2625.813	10841.22	949.625	12.29625		0.002214	
					(over range discarded)						
PET3	10	0.097	0	0	4138	10385	668	10.8	24.242	0.001	
PET3	20	0.36	0	0	3312	12176	692	12.7	22.968	0.004	
PET3	40	0.36	0	NM	2065	12968	917	13.4	26.593	0.003	
PET3	60	0.17	0	NM	1406	12746	953	12.9	17.757	0.002	
PET3	80	0.083	0	0	1167	11443	684	10.8	21.354	0.001	
PET3	100	9.9 RO	0	0	1277	12886	957	12.3	21.410	RO	
PET3	120	<DL	0	NM	845	11283	823	12.78	18.624	0.000	
PET4	5	0.068	0	0	5765	9633	558	10.3	30.360	0.001	
PET4	10	0.064	0	0	7312	10515	895	12.8	16.086	0.001	
PET4	20	0.34	0	71	13068	9781	944	12.4	18.352	0.005	
PET4	40	0.34	0	NM	7980	10266	948	13.1	33.786	0.003	
PET4	60	0.47	0	NM	1796	10515	1091	13.1	18.607	0.006	
PET4	80	<DL	0	NM	1915		1035	12.9	16.653	0.000	
PET4	100	0.14	NM	NM	1077	14000	1171	13.2	20.674	0.002	
PET4	120	<DL	0	0	908	12301	1087	12.39	17.899	0.000	
AVERAGE					3602.067	11492.71	894.8667	12.37467		0.002027	
POOLED STD. DEV.					3668.952	3242.388	188.8272	1.020831		0.001967	

NM indicates Not Measured.

DL indicates lowest detection limit = 0.063mg/L.

RO indicates a value that was rejected as a statistical outlier. The average will not include this value.

NOTE: Tune Ups Performed Every 10000 cycles.  
 Includes oil change, timing check, and injector cleaning.  
 UBC additive used for first 10000 cycles on stands 3 and 4.  
 Commercial SAE 5w-30 API SG Engine oil used at all times.  
 Background Impinger sample on 9/17/92 was 0.15mg/L

Exhaust Flow was set with a rotameter at 1 lpm.

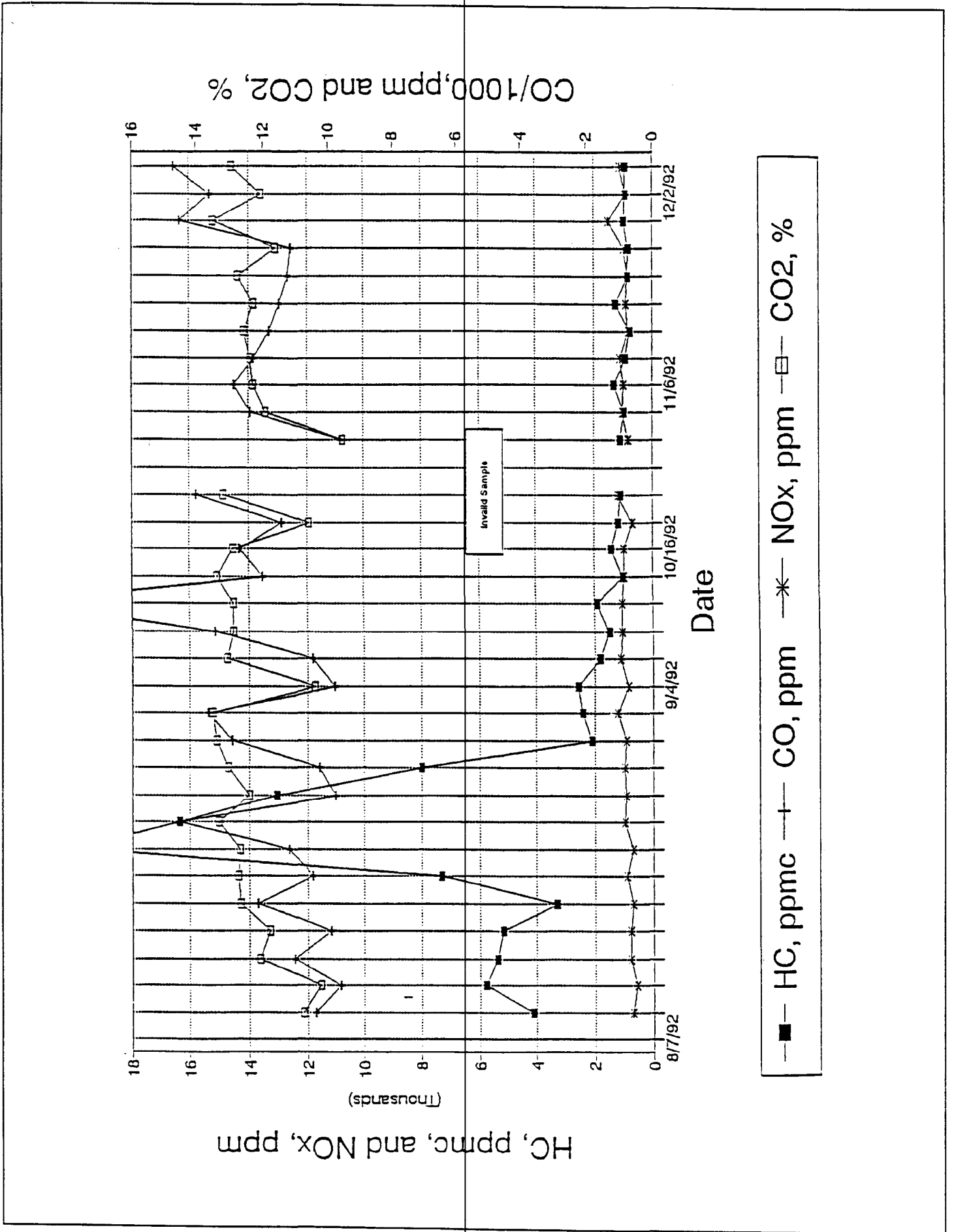


Figure 15. Gaseous Engine Emissions Petrolon Transmission Cycling Test

of a leading API SG/ECII oil and (2) the extent to which the UBC treatment fuel economy benefits, if any, carry over (favorable or unfavorable conditioning of the working surfaces) after the oil is changed back to fresh API SG/ECII oil with no UBC chemistry. To accomplish this, a back-to-back fuel economy comparison of the UBC chemistry (20%) and an SAE 5W-30 API SG/ECII oil (80%) versus 100% of the same SAE 5W-30 API SG/ECII oil was carried out on the same test stand using the modified Sequence VI procedure described in the experimental section of this paper.<sup>(15)</sup> The results of this study are summarized in Appendix C and are discussed as follows:

1. At 66°C (150°F) oil gallery temperature, experience has taught that fuel economy benefits are mostly sensitive to oil viscosity. Since the multigrade API SG/ECII SAE 5W-30 motor oil has more favorable viscosities (lower) than the HR reference oil, it would be expected to give improved fuel economy which, indeed, it did (+2.95%). The addition of 20% UBC Engine Treatment has little effect on the viscometric properties as compared to the neat API SG/ECII SAE 5W-30, and thus, there is little effect on the difference in fuel economy with either the neat or blended two component oil.

2. As oil and engine temperature increase, boundary lubrication plays a more important role. Since both the API SG/ECII SAE 5W-30 oil and UBC Engine Treatment contain antifriction agents to help protect against surface-to-surface contact, they both act to give improved fuel economy at higher temperatures. At 107°C (225°F) oil gallery temperature, the API SG/ECII SAE 5W-30 gave a +4.18% improvement over the HR reference oil; and the added 20% UBC Engine Treatment gave an additional +0.50% improvement. There was no significant fuel economy carryover effect observed in the subsequent API SG/ECII SAE 5W-30, only tests.

At 135°C (275°F) oil temperature, the improved fuel economy with the API SG/ECII SAE 5W-30 oil decreased to +2.91% as compared to the reference oil, and the benefit of the added 20% UBC Engine Treatment gave an additional +2.69% improvement over that of the API SG/ECII SAE 5W-30 oil alone (total +5.51% as compared to the HR reference oil.) In addition, the carryover benefit during the next two API SG/ECII SAE 5W-30 test runs was +2.75 and +1.81, respectively.

3. Industry experience during the development of the Sequence VI test procedure indicates that antifriction additives, such as those used in ECI and ECII engine oils, are most effective at low-to-moderate load conditions. Thus, in a fully-warmed engine operating under part throttle/high-temperature conditions with the throttle opened to exactly the same position, the vehicle operator would experience a performance or horse power gain when using a fuel efficient oil, such as one containing UBC Engine Treatment. This improvement occurs because better protection against metal-to-metal contact reduces frictional losses, leading to more energy to do useful work.

A second fuel economy study was carried out with the UBC chemistry under standard Sequence VI conditions. In this study, the UBC chemistry was incorporated 0.9463 L (1 quart) into a leading API SH/ILSAC GF-1 SAE 10W-30 oil 3.785 L (4 quarts) and the mixture was evaluated in a standard Sequence VI fuel economy test. This result (Table 16, Appendix D), in EFEI, was compared to the EFEI obtained with 100% of the API SH/ILSAC GF-1 SAE 10W-30 oil (Table 17, Appendix D). A comparison of the data in Appendix D shows that incorporation of the UBC

chemistry (oil 340-5) improves the EFEI from 2.48% to 2.65%. In addition, a careful inspection of the data shows that the EFEI benefit for the UBC chemistry increases with increasing test temperature, again demonstrating the positive benefits of this chemistry as boundary conditions increase in the engine. This early work shows that the UBC chemistry has potential for further improving the fuel economy benefits of current API SH/ILSAC GF-1 oils. Work is in progress to more precisely define and optimize the fuel economy benefits of the UBC chemistry relative to ECII oils of today.

F. MECHANISM OF UBC ENGINE TREATMENT ACTION – As has been the theme throughout this paper, the UBC chemistry is a boundary lubricant and, as such, is effective when there is a very thin or essentially no oil film between moving parts of the engine and the load between any two sliding surfaces is predominately supported by metal-to-metal contact. It is proposed that boundary lubricants such as the UBC chemistry undergo two distinct modes of action: (1) First, they form a very tenacious film on the metal surface and (2) as two sliding surfaces with this tenacious film contact in the boundary (metal-to-metal contact) regions of the engine, chemical reactions occur at the asperities (surface irregularities) of the metal surfaces due to excessive localized heating<sup>(16,17)</sup> The chemistry which is associated with the earlier formed boundary lubricant film participates in the chemical reactions at or near the metal surface asperities, eventually becoming part of a diffusion reaction film within the near inorganic layer below the metal surface.<sup>(18)</sup> In other words, when metallic engine parts contact and heat in the presence of the UBC surface film chemistry, changes in the metals below surface chemistry occur, leading to modified mechanical properties of the engine's metallurgy. Specifically, the melting point (hardness) may be lowered, causing surface irregularities (asperities) to deform in a more uniform way – resulting in a smoother, lower friction and lower wear surface.

This proposed mechanism helps explain why an extended conditioning period ~80,500 km (~50,000 miles) is needed to achieve the full benefits of the UBC antiwear chemistry and why a very strong carryover effect is observed for this chemistry, even after relatively short exposure to the engine. It is the engine metallurgy which is being modified, rather than the engine oil.

The UBC Engine Treatment chemistry is a blend of five ingredients including polytetrafluoroethylene (PTFE) in a premium multi-viscosity motor oil (carrier oil). PTFE is a polymer that is mechanically strong, durable, and chemically inert and that has an extremely low coefficient of friction. The other ingredients hold the PTFE in suspension and help ensure that it bonds effectively to metal surfaces within the engine.

During the manufacture of UBC, the PTFE particles are bombarded with an electron beam, which shortens the molecular chain and reduces particle size. This bombardment process also charges the PTFE particles, which helps them bond with the metal surfaces in the engine. In addition, where the PTFE molecules have been split by the electron beam, other chemically active functional groups are formed which can bond to engine surfaces. Moreover, PTFE is a material with low surface tension. It seeks and physically bonds (wets) to engine parts made of metal with higher surface tension. In the same way that soap works its way under grease in a pan, PTFE is able to displace the motor oil on engine parts, find its way to metal surfaces, and bond there.

Two of the five interactive ingredients in UBC Engine Treatment are designed to further facilitate this bonding with the working metal surfaces in the engine. These materials include: (1) a surface preparation ingredient that helps PTFE compete effectively with other chemicals in the engine to make direct physical contact with working metal surfaces so that bonding can occur and (2) a process support ingredient that aids the interaction between the PTFE particles and metal.

Another of the five ingredients keeps the microscopic PTFE particles in colloidal suspension, thus preventing them from being trapped by the oil filter or bunching together or settling to the bottom of the oil pan. This ingredient is similar to dispersion agents used in motor oils to keep microscopic particles of sludge in suspension.

Of the five ingredients in UBC Engine Treatment, carrier oil represents the largest component. The current carrier oil meets or exceeds the requirements for API Service Classification SH.

#### IV. SUMMARY AND CONCLUSIONS

A unique boundary chemistry (UBC) has been formulated to give statistically significant wear control benefits in boundary (metal-to-metal contact) lubricated areas of a running engine. This chemistry is added to the engine once, for 4,800 km (3,000 miles), or one oil drain interval, as a 20% treatment with the remaining 80% of the oil charge being a current API SH quality oil. More specifically, wear control was observed in piston rings, rod bearings, rocker arms and valve train cams and lifters. The pertinent test results are summarized as follows:

(1) Early Sequence IIID Wear Screener Tests, run for only 8 hours past break-in, gave positive valve train wear protection benefits with the UBC chemistry. The data are summarized as follows:

	1989 Screener			1990 Screener		
	UBC	Ref	%Benefit	UBC	Ref	%Benefit
Maximum						
Cam + Lifter Wear, mm	0.2413	0.6147	61	0.0635	0.1778	64
Average						
Cam + Lifter Wear, mm	0.1372	0.3175	57	0.0381	0.0762	50
Maximum						
Cam + Lifter Wear, in	0.0095	0.0242	61	0.0025	0.0070	64
Average						
Cam + Lifter Wear, in	0.0054	0.0125	57	0.0015	0.0030	50

(2) In Stop/Start Cyclic Modified Sequence IIIE Tests, where the engines were broken-in, drained and then put through 500 cycles of starting, revving and stopping without oil, the UBC treated engines showed the following advantages:

Part	% Mean Reduction		Differences Significant At Confidence Level
	Total Wear		
Top Ring	33		.98
2nd Ring	48		.99
Top Rod Bearings	25		.86
Bottom Rod Bearings	—		—
Rocker Arms	22		—

(3) In specially designed modified protocol ASTM Sequence IIIE Tests, where the engines were broken-in using the standard IIIE 4-hour procedure and then run for 96 and 480 hours, respectively, and the oil was changed every 32 hours, the UBC treated engines showed the following advantage:

Part	Mean Reduction In Wear %	Difference Significant At Confidence Level
<u>Lifter Wear</u>		
From 32 to 96 Hrs	25	—
From 96 to 480 Hrs	31	.99

(4) Progressive wear appears to occur only in boundary lubricated areas of the automotive engine. Summing the wear in those engine parts where progressive wear occurs and is measured gravimetrically (piston rings, rod bearings, rocker arms) for engines treated with UBC chemistry and those without UBC treatment, gives a rank order of performance. This rank order always shows the UBC chemistry giving the lowest summed wear. This is true for both the Start/Stop tests and the Extended Modified Sequence IIIE tests. Taking the rank order results of both types of tests together, the probability of the UBC chemistry always giving the lowest wear results by chance was shown to be less than 2%.

(5) Radiotracer engine wear studies carried out in a 2.3 L prototype Sequence VE engine showed ring and connecting rod bearing wear benefits for the UBC Engine Treatment chemistry. In particular:

(a) The UBC chemistry substantially reduced both the level of wear and the test repeatability for both a 0.05% P SAE 20 reference oil and an API SH/ILSAC GF-1 oil.

(b) The PTFE dispersion alone gave approximately equivalent wear protection in the piston rings as the 0.05% P SAE 20 reference oil, but poorer wear protection to the reference oil in the bearings. The PTFE dispersion is the same composition and concentration as the PTFE used in the five (5) component UBC Engine Treatment.

(c) The UBC Engine Treatment chemistry far outperforms the PTFE dispersion of comparable composition and concentration to that in the five component mix of UBC.

(6) (a) No measurable levels of fluorine or fluoride compounds were found in the exhaust samples from any of the four 1992 5.0 L engines in vehicles pre-aged on the road for 80,500 km (50,000 miles).

(b) All vehicles showed an increase in controlled gaseous emissions (CO, CH, NO<sub>x</sub>) during the FTP driving cycle between 6,400 and 80,500 km (4,000 and 50,000 miles). This was equally true for the two vehicles using the UBC treatment and also for the two without the treatment. There was no evidence of catalyst deterioration due to the UBC Engine Treatment.

(c) Exhaust emissions from the Dexron<sup>4</sup> ATF Cycling Test showed no significant levels of fluorine or fluoride compounds in the exhaust of the 5.7 L engine treated with the UBC chemistry.

(7) (a) In a modified back-to-back Protocol Sequence VI Test, the UBC Engine Treatment chemistry was shown to substantially improve the 135°C (275°F) fuel economy benefit of an API SG/ECII SAE 5W-30 oil. The improvement over the SG/ECII oil is +2.69% at 135°C (275°F).

(b) The UBC treatment also showed substantial carryover when replaced by the SG/ECII oil.

(c) The incorporation of the UBC chemistry at 20% treat into an API SH/ILSAC GF-1 SAE 10W-30 oil improved the EFEI of the API SH/ILSAC GF-1 SAE 10W-30 oil (100%) from 2.48% to 2.65% in a standard ASTM Sequence VI Test comparison. Most of the benefit for the UBC chemistry was again under the 135°C (275°F) (boundary) engine condition.

## V. REFERENCES

- 1) A. Pye, "Liquid Engineering," *Engineering* (July/Aug. 1992)
- 2) R. D. Allen, "Improved Vehicle Efficiency", McDonnell Douglas Corp (1977)
- 3) R. Sikorsky, "Drive It Forever" (1989) Ch. 1 ("Engine Wear")
- 4) ASTM Task Force D 02.07.OB Task Force/Engine Correlation on the Correlation of High Temperature Oil Rheology and Engine Performance, "The Relationship Between High-Temperature Oil Rheology and Engine Operation - A Status Report", ASTM Data Series DS62, Page 50, December 1985
- 5) T. F. Lonstrup, M. F. Smith, Jr., "Engine Oil And Bearing Wear", SAE Paper # 810330, February, 1981
- 6) B. Koehler, "Reports on 1977 Oldsmobile Wear Screener Evaluation" Conducted for Petrolon at SwRI, May 1 and 2, 1990
- 7) National Advertising Division (NAD) Case Report, Vol. 21, No. 7, pages 35-36, September 16, 1991
- 8) R. E. Paggi, *Lubrication*, Vol. 57, # 7 (1971) at 78
- 9) General Motors (GM) THCT 6137M
- 10) C. C. Ankrum, "Exhaust Emissions Evaluation of an Experimental Engine Oil", Final Letter Report, SwRI Project 08-5147-101/201, April 1993
- 11) J. P. Hsu, G. Miller and V. Moran, III, "Analytical Method for Determination of Trace Organics In Gas Samples Collected By Canister", *Journal of Chromatographic Science*, Vol. 29, February, 1991, pp. 83-87
- 12) ASTM Research Report No. RR:D02:1204 - "Fuel Efficient Engine Oil Dynamometer Test Development Activities, Final Report, Part II, August, 1985". Also SAE J1423, Feb. 1992
- 13) B. Koehler, "Reports on 1977 Oldsmobile Wear Screener Evaluation," CMIR-7597 SR1187 and CM1R-7597 SK-1187 plus S-50, March, 1989
- 14) E. A. Bass, "Fluorine Investigation of Exhaust Emissions with an Experimental Engine Oil in the Dexron® ATF Cycling Test", SwRI Project 08-5147-301/401, October 11, 1993
- 15) H. Langan, "Report on ASTM Sequence VI Evaluation Conducted for Petrolon", Test No: 74-372-103-16A, SwRI, May 30, 1992
- 16) H.S. Kong and M.F. Ashby, "Friction-Heating Maps and Their Applications", *MRS Bulletin*, October, 1991, pp. 41-47
- 17) A. Erdemir, F.A. Nichols, G.R. Fenske and J.J. Hsieh, "Sliding Friction and Wear of Ceramics With and Without Soft Metallic Films", *MRS Bulletin*, October, 1991, pp. 49-53
- 18) L. L. Cao, Y. M. Sun and L.Q. Zheng, "Chemical Structure Characterization of the Boundary Lubrication Film Using X-Ray Photoelectron Spectroscopy and Scanning Auger Microprobe Techniques", *Wear*, 140 (1990), pp. 345-357 D. A. Cole, "X-Ray Photoelectron Spectroscopy Analytical Report", Evans East, Plainsboro, New Jersey, November 16, 1993

# Appendix A

## BREAD-IN PROCEDURE FOR RADIOTRACER ENGINE

**ENGINE OIL: COMMERCIAL SAE 5W-30  
API SH/GF-1 ENGINE OIL (REFERENCE OIL B)**

**TEST PROCEDURE:**

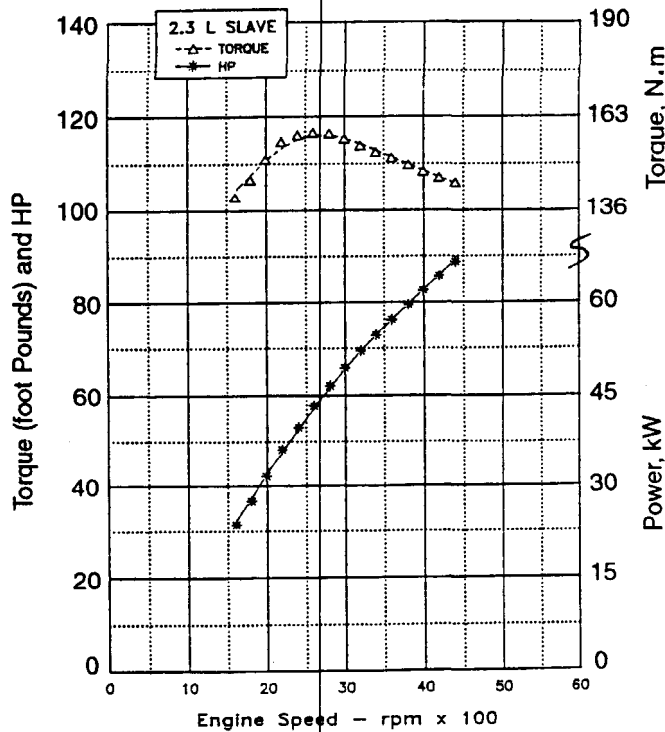
Test Conditions			Time/Step (min)	Cumulative (Hrs)	Comments
Torque (N·m)	Speed (rpm)	Coolant Out (°C)			
(1) BREAK-IN PROCEDURE (Use 5W-30 SH RMX 3520 Oil)					
a) No load	1500	Ambient	30	0.50	Cold start
b) 88	2000	85	46	1.25	
c) 95	2500	85	46	2.00	
d) 95	2800	85	30	2.50	
e) No load	1000	Ambient	30	3.00	
f) 88	2000	85	30	3.50	
g) 142	3000	85	30	4.00	
h) 142	2000	85	30	4.50	
i) 142	3500	85	30	5.00	
j) 95	2800	85	60	6.00	
k) 156	2800	85	60	7.00	

**Comments:**

This break-in schedule was developed from a review of the Sequence VE Break-in and operating schedule, an OEM dynamometer bread-in schedule used to simulate vehicle break-in to control oil consumption, and some additional speed load conditions which were considered appropriate to obtain wear stabilization prior to initiating the primary test matrix.

A performance curve, at full load, obtained on an identical engine is also enclosed for reference.

**TORQUE AND HORSEPOWER VS ENGINE SPEED**



## CATALYST EFFICIENCY EVALUATION PROCEDURE

1. Set up engine to the proper configuration.
  - a. Retard the timing to a preset position.
  - b. Divert engine exhaust gas around the catalyst until the proper conditions are achieved.
  
2. Light-off.
  - a. No perturbation.
  - b. Run at 14.6 A/F ration.
  - c. Reroute the exhaust gas through the catalyst. Measure the time necessary to reach a 50% conversion of the emissions.
  
3. Catalyst efficiency evaluation.
  - a. Run with perturbation,  $\pm 0.5$  A/F at 1 hertz and 400°C (752°F) inlet temperature.
  - b. Run from lean to rich. Start at about 0.7 A/F lean (use 15.3). Take data from 0.5 A/F lean to 0.5 A/F rich (15.1 to 14.1).
  - c. Run for 240 seconds. Efficiency readings taken approximately every 0.1 A/F ration.
  - d. Repeat three times.
  - e. Space velocity = 80,000 / hr.

## Test Results Modified Protocol Sequence VI Test

## At 66°C (150°F) Oil Gallery Temperature

	Test Oil	Fuel Consumption		Percent Fuel Economy Increase	
		g/MJ	lbs/bhp-hr	vs HR Oil	vs API SG/ECII
2)	HR Reference	152.5	0.9026	--	--
3)	API SG ECII SAE 5W-30	148.0	0.8760	+2.95	--
4)	20 UBC/80 API SG/ECII	148.4	0.8783	+2.69	-0.26
5)	API SG/ECII SAE 5W-30	147.6	0.8733	+3.25	+0.31
6)	API SG/ECII SAE 5W-30	148.0	0.8761	+2.94	-0.01

## At 107°C (225°F) Oil Gallery Temperature

	Test Oil	Fuel Consumption		Percent Fuel Economy Increase	
		g/MJ	lbs/bhp-hr	vs HR Oil	vs API SG/ECII
2)	HR Reference	148.7	0.8802	--	--
3)	API SG ECII SAE 5W-30	142.5	0.8434	+4.18	--
4)	20 UBC/80 API SG/ECII	141.8	0.8392	+4.66	+0.50
5)	API SG/ECII SAE 5W-30	143.0	0.8462	+3.86	-0.33
6)	API SG/ECII SAE 5W-30	142.1	0.8412	+4.43	+0.26

## At 135°C (275°F) Oil Gallery Temperature

	Test Oil	Fuel Consumption		Percent Fuel Economy Increase	
		g/MJ	lbs/bhp-hr	vs HR Oil	vs API SG/ECII
2)	HR Reference	150.6	0.8914	--	--
3)	API SG ECII SAE 5W-30	146.2	0.8655	+2.91	--
4)	20 UBC/80 API SG/ECII	142.3	0.8423	+5.51	+2.69
5)	API SG/ECII SAE 5W-30	142.2	0.8417	+5.58	+2.75
6)	API SG/ECII SAE 5W-30	143.6	0.8499	+4.66	+1.81

Table 17

SEQUENCE VI  
ASTM FUEL EFFICIENT ENGINE OIL DYNAMOMETER TEST  
TEST DOCUMENTATION

Test No.: 73      Stand      -      Stand Runs      -      Eng. No.      -      Eng. No. Runs  
127      307      18

Oil Code: RMX3595      Calibration Oil Start Date: 02/16/94

SAE Grade: N/A      Calibration Oil Start Time: 19:30

Lab Oil Code: LO-77167      Candidate Oil Start Date: 02/17/94

Engine Type: 3.8L Buick V6      Candidate Oil Start Time: 08:10

Fuel Batch: Indolene, EEE      Eng Hrs @ Start of Test: 1204

New Oil Viscosity:      Hours Test Duration: 62

at 40° C, cSt: 67.69      Eng. Hrs. @ End of Test: 1266

at 100° C, cSt: 10.33      End of Test Date: 02/19/94

Reference Oils:      LR: FEE0-102-7      FM: FEE0-103-7  
HR: FEE0-100-8      FO: FEE0-201-6

Sequence of Test Stages:

| LR | FM | HR-8 | AGED RMX3595 | HR-8 |  
| 150 | 275 | 275, 150, 225 | 225, 150, 275, 150, 275 | 150, 275, 150, 275, 225 |

OVERVIEW OF RESULTS

\* Engine Calibration:      Viscometric      -7.97 %  
Boundary vs. HR 150      9.31 %  
Boundary vs. HR 275      5.09 %

\* Test Oil Results

STAGE	CAND.	HR	BSFC MEAN	%BSFC REDUCTION	MULTIPLIER	WEIGHTED REDUCTION
150	0.8778	0.8986		2.31	0.66	1.53
225	0.8346	0.8484		1.63	N/A	N/A
275	0.8336	0.8328		2.25	N/A	N/A
CAND. 275 VS. HR 150						
						0.34
						7.23
						2.46
WEIGHTED TOTAL -						3.99
FM ADJUSTMENT -						3.16
EFEI -						2.48

Table 16

SEQUENCE VI  
ASTM FUEL EFFICIENT ENGINE OIL DYNAMOMETER TEST  
TEST DOCUMENTATION

Test No.: 73      Stand      -      Stand Runs      -      Eng. No.      -      Eng. No. Runs  
127      308      19

Oil Code: 340-5      Calibration Oil Start Date: 02/21/94

SAE Grade: N/A      Calibration Oil Start Time: 20:00

Lab Oil Code: LO-77168      Candidate Oil Start Date: 02/22/94

Engine Type: 3.8L Buick V6      Candidate Oil Start Time: 09:25

Fuel Batch: Indolene, EEE      Eng Hrs @ Start of Test: 1266

New Oil Viscosity:      Hours Test Duration: 67

at 40° C, cSt: 67.98      Eng. Hrs. @ End of Test: 1333

at 100° C, cSt: 10.39      End of Test Date: 02/24/94

Reference Oils:      LR: FEE0-102-7      FM: FEE0-103-7  
HR: FEE0-100-8      FO: FEE0-201-6

Sequence of Test Stages:

| LR | FM | HR-8 | AGED 340-5 | HR-8 |  
| 150 | 275 | 275, 150, 225 | 225, 150, 275, 150, 275 | 150, 275, 150, 275, 225 |

OVERVIEW OF RESULTS

\* Engine Calibration:      Viscometric      -7.40 %  
Boundary vs. HR 150      9.03 %  
Boundary vs. HR 275      4.03 %

\* Test Oil Results

STAGE	CAND.	HR	BSFC MEAN	%BSFC REDUCTION	MULTIPLIER	WEIGHTED REDUCTION
150	0.8786	0.9026		2.66	0.66	1.75
225	0.8370	0.8665		3.40	N/A	N/A
275	0.8390	0.8860		5.30	N/A	N/A
CAND. 275 VS. HR 150						
						0.34
						7.05
						2.40
WEIGHTED TOTAL -						4.15
FM ADJUSTMENT -						3.07
EFEI -						2.65