STUDY OF RE-REFINED OIL USE IN DIESEL ENGINES: FINAL REPORT

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16. Abstract

Because of the concern that re-refined oil was causing engine failures, a study was initiated to compare the wear effects of re-refined and virgin oils using the two Detroit Diesel engines in a ferryboat that would experience similar duty cycles, weather, and hours of operation. Ideally, both engines would have been rebuilt to the manufacturer's specifications and the precise dimensions of bearings and other internal wear components documented. The condition of both engines was essentially the same for later comparison. One engine was to run on virgin oil and the other engine on re-refined oil. Two oil samples were taken every oil change and analyzed. Halfway through the program the oils were to be switched. During this process, some of the results were inconsistent due to a mix up. Thus, the results of these tests were limited. Inferences could be made from the test data, however: there was no indication of an effect between re-refined oil versus virgin oil; the engines should run on oil specified by Detroit Diesel, whether virgin or re-refined; and that engine oil changes should be much shorter than is typical for the ferryboat.

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IN DIESEL ENGINES: FINAL REPORT

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate

(Revised September 1993)

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1 INTRODUCTION

1.1 Background

For some time TxDOT has experienced problems with Detroit Diesel 8V–92 engines used in ferryboat applications. The problems were included but not limited to burned exhaust valves and bearing failures. The engines involved operated on re–refined oil. Ferryboat operators were concerned that the engine problems were related to the use of re–refined oil, or at least to the particular oil used in the engines.

Before the spring of 1998, the ferryboat engines operated on virgin oil (Costal Fleet HD–40 MIL–L 2104F, which also meets API CF–2 specs). Beginning in the spring of 1998, use of re–refined oil from Safety–Kleen, distributed by Kino Oil Company in Fredericksburg, TX, was begun. The re–refined oil was initially an SAE 40 CF–2/SH formulation. However, TxDOT requested oil with higher TBN to help reduce oil consumption. The initial Safety–Kleen SAE 40 CF–2/SH oil was replaced approximately August 1998, with a low zinc formulation developed for railroad engines.

1.2 Overview of Study

Because of the concern that re–refined oil was causing the engine failures, TxDOT initiated a study with the Institute for Design and Advanced Research (IDEATE) at Texas Tech University. An initial meeting was held in November 1999 at the ferryboat headquarters in Port Aransas to discuss the project objectives and to provide input to the development of a project plan. Personnel attended this meeting from the TxDOT Ferryboat Headquarters, the TxDOT Corpus Christi District Office, the TxDOT General Services Division, Texas Tech University, Safety Kleen, and Kino Oil. In addition, engineers from Detroit Diesel and Safety Kleen provided input during the meeting by telephone. The essential aspects of the study were determined from the results of this meeting.

Basically, the study would involve the use of both engines in one ferryboat to compare the wear effects of re–refined and virgin oils. By using the engines in one boat, both engines would experience similar duty cycles, weather, and hours of operation. Ideally, both engines for one ferryboat would have been rebuilt to the manufacturer's specifications and the precise dimensions of bearings and other internal wear components documented. Thus, the initial condition of both engines would be essentially the same and would be documented for later comparison. However, both engines from the ferryboat Oliver, had been recently rebuilt by authorized Detroit Diesel representatives and were put back in service during the second week of November 1999. Unfortunately, the same vendor did not rebuild the engines and there was no documentation of engine tolerances except that they were within Detroit Diesel specifications.

The Oliver's engines were selected to be the basis for the study. One engine was to run on virgin oil and the second engine on re–refined oil. Two oil samples were to be taken every engine oil change; one at midpoint (after 75 hours of operation), and the second during the oil change (150 hours of operation). These oil samples were to be analyzed and the results compared to determine engine wear rates. Approximately halfway through the test program the oils were to be switched (the engine initially using re–refined oil would be switched to virgin oil and vise versa) so that any inherent differences in the engines, which might produce disproportionate wear not related to oil type used, would be detected. Based on the input from Mr. Trevor Moore at Detroit Diesel, both the re–refined and the virgin oil used for the tests was to be SAE 40 CF–2/SH rated as specified by Detroit Diesel. Mr. Moore indicated that the use of low zinc oil could increase the rate of valve train wear; hence, could have at least aggravated the engine failure problems. Hour meters were to be installed on the engines to facilitate the taking of oil samples. Further, it was decided that an air box inspection would be performed before the tests began, after six months (approximately half way through the study), and at the end of the study.

Although the study did not formally begin until March 2000, the ferryboat operations began collecting oil samples in December 1999. During a meeting at the Ferryboat Headquarters in Port Aransas in May 2000, it was decided to pull the engines from the Oliver during a routine dry maintenance scheduled for the summer of 2000. The engines were removed from the Oliver, torn down, and inspected for wear in July 2000 by Stewart & Stevenson of Corpus Christi, an authorized Detroit Diesel Dealer. Pictures of the disassembled engines were taken and bearings, pistons, cylinder liners, etc. were measured and documented. In addition, Stewart and Stevenson mounted thermocouples on the engines. These thermocouples, mounted in the intake and exhaust manifolds, the oil lines, and cooling water inlet and exit, were to be used with a data acquisition system to characterize the typical operating cycle for the boat. This portion of the test was not completed due to the cancellation of the project.

The oil samples were to be sent to an oil analysis laboratory, selected by Texas Tech University, approximately each month, as they were collected. Unfortunately, due to several changes of personnel at the ferryboat operations directly involved in the study, the samples were stored for several months. In mid December 2000 a student working on the study was sent to the ferryboat headquarters to label and ship the 38 samples collected to date to the oil analysis lab. The oil sample data was presented to the Project Director and his staff on February 16, 2001 during a meeting at TxDOT in Austin, Texas. The oil sample data indicated inconsistent results, especially during the operation of the engines since the teardown in July 2000, and the data were much less frequent with respect to time after July 2000. Because of the oil sample results, a meeting was scheduled at the ferryboat headquarters in Port Aransas for March 12, 2001. During this meeting it was discovered that for some time, perhaps since the engines were reinstalled in the Oliver, that virgin oil was used in both engines.

2 STUDY RESULTS

Because of the mix up in oils being used in the Oliver's engines the study was terminated. Thus, the results of the study were limited. The oil sample data and the results of the engine teardowns are discussed below.

2.1 Oil Sample Results

The results of the oil samples for reference samples of the oil used are shown in Table A.1. Note that three samples were taken from a barrel of the re–refined oil and are denoted as: RRB—from the bottom of the barrel, RRM—from the middle of the barrel, and RRT—from the top of the barrel. Three samples were taken to check for stratification of the additives in the barrel. Samples for two different virgin oils were included. The sample V1M is from the middle of a barrel of Fina virgin oil and the samples V2B, V2M, and V2T are from the bottom, middle and top, respectively, of a barrel of Chevron virgin oil. It also should be noted that data for these samples was received after the data for the samples from the engine. It is unknown when these samples were taken and it is only known that the barrels were Fina and Chevron oils, no specifications were provided. Note in Figure A.2 that the zinc level for virgin oil 2, V2, is significantly lower than for V1 and the calcium level is much higher. This lower zinc level could indicate that the original low zinc formulation was for railroad engines. Figure A.3 indicates that oil V1 has a much higher molybdenum level than either RR or V2. There is no definite indication of what oils were used in the Oliver engines, and no certainty if the same oils were used in each engine during the entire test program.

Tables A.2 and A.3 present the oil sample test results for the oil samples taken from the engines. Figures A.4 through A.19 present graphical representations of some of the constituents found in the oil samples versus time. The dates on which the samples were taken were provided, however, the samples were not marked mid oil change or end of oil change. The IDEATE investigators were not informed which engine was to run on virgin oil and which engine was to run on re–refined oil; the engines were specified as Engine A and Engine B.

Cursory examination of the figures indicates that the frequency of sampling decreased significantly at about the time the engines were torn down (approximately June/July 2000) and inspected. One of the problems initially identified with the ferryboat operations procedures in not changing engine oil frequently enough. It appears that the oil change frequency may have been based on the recommended 150-hour period determined for the test program from December 1999 through March 2000, and then perhaps it reverted to much longer periods. The oil change frequency is not known specifically, but can be estimated from the sample dates.

Trends shown in the oil sample data tend to track fairly well for the samples taken early in the program. However, for the later samples, trends are less understandable. Because it is not known what oils were used in the engines for a significant part of the test and possibly for the entire test period, it is difficult to interpret what effect re–refined oil had on engine wear versus virgin oil.

2.2 Engine Teardown Results

During the summer of 2000 the Oliver was put in dry dock for scheduled maintenance. During that time the engines were removed and torn down for inspection. A Detroit Diesel authorized representative preformed the disassembly, inspection and reassembly of the engines. While the engines were disassembled, major wear components were measured, data was recorded, and pictures were taken of the major engine components. This data was to be used for comparison when the engines were torn down again at the end of the test. Unfortunately, since the confusion over oils being used occurred, the test was canceled and the second teardown did not occur. The measurements made on the engines are presented in Tables B.1 through B.4 and the pictures are presented in Figures B.1 through B.8. The engines were denoted as Engine #1 8VF169252 and Engine #2 8VF169240. The IDEATE investigators do not know which engine was to run on re–refined oil and which was to run on virgin oil. Two different Detroit Diesel authorized representatives prior to the start of the tests rebuilt the engines. It is only known that both engines were within Detroit Diesel specifications. The measurement data in Tables B.1 through B.4 show only insignificant differences in the engines' conditions at the time of the inspection. The pictures also indicate very similar conditions for the engines.

One engine was found to have an actuator for one exhaust valve for a cylinder not properly working, such that the valve was not opening properly. The personnel that disassembled the engines indicated that although this was not a typical problem, they occasionally found other engines with the same problem. The ineffective exhaust valve probably accounts for the complaints from operators of the Oliver that one engine did not seem to have as much power as the other.

The engine teardown and inspection indicated essentially equal wear for both engines and in no way indicated any oil related problems.

3 CONCLUSIONS

Because the test was terminated as a result of the confusion related to what oils had been used in the Oliver's engines, it is not possible to draw specific conclusions as to the effect of re–refined oil versus virgin oil on wear and other problems related to the operation of the 8V–92 Detroit Diesel engines used in the ferryboats. However, a couple of inferences can be made.

- The early oil sample results and the engine teardown inspection indicated no effect of re–refined oil versus virgin oil. (This is based on the assumption that re–refined oil was used in one engine and virgin oil in the other engine during the early portion of the test before the engine teardowns.)

- The engines should be run on SAE 40 CF–2/SH oil, as specified by Detroit Diesel, whether the oil is virgin or re–refined.

- The engine oil change intervals should be much shorter than is typical for the ferryboat engines. Detroit Diesel recommended the 150-hour interval selected for the test program.

Appendix A

Oil Sample Results

Table A.1 Oil Sample Data for Reference Oils

PPM	RRB	RRM	RRT	V1M	V2B	V2M	V2T
iron	3.00	3.00	2.00	2.00	4.00	3.00	3.00
chromium	0.99	0.99	0.99	0.99	1.00	0.99	0.99
nickel	0.99	0.99	0.99	0.99	0.99	0.99	0.99
aluminum	0.99	0.99	0.99	0.99	3.00	3.00	2.00
lead	0.99	0.99	0.99	0.99	0.99	0.99	0.99
copper	0.99	0.99	0.99	0.99	0.99	0.99	0.99
tin	0.99	0.99	0.99	0.99	0.99	0.99	0.99
silver	0.10	0.10	0.10	0.10	0.10	0.10	0.10
titanium	0.99	0.99	0.99	0.99	0.99	0.99	0.99
silicon	8.00	8.00	9.00	4.00	11.00	8.00	10.00
boron	3.00	3.00	3.00	164.00	20.00	20.00	22.00
sodium	3.00	4.00	3.00	7.00	15.00	15.00	15.00
potassium	9.99	9.99	9.99	9.99	9.99	9.99	9.99
molybdenum	4.99	4.99	4.99	17.00	4.99	4.99	4.99
phosphorus	1348.00	1200.00	1278.00	1281.00	414.00	418.00	439.00
zinc	1397.00	1247.00	1316.00	1313.00	456.00	464.00	493.00
calcium	1855.00	1680.00	1795.00	853.00	4337.00	4457.00	5059.00
barium	9.99	9.99	9.99	9.99	9.99	9.99	9.99
magnesium	505.00	399.00	481.00	992.00	25.00	25.00	28.00
antimony	9.99	9.99	9.99	9.99	9.99	9.99	9.99
vanadium	0.99	0.99	0.99	0.99	0.99	0.99	0.99

Note: RR = re-refined oil V1 = Chevron virgin oil
T = top of barrel V2 = Fina virgin oil
M = middle of barrel
B = bottom of barrel

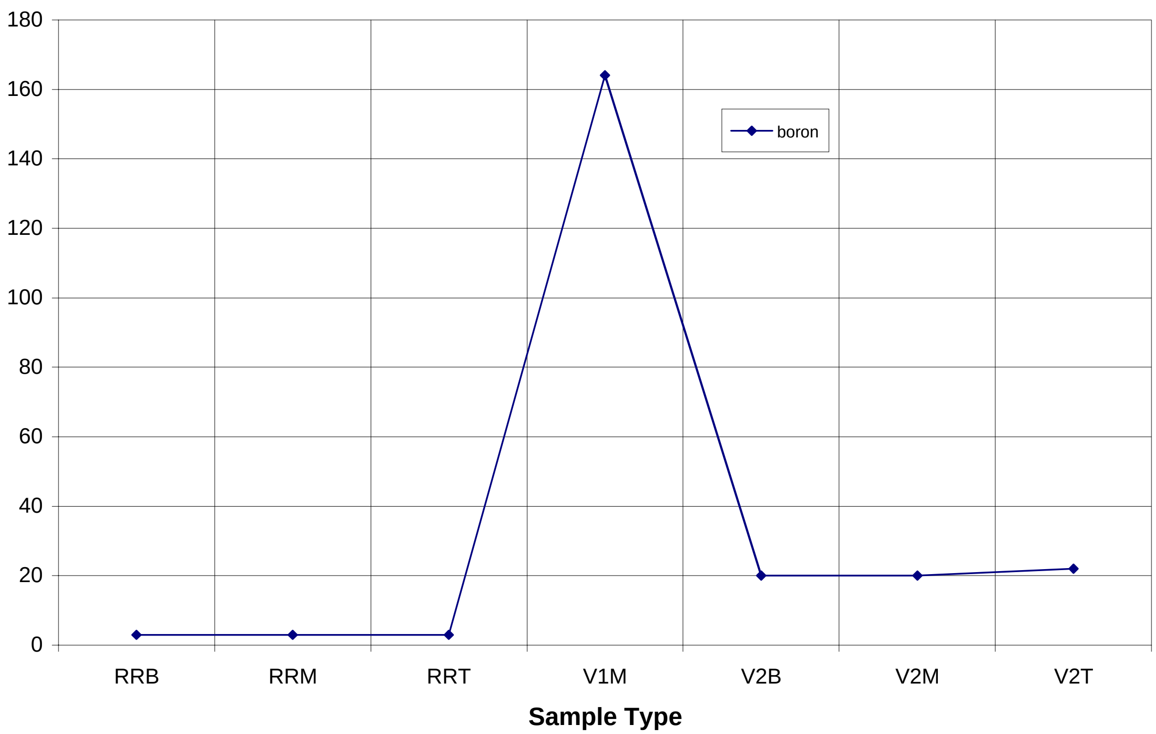


Figure A.1 Species Concentrations for Reference Oils

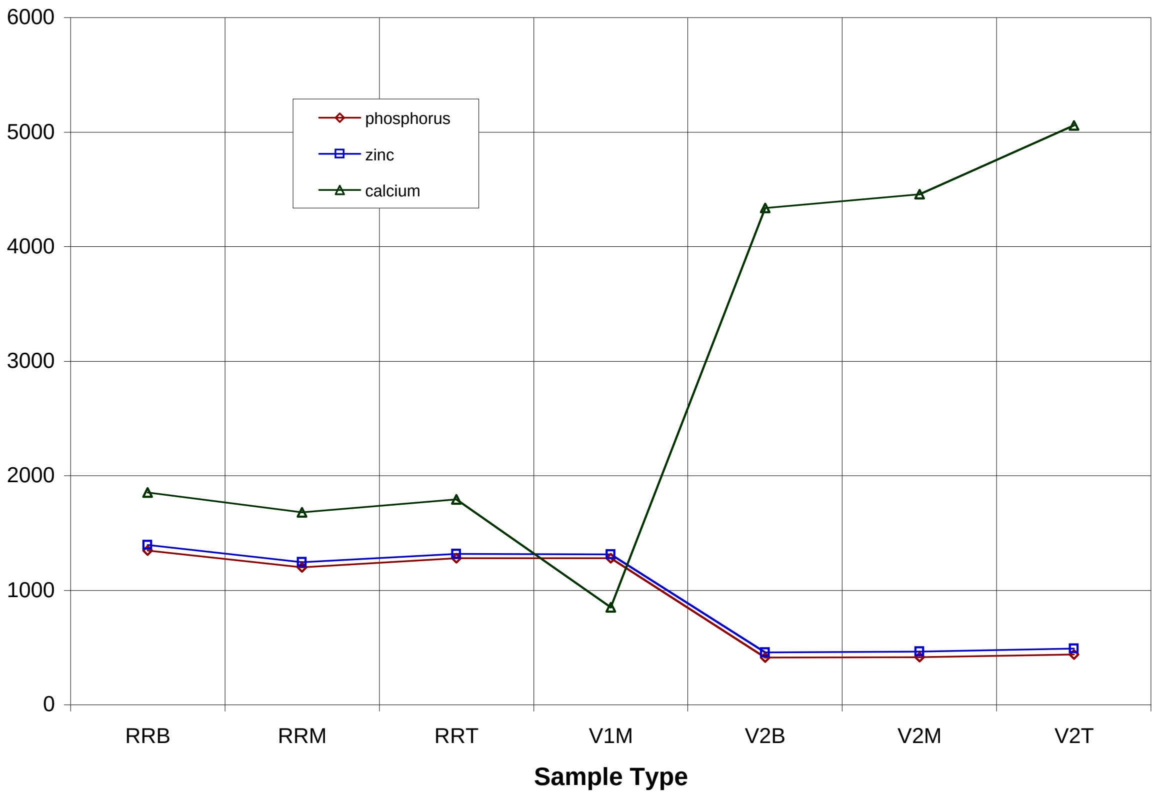


Figure A.2 Species Concentrations for Reference Oils

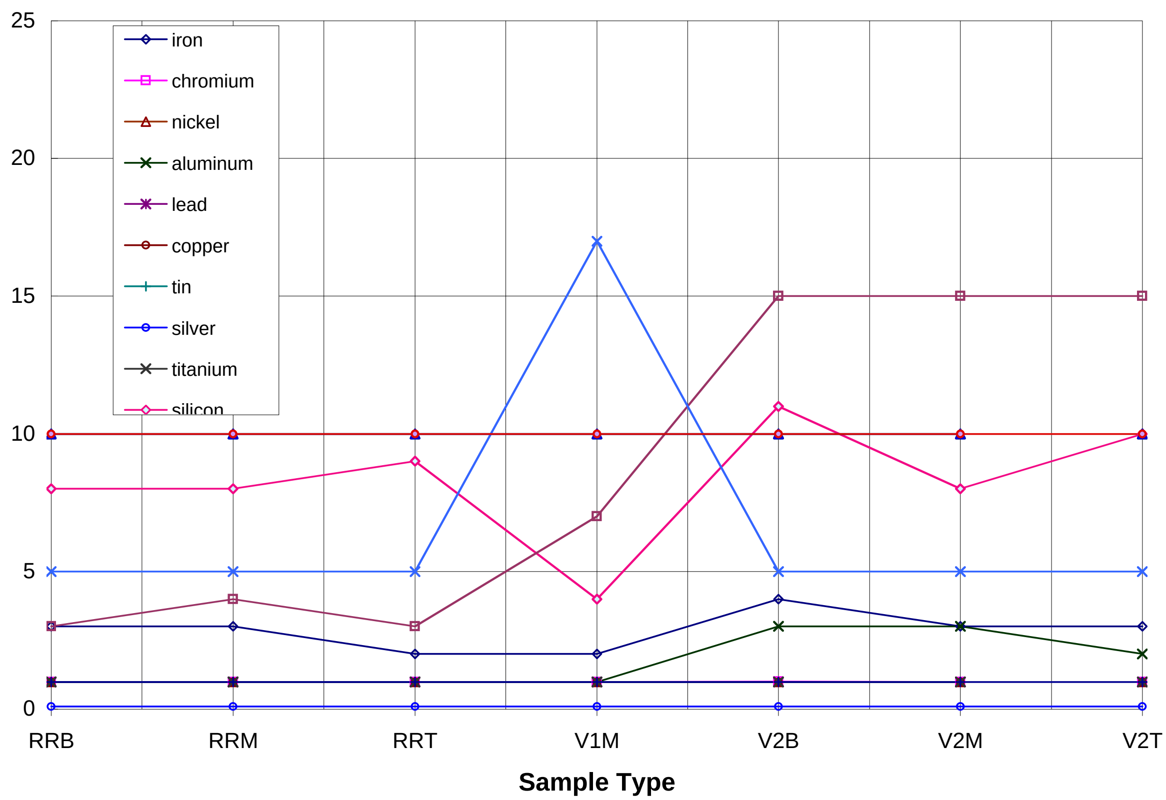


Figure A.3 Species Concentrations for Reference Oils

Table A.2 Oil Sample Data for Engine A

PPM	1	2	3	4	5	6	7	8	9	10
iron	98.00	55.00	50.00	44.00	45.00	55.00	48.00	51.00	59.00	59.00
chromium	5.00	1.00	0.99	0.99	4.00	0.99	0.99	0.99	4.00	4.00
nickel	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
aluminum	4.00	3.00	3.00	3.00	0.99	3.00	2.00	3.00	1.00	0.99
lead	6.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	2.00	2.00
copper	23.00	10.00	5.00	3.00	4.00	3.00	2.00	2.00	20.00	20.00
tin	10.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
silver	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
titanium	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
silicon	**72.00**	**29.00**	17.00	13.00	13.00	16.00	14.00	11.00	11.00	8.00
boron	3.00	1.00	2.00	0.99	2.00	0.99	1.00	0.99	1.00	1.00
sodium	29.00	11.00	8.00	6.00	4.00	7.00	6.00	7.00	6.00	6.00
potassium	10.00	13.00	9.99	11.00	9.99	10.00	11.00	10.00	9.99	0.99
molybendum	43.00	72.00	74.00	74.00	4.99	84.00	76.00	86.00	9.00	4.99
phosphorus	732.00	293.00	159.00	162.00	1567.00	102.00	281.00	77.00	1392.00	1539.00
zink	772.00	342.00	224.00	226.00	1588.00	154.00	314.00	94.00	1413.00	1610.00
calcium	3181.00	3650.00	3636.00	3599.00	1487.00	3827.00	3632.00	3825.00	1951.00	1636.00
barium	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
magnesium	344.00	150.00	106.00	97.00	467.00	83.00	136.00	66.00	452.00	490.00
antimoney	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
vanadium	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Date	11/26/99	12/3/99	12/10/99	12/20/99	12/30/99	1/7/00	1/14/00	1/24/00	2/7/00	2/18/00

Physical Test Results

% vol fuel	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
% fuel soot	0.47	0.40	0.28	0.29	0.22	0.32	0.26	0.26	0.27	0.67
% vol water	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
visc. (100'C)	14.10	15.40	15.70	16.20	16.20	14.40	15.90	16.00	15.80	14.90
SAE grade	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
TBN	7.50	8.29	10.42	11.20	11.65	6.27	11.31	11.54	10.64	8.06

Table A.2 Oil Sample Data for Engine A, cont.

PPM	11	12	13	14	15	16	17	18	19
iron	63.00	84.00	47.00	35.00	70.00	23.00	**128.00**	**100.00**	82.00
chromium	0.99	2.00	0.99	0.99	2.00	0.99	3.00	3.00	2.00
nickel	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
aluminum	4.00	5.00	3.00	3.00	5.00	9.00	6.00	5.00	5.00
lead	0.99	0.99	0.99	0.99	3.00	1.00	8.00	11.00	2.00
copper	2.00	3.00	2.00	1.00	2.00	2.00	10.00	19.00	6.00
tin	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
silver	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
titanium	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
silicon	11.00	12.00	11.00	7.00	8.00	9.00	15.00	11.00	9.00
boron	0.99	0.99	0.99	1.00	2.00	2.00	7.00	6.00	6.00
sodium	8.00	16.00	31.00	8.00	19.00	5.00	**77.00**	**64.00**	48.00
potassium	15.00	15.00	14.00	13.00	18.00	9.99	23.00	21.00	19.00
molybendum	87.00	81.00	77.00	80.00	82.00	11.00	68.00	75.00	86.00
phosphorus	59.00	145.00	87.00	19.00	9.99	1160.00	246.00	371.00	166.00
zink	68.00	210.00	117.00	29.00	20.00	1133.00	318.00	462.00	240.00
calcium	3855.00	3880.00	3732.00	3655.00	3813.00	1677.00	3534.00	3465.00	3521.00
barium	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
magnesium	49.00	61.00	44.00	31.00	34.00	374.00	131.00	203.00	95.00
antimoney	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
vanadium	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Date	2/28/00	3/1/00	3/11/00	4/7/00	6/1/00	9/21/00	10/16/00	11/17/00	12/19/00

Physical Test Results

% vol fuel	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
% fuel soot	0.76	0.40	0.61	0.29	0.22	0.80	0.61	0.75	0.57
% vol water	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
visc. (100'C)	14.58	15.40	17.10	16.20	15.90	16.70	15.80	15.60	15.30
SAE grade	40.00	50.00	50.00	40.00	40.00	50.00	40.00	40.00	40.00
TBN	6.94	8.29	10.08	11.20	11.42	11.87	9.41	9.18	9.52

Table A.3 Oil Sample Data for Engine B

PPM	1	2	3	4	5	6	7	8	9	10
iron	101.00	42.00	37.00	35.00	51.00	42.00	42.00	38.00	56.00	59.00
chromium	15.00	5.00	4.00	4.00	0.99	4.00	3.00	3.00	0.99	0.99
nickel	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
aluminum	4.00	1.00	1.00	0.99	3.00	1.00	1.00	1.00	3.00	3.00
lead	5.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
copper	16.00	5.00	5.00	4.00	4.00	4.00	9.00	10.00	2.00	2.00
tin	**39.00**	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
silver	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
titanium	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
silicon	**60.00**	17.00	14.00	14.00	16.00	10.00	7.00	8.00	12.00	12.00
boron	132.00	21.00	5.00	2.00	0.99	2.00	1.00	2.00	0.99	0.99
sodium	19.00	6.00	5.00	4.00	7.00	5.00	5.00	6.00	7.00	7.00
potassium	9.99	9.99	9.99	9.99	13.00	9.99	9.99	9.99	9.99	12.00
molybendum	28.00	4.99	4.99	4.99	67.00	4.99	4.99	4.99	70.00	83.00
phosphorus	1452.00	1551.00	1573.00	1529.00	314.00	1481.00	1625.00	1416.00	55.00	50.00
zink	1675.00	1609.00	1631.00	1645.00	358.00	1544.00	1635.00	1477.00	53.00	55.00
calcium	1335.00	1445.00	1499.00	1510.00	3605.00	1500.00	1571.00	1585.00	3799.00	3739.00
barium	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
magnesium	1014.00	454.00	467.00	456.00	145.00	425.00	484.00	456.00	46.00	48.00
antimoney	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
vanadium	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Date	11/26/99	12/3/99	12/10/99	12/20/99	12/30/99	1/7/00	1/14/00	1/24/00	2/7/00	2/18/00

Physical Test Results

% vol fuel	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
% fuel soot	0.30	0.20	0.22	0.23	0.33	0.40	0.41	0.46	0.29	0.35
% vol water	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
visc. (100'C)	15.30	14.50	14.50	14.50	16.00	14.40	14.60	14.60	16.20	16.30
SAE grade	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
TBN	6.83	6.05	7.17	7.39	8.06	6.94	6.61	6.83	10.75	12.54

Table A.3 Oil Sample Data for Engine B, cont.

PPM	11	12	13	14	15	16	17	18	19
iron	54.00	116.00	52.00	40.00	**154.00**	24.00	**161.00**	**104.00**	30.00
chromium	4.00	5.00	2.00	2.00	5.00	0.99	6.00	4.00	0.99
nickel	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
aluminum	2.00	0.99	0.99	0.99	2.00	9.00	2.00	2.00	0.99
lead	3.00	2.00	0.99	0.99	0.99	0.99	6.00	**70.00**	2.00
copper	19.00	13.00	4.00	3.00	6.00	2.00	21.00	**225.00**	**61.00**
tin	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
silver	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
titanium	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
silicon	10.00	11.00	8.00	7.00	11.00	10.00	17.00	14.00	16.00
boron	2.00	0.99	0.99	0.99	1.00	0.99	4.00	23.00	3.00
sodium	5.00	9.00	6.00	5.00	11.00	6.00	**62.00**	**193.00**	**26.00**
potassium	9.99	15.00	9.99	9.99	9.99	9.99	10.00	48.00	9.99
molybendum	4.99	4.99	4.99	4.99	4.99	9.00	4.99	4.99	4.99
phosphorus	1352.00	1315.00	1320.00	1579.00	1379.00	1110.00	1355.00	1317.00	1555.00
zink	1473.00	1513.00	1443.00	1597.00	1543.00	1097.00	1417.00	1377.00	1543.00
calcium	1669.00	1556.00	1719.00	1524.00	1560.00	1909.00	1571.00	1593.00	1479.00
barium	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
magnesium	418.00	413.00	435.00	433.00	412.00	355.00	398.00	380.00	432.00
antimoney	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
vanadium	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Date	2/28/00	3/1/00	3/11/00	4/7/00	6/1/00	9/21/00	10/16/00	11/17/00	12/19/00

Physical Test Results

% vol fuel	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
% fuel soot	0.81	1.14	0.69	0.50	1.51	0.47	0.71	0.58	0.10
% vol water	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
visc. (100'C)	14.80	15.20	14.80	14.50	15.10	14.20	14.60	15.70	14.70
SAE grade	40.00	50.00	50.00	40.00	40.00	50.00	40.00	40.00	40.00
TBN	6.16	6.38	6.61	6.94	5.49	6.94	7.06	5.71	6.83

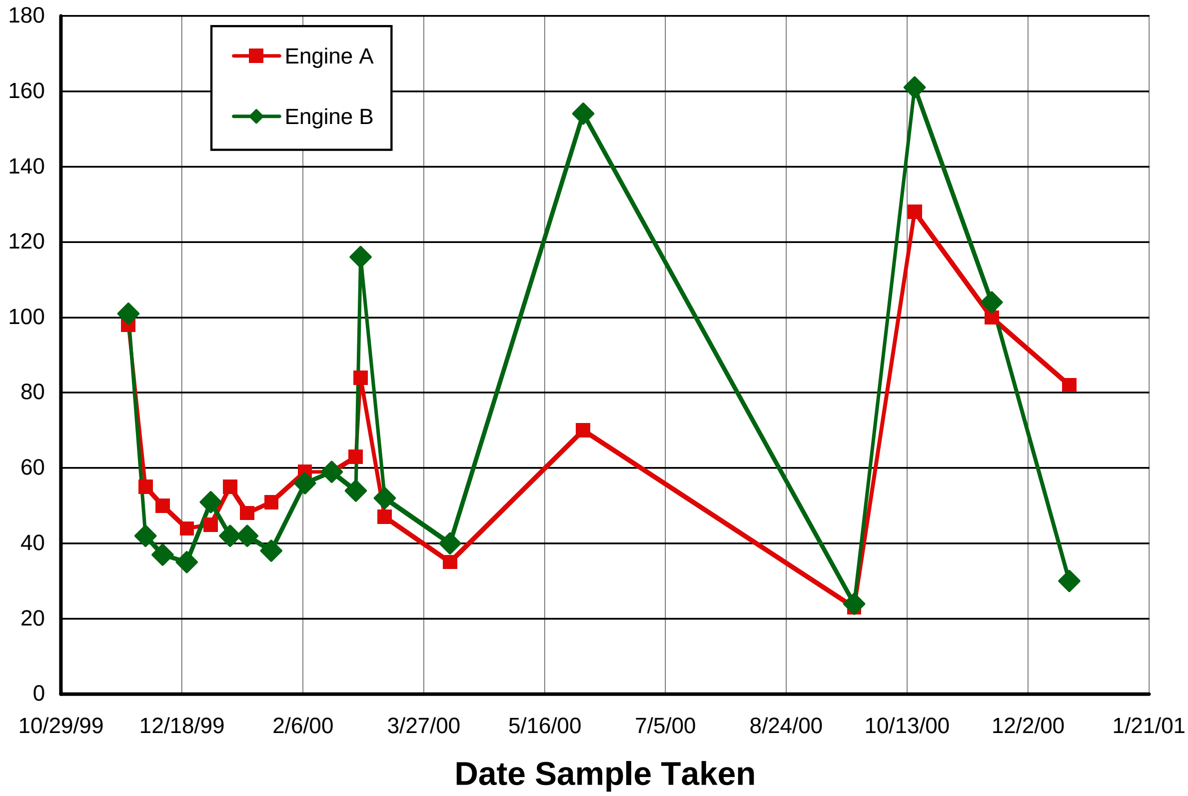
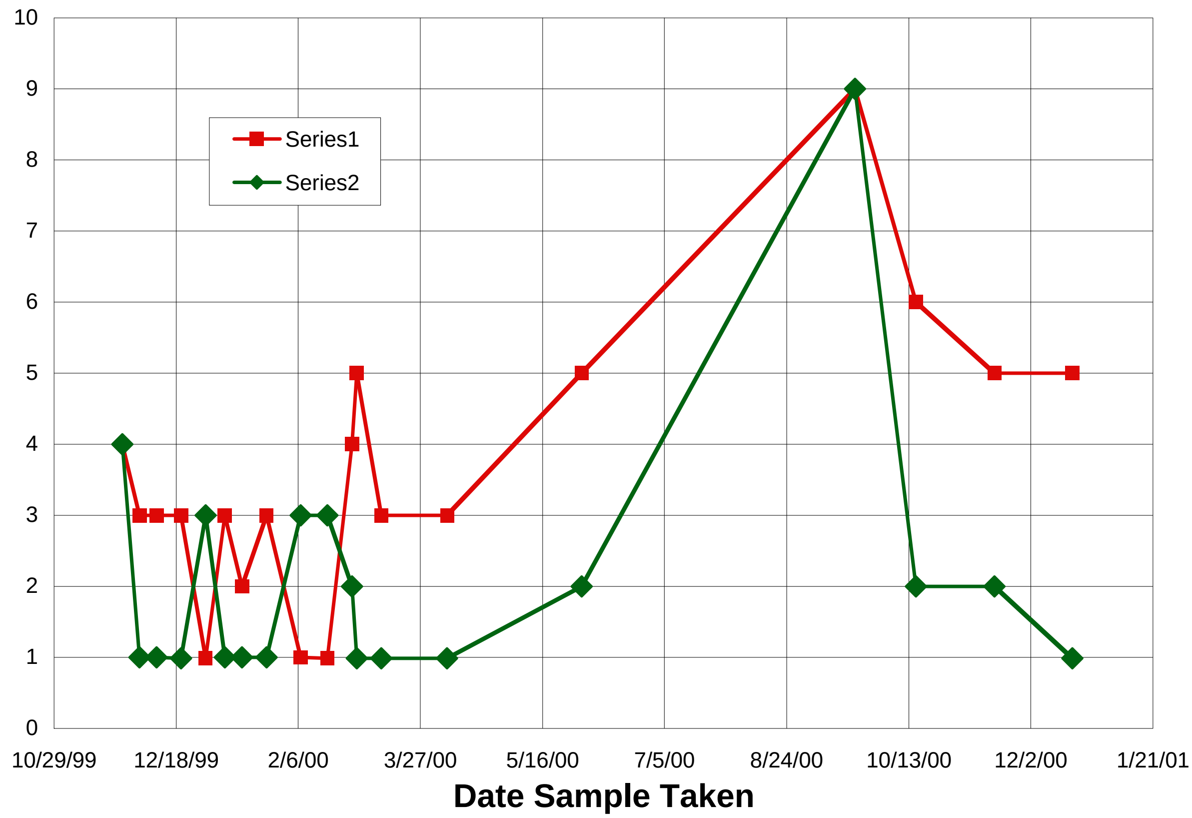


Figure A.4 Iron Concentration for Engine Oil Samples

Figure A.5 Aluminum Concentration for Engine Oil Samples



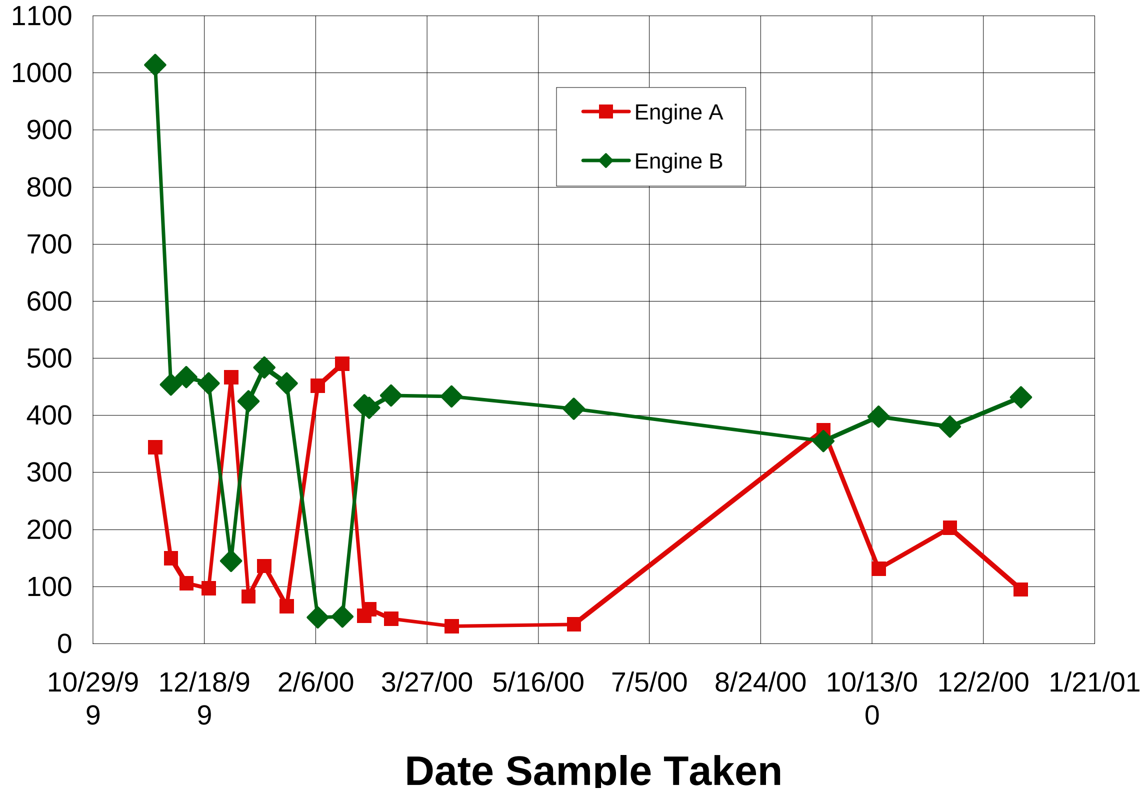


Figure A.6 Magnesium Concentration for Engine Oil Samples

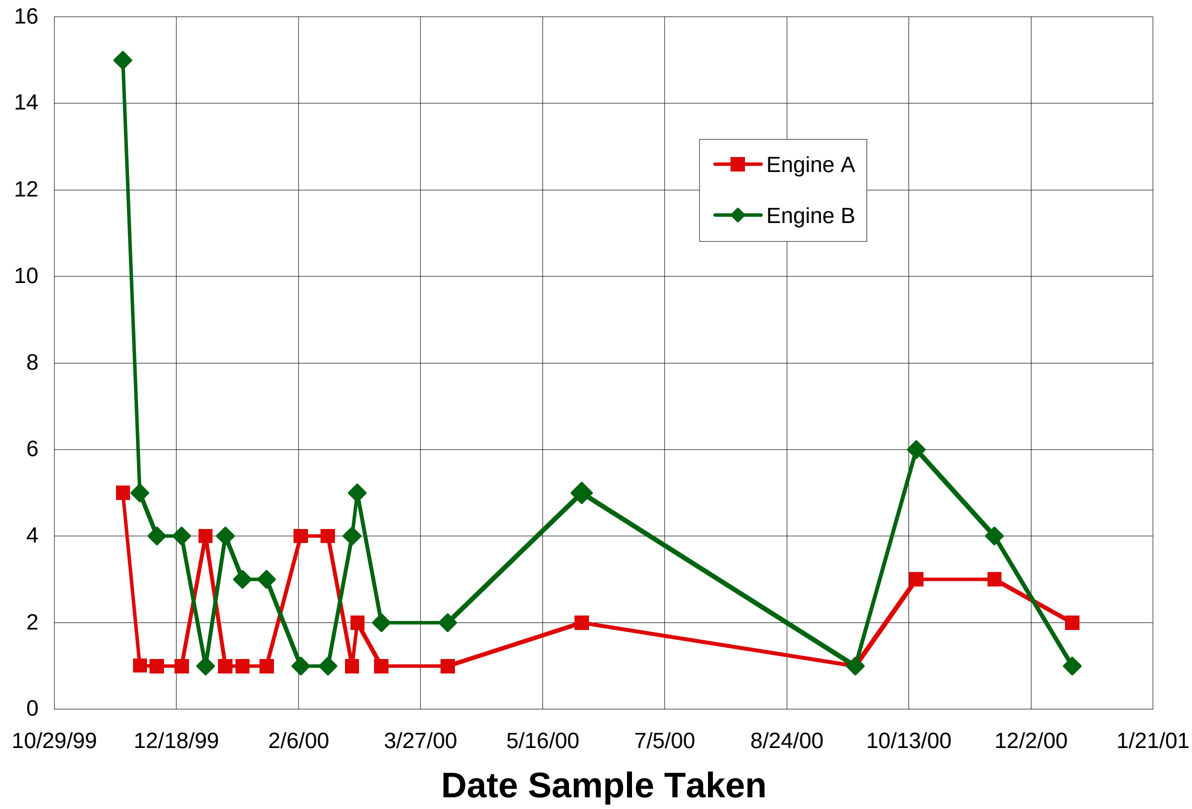


Figure A.7 Chromium Concentration for Engine Oil Samples

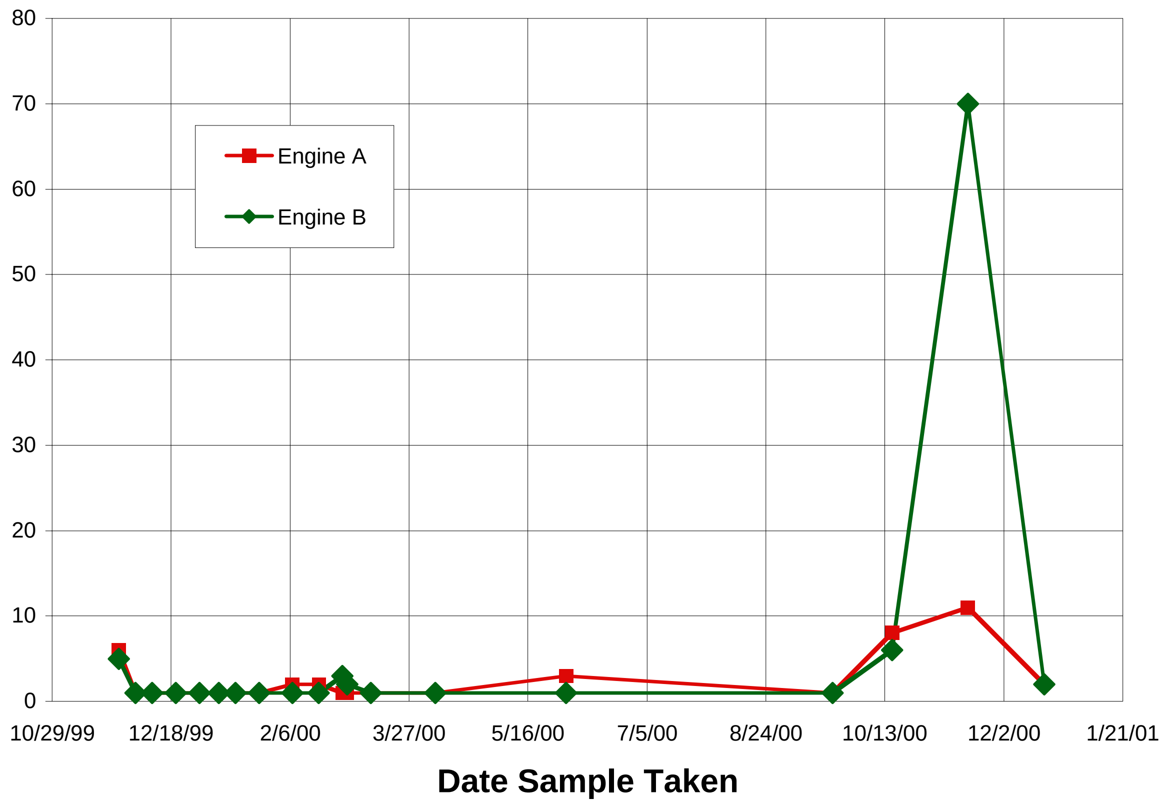


Figure A.8 Lead Concentration for Engine Oil Samples

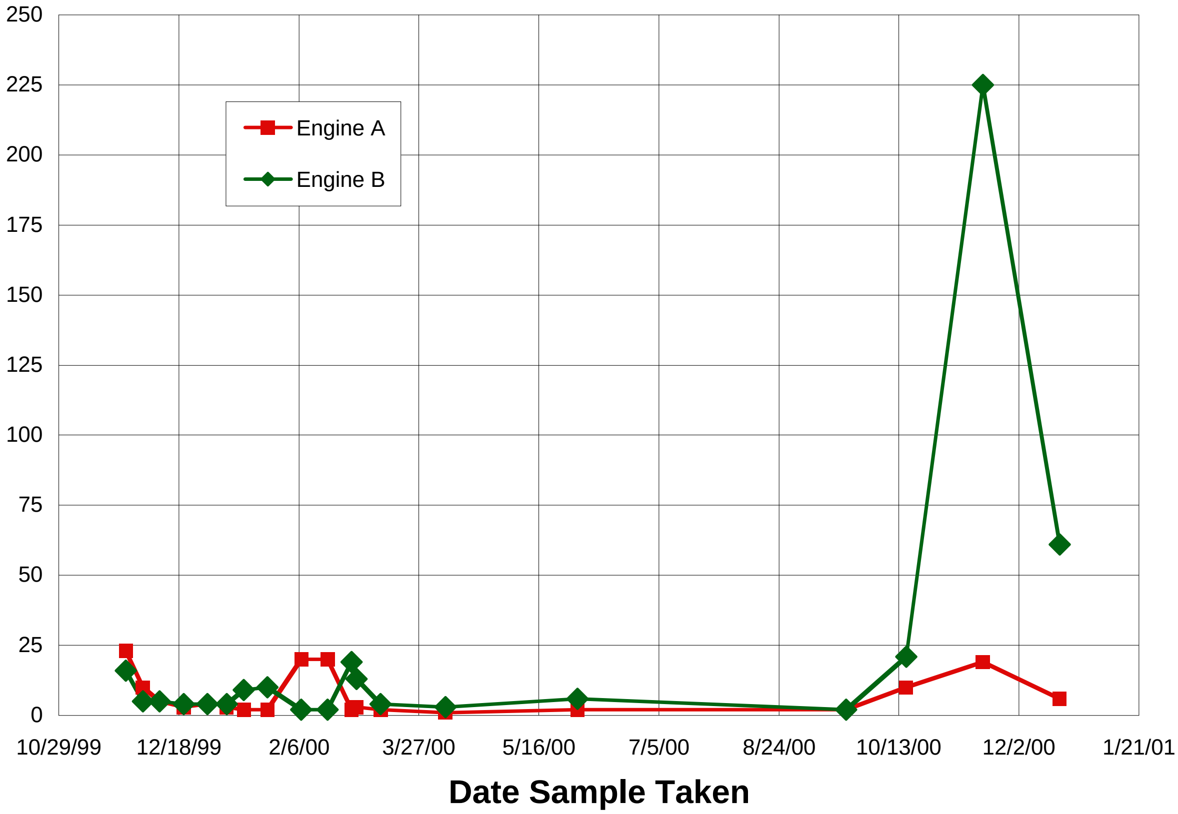


Figure A.9 Aluminum Concentration for Engine Oil Samples

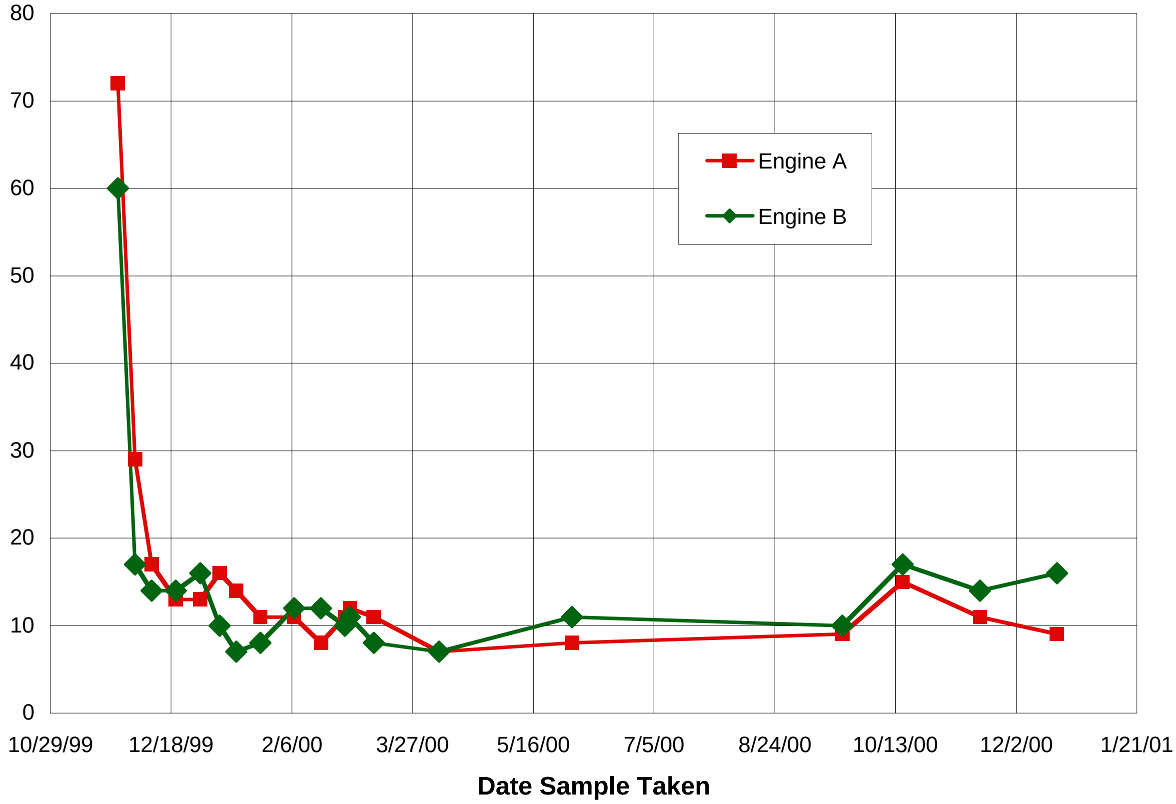


Figure A.10 Silicon Concentration for Engine Oil Samples

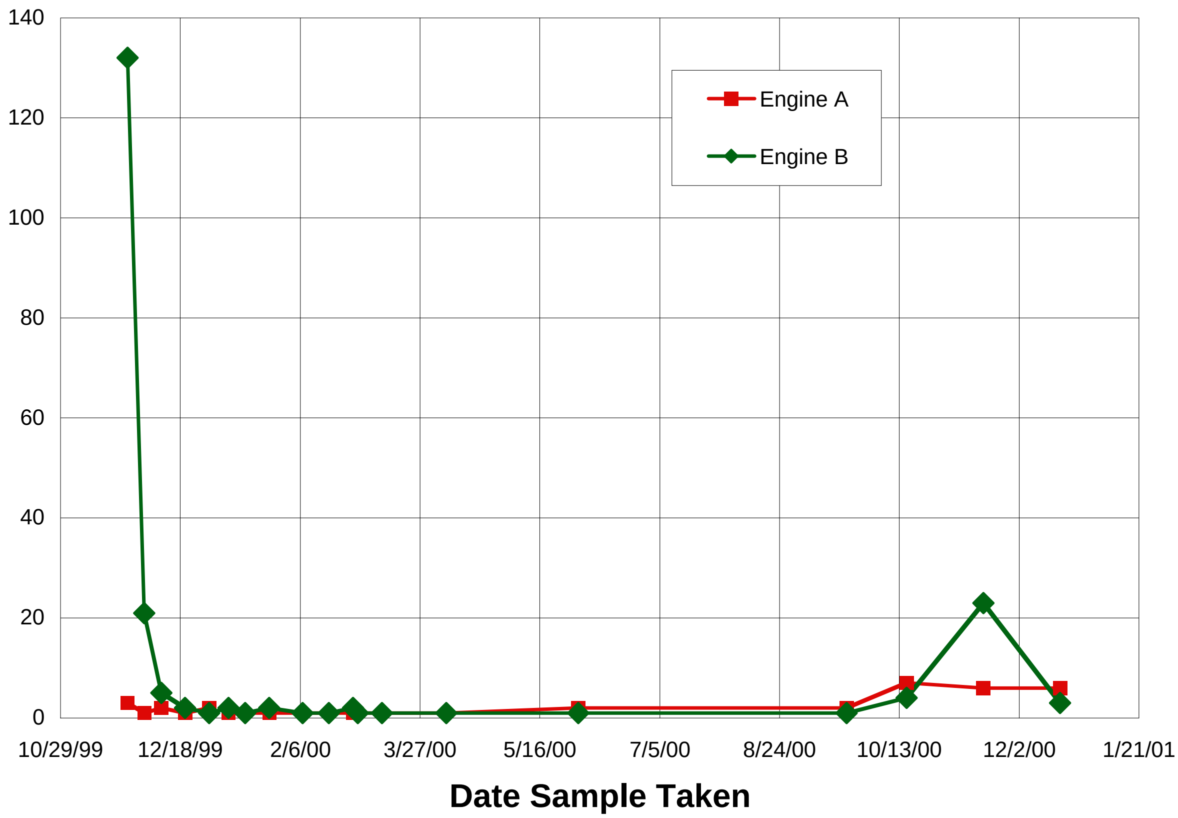


Figure A.11 Boron Concentration for Engine Oil Samples

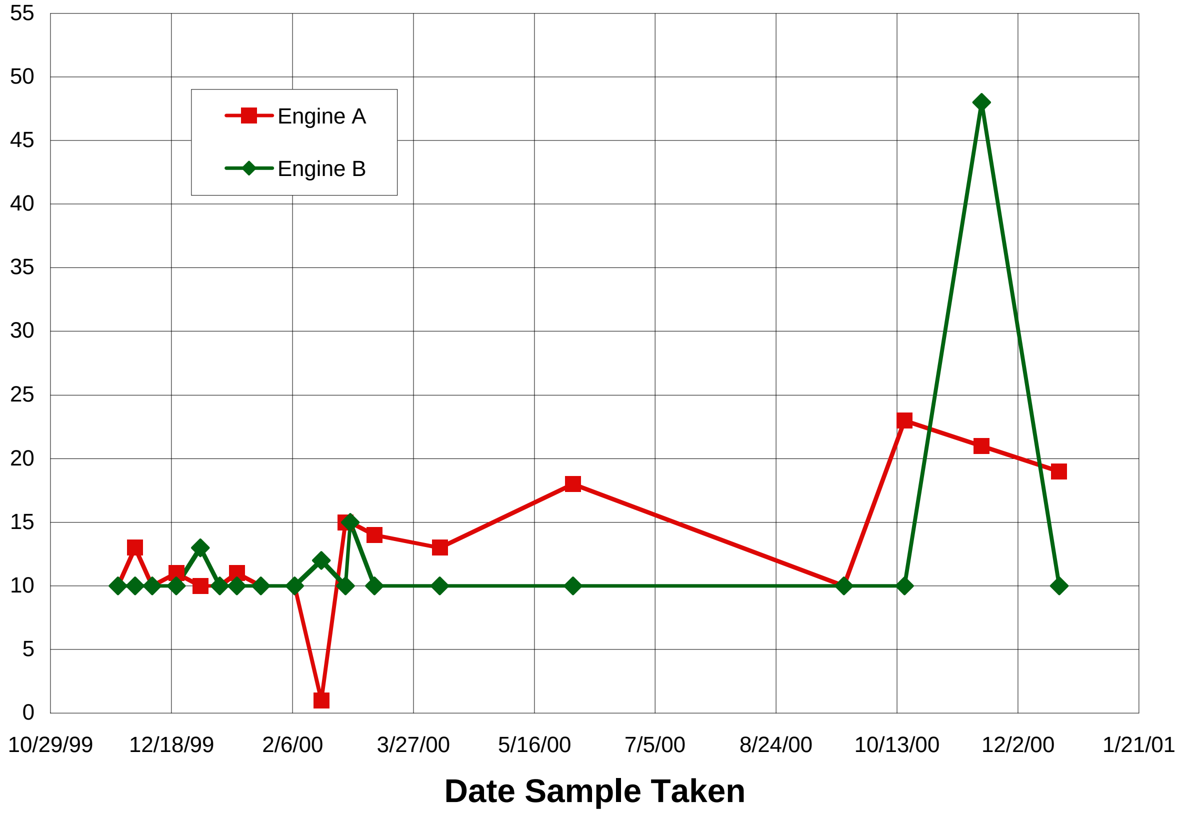


Figure A.12 Potassium Concentration for Engine Oil Samples

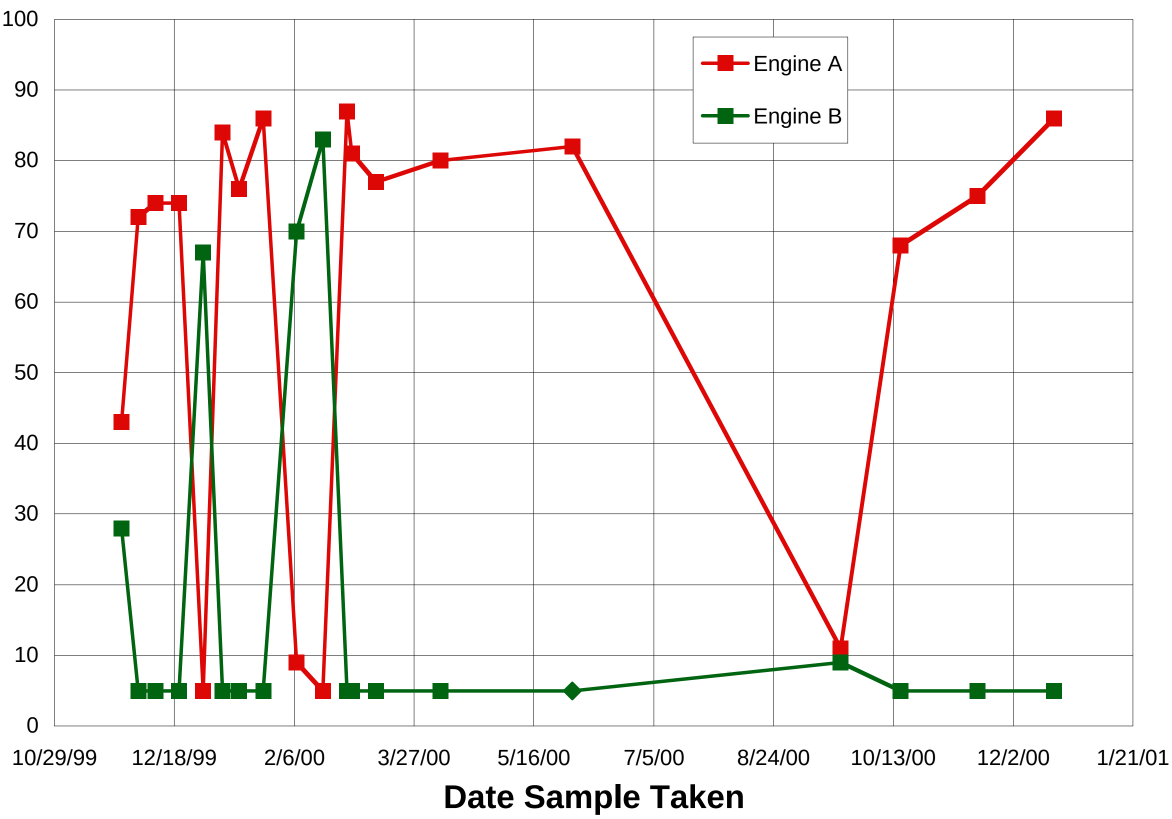


Figure A.13 Molybdenum Concentration for Engine Oil Samples

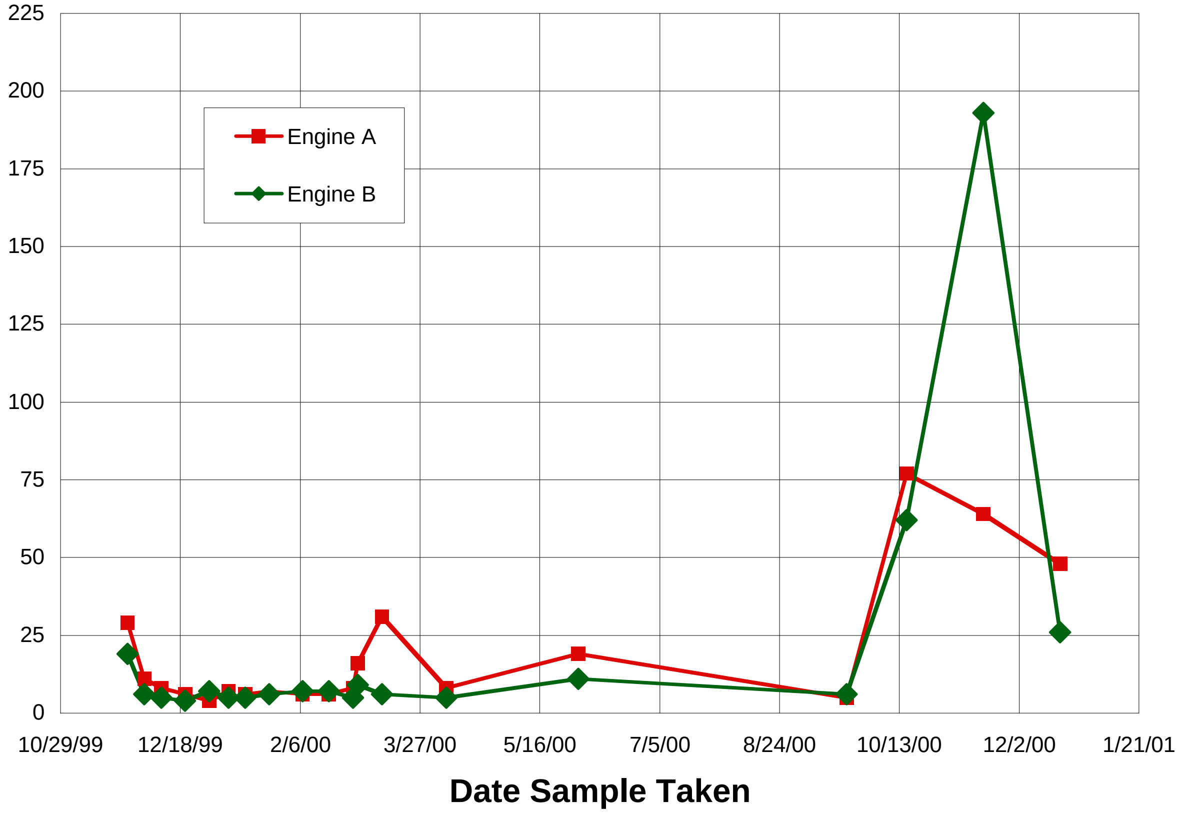


Figure A.14 Sodium Concentration for Engine Oil Samples

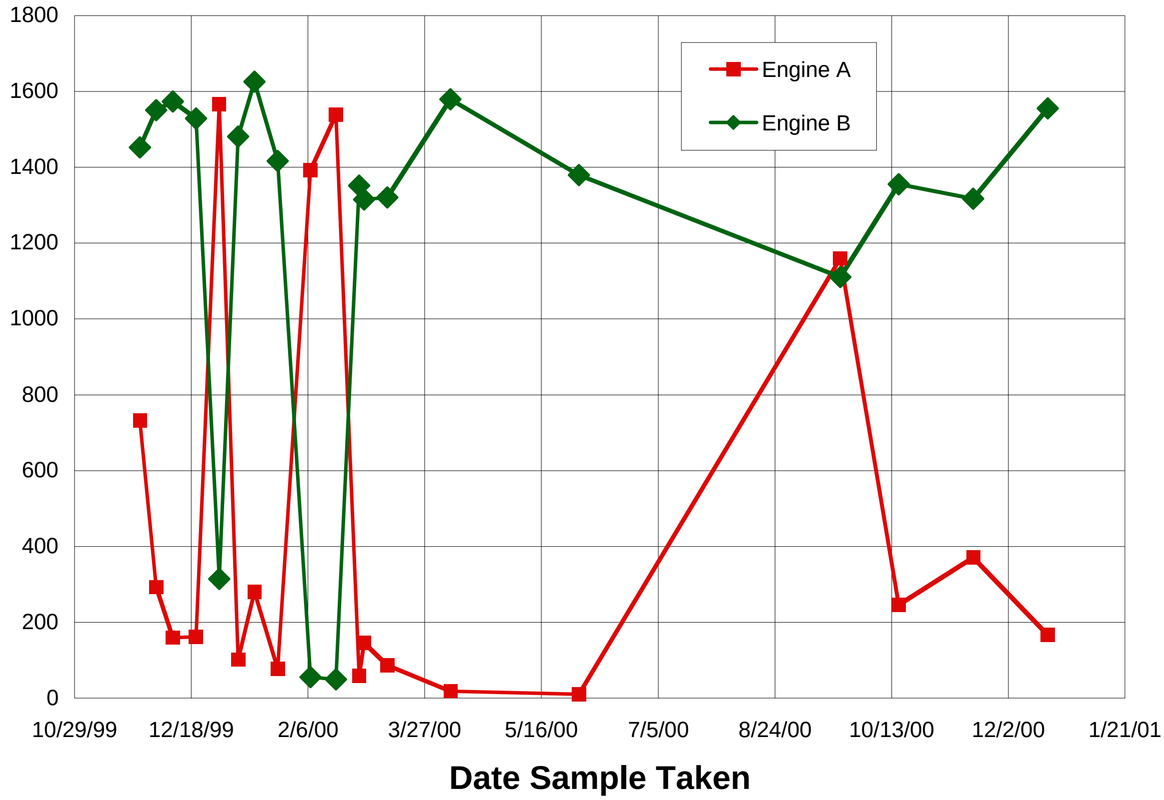


Figure A.15 Phosphorus Concentration for Engine Oil Samples

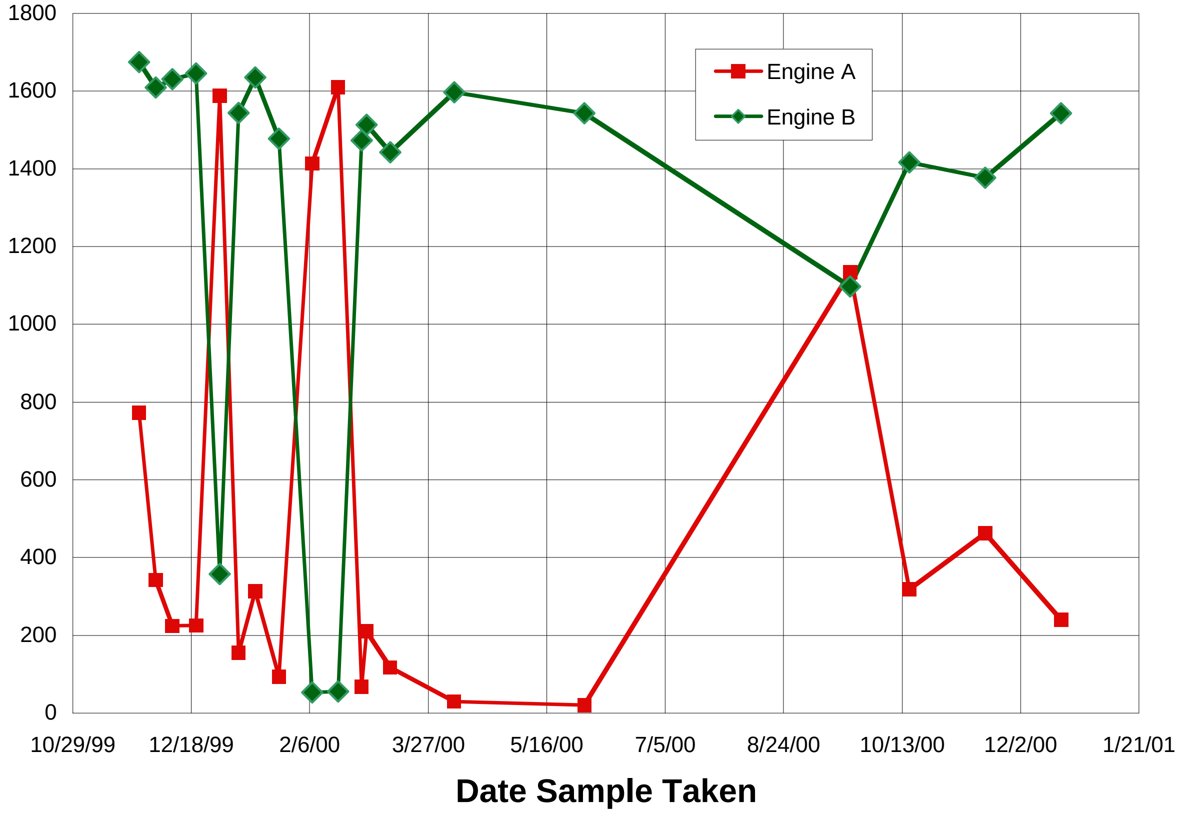


Figure A.16 Zinc Concentration for Engine Oil Samples

Figure A.17 Calcium Concentration for Engine Oil Samples

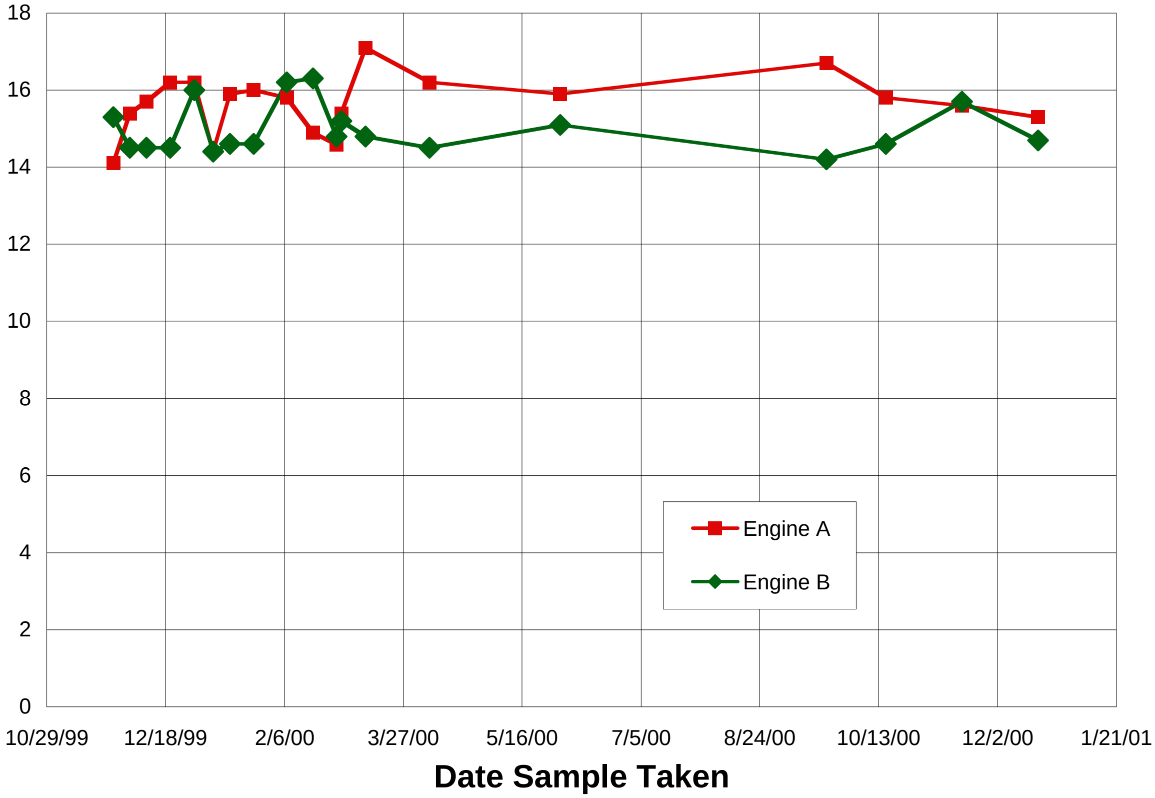


Figure A.18 Viscosity for Engine Oil Samples

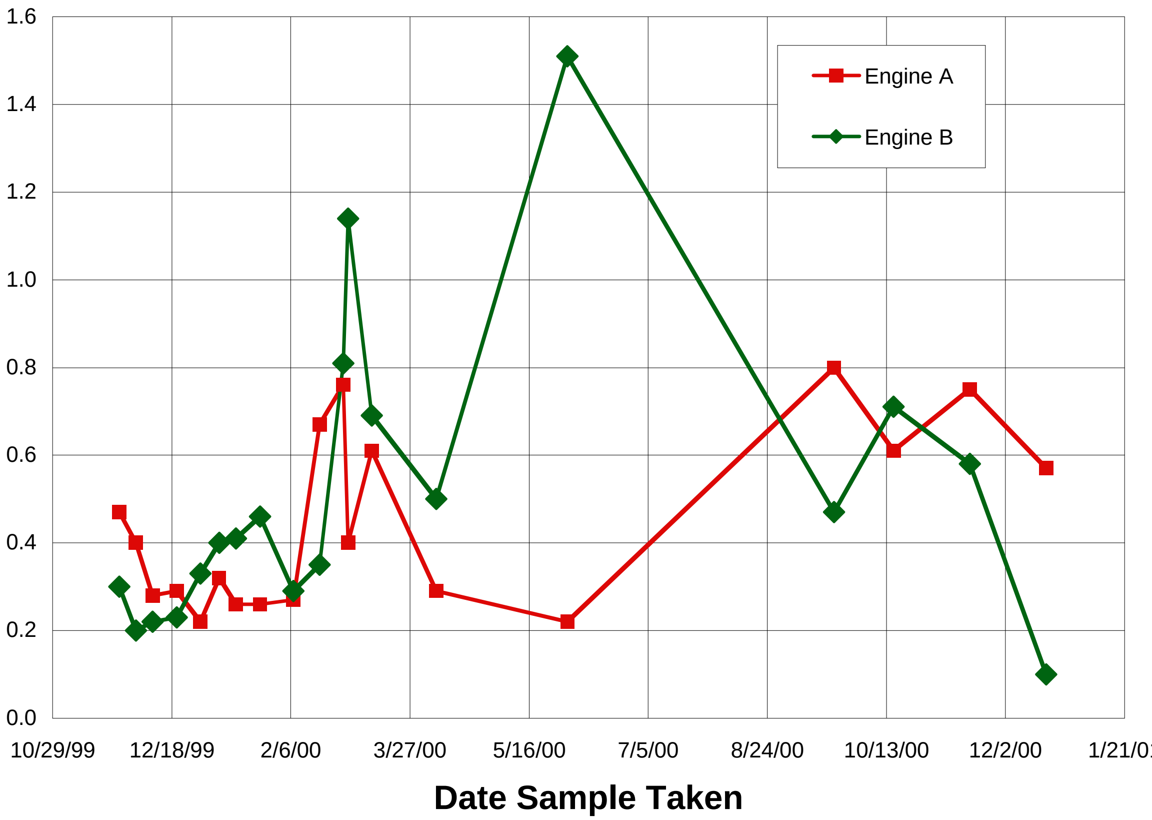


Figure A.19 % Soot for Engine Oil Samples

Appendix B

Engine Teardown Results

Table B.1 Main Bearing Measurements

	Engine #1 8VF169252		Engine #2 8VF169240	
Bearing #	**Upper**	**Lower**	**Upper**	**Lower**
#1	0.1549	0.1545	0.1546	0.1546
#2	0.1548	0.1548	0.1548	0.1548
#3	0.1548	0.1548	0.1547	0.1544
#4	0.1548	0.1547	0.1548	0.1547
#5	0.1548	0.1547	0.1546	0.1545
Small	0.1545		0.1544	
Large	0.1549		0.1548	
Range	0.0004		0.0004	
Average	0.15476		0.15465	

Table B.2 Crankshaft Thrust Bearing Measurements

	Engine #1 8VF169252	Engine #2 8VF169240
	0.1201	0.1200
	0.1201	0.1201
	0.1202	0.1200
	0.1201	0.1200
Small	0.1201	0.1200
Large	0.1202	0.1201
Range	0.0001	0.0001
Average	0.12013	0.12003

Table B.3 Crankshaft Thrust Bearing Measurements

	Engine #1 8VF169252		Engine #2 8VF169240	
	Top	**Bottom**	**Top**	**Bottom**
1 Left	4.8400	4.8410	4.8405	4.8390
2 Left	4.8410	4.8405	4.8410	4.8405
3 Left	4.8415	4.8405	4.8415	4.8410
4 Left	4.8410	4.8410	4.8410	4.8405
1 Right	4.8395	4.8390	4.8405	4.8395
2 Right	4.8410	4.8410	4.8400	4.8400
3 Right	4.8415	4.8410	4.8405	4.8410
4 Right	4.8407	4.8400	4.8397	4.8400
Small	4.8395		4.8390	
Large	4.8415		4.8415	
Range	0.0020		0.0025	
Average	4.8406		4.8404	

Table B.4 Compression Ring Measurements

Engine #1 8VF169252				
	Gap	**1st Location**	**2nd Location**	**3rd Location**
1 Left	0.0410	0.1875	0.1870	0.1874
2 Right	0.0400	0.1900	0.1888	0.1874
3 Right	0.0420	0.1865	0.1876	0.1875
4 Left	0.0415	0.1890	0.1875	0.1874
Engine #2 8VF169240				
	Gap	**1st Location**	**2nd Location**	**3rd Location**
1 Left	0.0330	0.1863	0.1863	0.1863
2 Right	0.0330	0.1860	0.1790	0.1854
3 Right	0.0400	0.1870	0.1794	0.1865
4 Left	0.0400	0.1870	0.1867	0.1861
New Ring				
	Gap	**1st Location**	**2nd Location**	**3rd Location**
	0.0307	0.1885	0.1885	0.1885

Note: Detroit Diesel specs for gap are 0.025 to 0.045

Note: Ring thickness measures at 3 location around circumference of ring

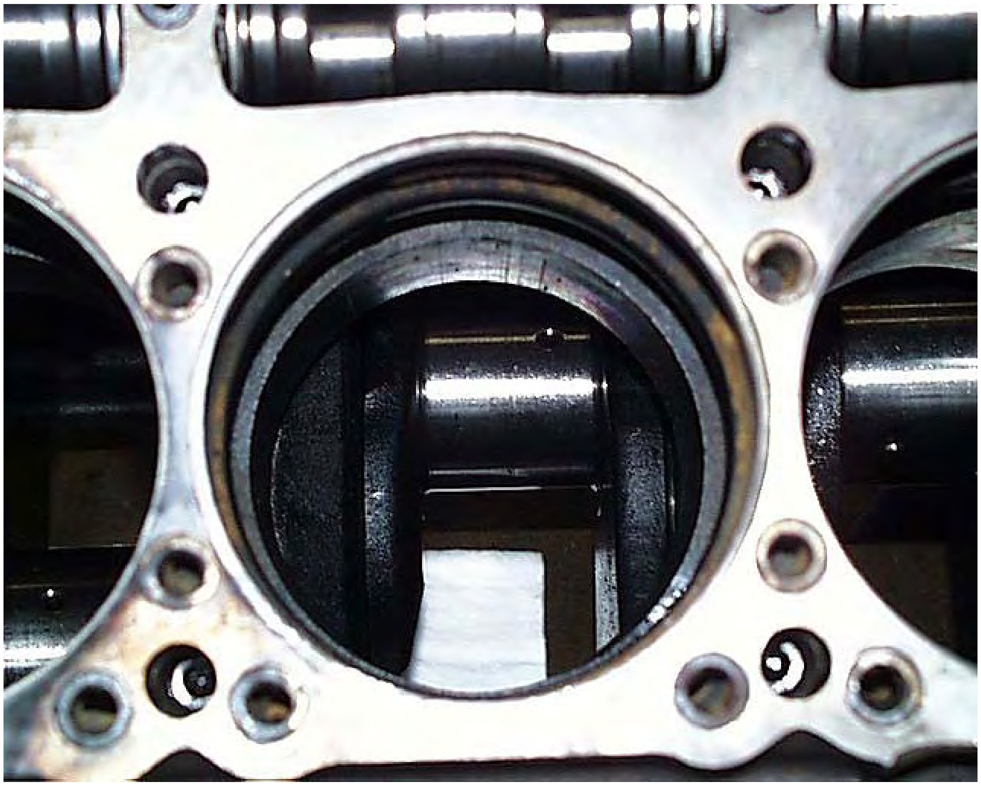


Figure B.1 Cylinder Deck Showing Cam and Cylinder Bore

Figure B.2 Cylinder Deck Showing Cam and Cylinder Bore

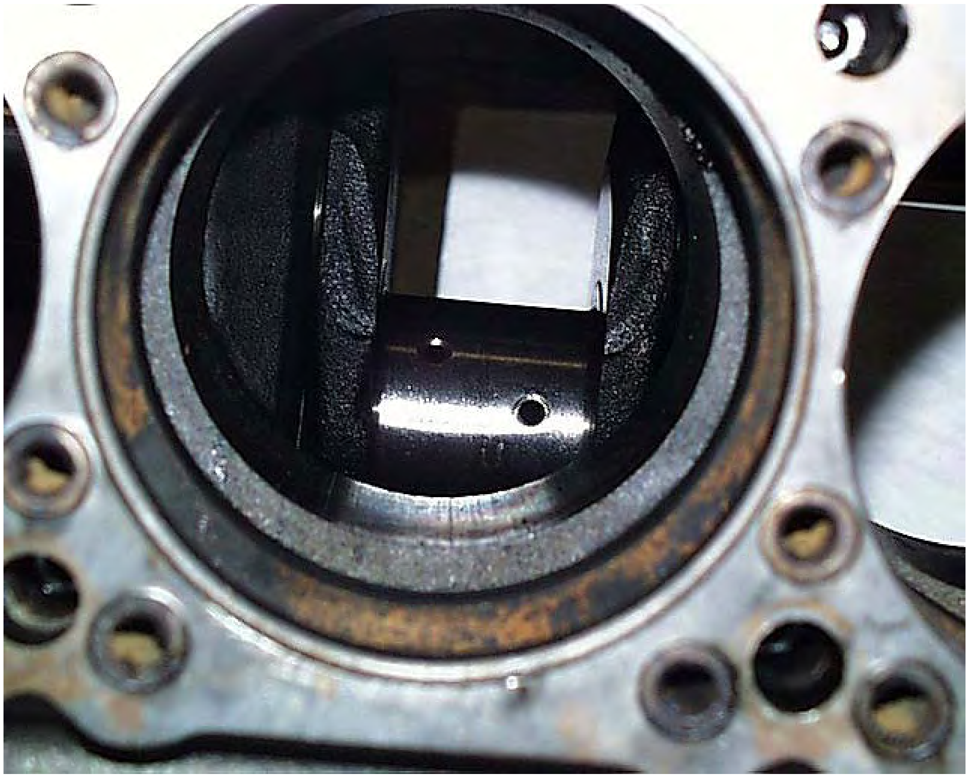


Figure B.3 Crankshaft Journal

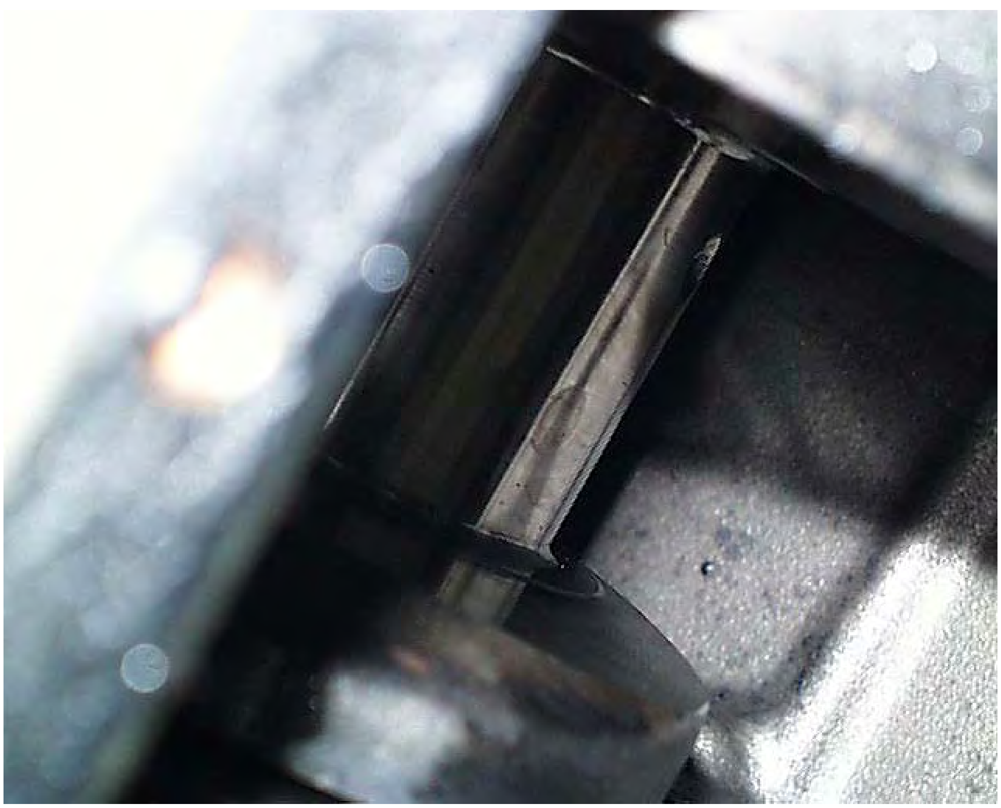


Figure B.4 Crankshaft Journal

Figure B.5 Top of Cylinder Head

Figure B.6 Cylinder Liner

Figure B.7 Top of Piston

Figure B.8 Top of Piston