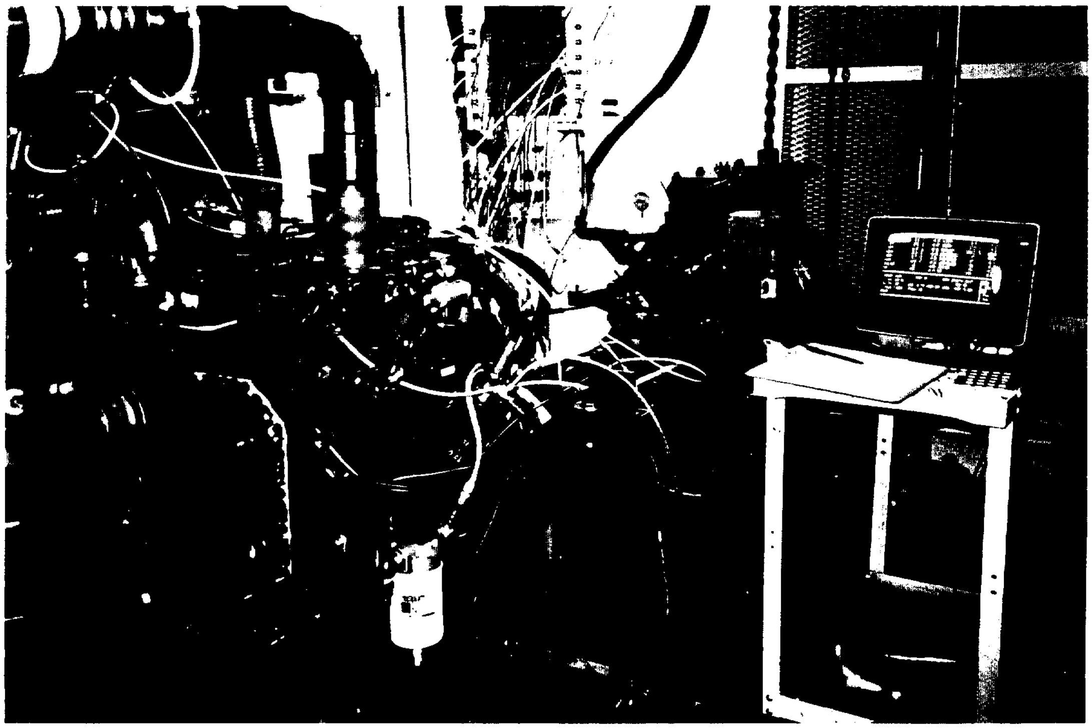
CUMMINS B5.9L PROPANE ENGINE

ARB "HD-10" LPG DURABILITY TEST

TRIBOLOGICAL OIL ANALYSIS



Prepared for

The ADEPT Group, Inc.,

Los Angeles, CA USA

by

P. B. Hertz, P.Eng.,

Hertz Mechanical Engineering

Saskatoon, SK Canada

December, 1999

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LICENSED PROFESSIONAL ENGINEER
Dec 11/99
P. B. HERTZ
PROVINCE OF ONTARIO

PROFESSIONAL ENGINEER
P. B. HERTZ
SASKATOON
SASKATCHEWAN

December, 1999

Acknowledgment

This research was carried out under the auspices of The ADEPT Group, Inc., of Los Angeles California at the request of Alex Spataru, president, and Jared Meyer, project engineer. Mehboob Sumar managed the commissioned dynamometer test facilities of Bodycote ORTECH Inc., Mississauga Ontario. Dian Yong Xie was test engineer with Dan Gowing senior test cell technician. Fluid Life Corp., of Edmonton Alberta performed the laboratory oil analyses directed by supervisor Cyril Kucovika. Many other individuals worked behind the scenes as a team, and are acknowledged and thanked for making this international engine durability test a success.

ABSTRACT

The durability of a prototype Cummins B5.9L propane engine was evaluated in a 500-hr full-load dynamometer test using California Air Resources Board "HD-10" LPG fuel. Tribological oil analysis techniques were used to infer metal wear rates by spectrometry, ferrography, magnetic-iron particle counts and oil filter debris examination.

The engine was found to generate an excessively large number of copper wear particles, traced to the thermal erosion and ultimate failure of the spark plugs. The initial selection and premature failure of the spark plugs merits further review. Crucial iron, lead, and chromium wear levels were considered normal, although the true wear generation rates of these metals were rather sporadic. The 250-hour oil change intervals employed caused the infrared oil oxidation and acidity condemnation levels to be marginally exceeded.

The application of ARB "HD-10" LPG fuel did not appear, in itself, to cause undue wear of this engine.

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1. INTRODUCTION

Alternative fuels are playing an increasing role in the reduction of global emissions while lowering our dependence on petroleum reserves. Specifically, urban diesel-powered bus and truck manufacturers are seeking cleaner fuels that will lower exhaust particulates, oxides of nitrogen, and other undesirable gases. Unfortunately, fuels such as low-sulfur diesel have exhibited higher engine and injection system wear due to low fuel lubricity. Various additives are being developed to restore the lubricity and wear protection offered by this more environmentally friendly fuel.

Liquid propane gas (LPG) has found acceptance in moderate climates and has helped reduce diesel smoke and particulate emissions. California Air Resources Board (ARB) has introduced a new "HD-10" propane fuel with emissions advantages. Cummins Engine Co. Inc. has developed a new prototype engine, the B5.9L LPG model, to take advantage of these fuels. Although emissions have been shown to be reduced with ARB "HD-10" propane, data on the durability of this engine/fuel combination was lacking. This study was initiated to measure the impact of the ARB "HD-10" fuel on engine performance, durability, and wear.

Traditional engine durability testing involves running an engine for long periods on a laboratory dynamometer. Engine power, fuel, and lubricant consumption are monitored during the test period. Engine wear is not readily determined until the engine is dissembled and its wear prone components are measured with micrometers and/or by weighing to determine metal losses.

Tribology, the science of friction, lubrication and wear, has developed detailed wear particle examination methods, which can be applied in engine durability testing. It is now possible to monitor the wear rates of a running engine by examining the wear metals generated in the lubricating oil and oil filter. This tribological approach was employed to supplement the traditional wear measurement methods used in this study.

2. TRIBOLOGICAL ANALYTICAL PROCEDURES

A prototype Cummins B5.9L spark ignition engine was fueled with California Air Resources Board (ARB) "HD-10" liquid propane gas (LPG) during some 500 hours of durability dynamometer testing under full rated horsepower. The ADEPT Group of Los Angeles commissioned the fully instrumented dynamometer facility at Bodycote ORTECH Inc. located in Mississauga, Ontario.

Detailed tribological oil analysis methods were used by Hertz Mechanical Engineering to monitor and to infer engine wear rates as the tests proceeded. Mobil Delvac Super Geo SAE 15W-40 motor oil was used exclusively along with Fleetguard LF 3349 oil filters from the same batch. Oil samples were drawn at 50-hour intervals using a "probalizer" valve installed on the main camshaft oil gallery. Reference oil samples taken 10 hours after fresh oil changes were used to establish engine wear baselines during two 250-hour runs. In all 14 oil samples were drawn and air-couriered to Fluid Life laboratory in Edmonton, Alberta for analysis.

Inductively coupled plasma atomic emission spectrometry (ICPS), as described in ASTM Standard D 5185, enabled small wear and oil additive particles less than 5 μm (microns) in size to be monitored. A total of 22 metallic elements were reported. ICPS resolutions down to 0.1 parts-per-million (ppm) were achieved for iron, copper, and chromium. A "True Wear" computer program enabled concentration corrections for oil consumed, make-up oil added and test oil levels to be compensated for. True engine wear rates were obtained for the most significant ICPS wear metals, namely - Copper, Iron, Chromium and Lead.

The ferrographic technique was used to prepare glass-slide "ferrograms" of magnetic and gravity sorted larger oil debris particles for micro-photographic identification, morphological classification, and concentration evaluations. Ferrographic particles were identified in 15 different classes, with each concentration rated on a 10-point scale ranging from a trace (0-2) to heavy (8-10). Magnetic particle counting enabled iron wear debris particle levels smaller, and larger, than 100 μm in dimension to be measured.

Oil filter debris analyses from four oil filters, one new and three used, were used to detect the largest wear and contaminant particles. Oil filter wear particles were microscopically examined at "0" hours after an initial pre-durability 10-hr run-in, and at the 250 and 500 engine-hour full-load oil-change points. Filter reports with photos of the trapped debris were prepared and presented.

The engine oil physical and chemical condition was monitored throughout the engine durability tests. Infrared absorption enabled the degree of oil nitration and oxidation to be checked. Viscosity tests at 40°C and 100°C allowed oil shear-down or oxidation thickening to be evaluated. The oil's acidity and neutralization ability was measured by ASTM D664 for Total Acid Number (TAN) and ASTM D 2896 for Total Base Number (TBN). Checks of potential oil contamination by siliceous dust (Si), coolant glycol, water, fuel, and solids were included for each oil sample throughout the durability testing.

A companion-report prepared for ADEPT by Bodycote ORTECH outlines the particulars of the dynamometer testing procedures as well as measurements of valve seat recession and engine bearing and piston-ring weight losses during these durability trials.

3. PRESENTATION OF TRIBOLOGICAL DATA WITH NOTES

The relevant tribological data charts, tables and graphs, with colored photographs of the various wear particles, have been provided as follows:

Charts A, B and C; These are Fluid Life Corp. laboratory oil analysis data sheets showing Spectro-Chemical (ICPS), Physical Tests, and Additional TAN, TBN and Infrared data for the 14 oil samples. Each indicated oil sample data set occupies two rows, and descends from most recent to the earliest sample date for engine hours and oil hours indicated. Measured values considered to be in increasing jeopardy are flagged as P- positive, R- reportable, U- unacceptable or S- severe. These charts were used to prepare the subsequent tables and figures, which assess and interpret the tribological data.

Table I- Summary of Indicated ICP oil analysis data for Cummins B5.9L LPG engine. On this table wear rates are based on indicated test data. Data reads down from earliest "New Oil Sample" taken on May 13, 1999 to the last oil sample obtained on October 1, 1999.

4. SPECTROMETRY

Figure 1- Graph of Spectrometry Copper and Iron concentrations for Runs 1 and 2. Copper peaks at 78.5 ppm in Run-1. The drops in indicated Cu ppm for the last samples in both runs are due to make-up oil dilution of the wear debris. Note the lower Cu concentration (33.2 ppm) in Run-2.

Table II- Cummins B5.9L LPG Engine Oil Consumption Summary provided by Bodycote ORTECH. Note oil consumption is about 32 mL/hr necessitating daily make-up oil additions totalling some 10.0L during each of the 250-hr runs.

HERTZ ENGINEERING
2 RUTTER CRESCENT
SASKATOON, SASKATCHEWAN
S7H 3B7
Attention : BARRY HERTZ
Phone : (306) 373–2754
Fax : (306) 955–5548

Unit Data

Unit # : AD5.9
Component : ENGINE
Location : MAIN
Manufacturer : CUMMINS
Serial # : 45406154
Model : G6B7A5.9

Lubricant

Manufacturer : MOBIL
Brand : D.S. GEO
Grade : 15W40

Sample : 06/24–158

Fluid Life *Oil Analysis*

9321 - 48 Street
Edmonton, Alberta T6B 2R4
Phone: (780) 462-2400
Fax: (780) 462-2420

CODE: Y - Yes N - Negative P - Positive R - Reportable U - Unacceptable S - Severe I - Insufficient Sample > - More Than < - Less Than

Spectro-chemical (ppm)

Sample Number	Sample Date	Silicon	Sodium	Potassium	Iron	Chrome	Lead	Copper	Tin	Aluminum	Nickel	Silver	Titanium	Boron	Phosphorus	Zinc	Calcium	Barium	Magnesium	Molybdenum	Vanadium	Antimony	Lithium	Beryllium
06/24–158	1999/06/23	20R	0	1	3	1	1	3	0	2	0	0	0	[illegible]	396	674	1157	0	5	0	0	0	0	0

Physical Tests

Sample Number	Oil Mfr.	Oil Brand	Oil Grade	Comp. Service	Oil Service	Units	Oil Chg	Water %	Glycol	Visc 40°C cSt	Visc 100°C cSt	Fuel %	Solids %
06/24–158	MOB	DSG	15W40	[illegible]	[illegible]	[illegible]	[illegible]	PR	N	[illegible]	[illegible]	[illegible]	[illegible]

Additional Tests

TBN D2896 (mgKOH/g)	TAN D664 (mgKOH/g)	NIT (A/cm)	OX (A/cm)
[illegible]	[illegible]	[illegible]	[illegible]

Results

1) Iron = 2.62 ppm; copper = 2.53 ppm; chrome = 0.62 ppm.
2) Note poor oil condition Water and flagged element Silicon.

Recommendations

Chart A - Fluid Life Corp. laboratory oil analysis data sheet, New and "0" hours

HERTZ ENGINEERING
2 RUTTER CRESCENT
SASKATOON, SASKATCHEWAN
S7H 3B7
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Unit # : AD5.9
Component : ENGINE
Location : MAIN
Manufacturer : CUMMINS
Serial # : 45406154
Model : G6B7A5.9

Lubricant

Manufacturer : MOBIL
Brand : D.S. GEO
Grade : 15W40

Sample : 09/17–316

Fluid Life
Oil Analysis

9321 - 48 Street
Edmonton, Alberta T6B 2R4
Phone: (780) 462-2400
Fax: (780) 462-2420

CODE: Y - Yes N - Negative P - Positive R - Reportable U - Unacceptable S - Severe I - Insufficient Sample > - More Than < - Less Than

Spectro-chemical (ppm)

Sample Number	Sample Date	Silicon	Sodium	Potassium	Iron	Chrome	Lead	Copper	Tin	Aluminum	Nickel	Silver	Titanium	Boron	Phosphorus	Zinc	Calcium	Barium	Magnesium	Molybdenum	Vanadium	Antimony	Lithium	Beryllium
New Oil:		2	0	3	0	0	1	0	0	2	0	0	0	1	579	629	1066	0	5	0	0	0	0	0
09/17–316	1999/09/15	14	0	3	12	2	8	71S	0	4	0	0	0	2	570	800	1438	0	7	0	0	0	0	0
09/14–184	1999/09/12	15	0	4	12	2	7	79S	0	3	0	0	0	1	551	772	1377	0	7	0	0	0	0	0
09/14–186	1999/09/10	16	0	4	12	2	4	64S	0	2	0	0	0	1	537	741	1310	0	7	0	0	0	0	0
09/14–185	1999/09/07	15	0	6	11	2	1	22R	1	2	0	0	0	1	544	719	1259	0	7	0	0	0	0	0
09/07–355	1999/09/03	16	0	2	9	1	1	7	2	3	0	0	0	2	587	708	1206	1	6	0	0	1	0	0
09/07–356	1999/08/31	12	0	2	8	1	1	4	2	3	0	0	0	2	627	700	1161	1	6	0	0	1	0	0

Physical Tests

Sample Number	Oil Mfr.	Oil Brand	Oil Grade	Comp. Service	Oil Service	Units	Oil Chg	Water %	Glycol	Visc 40°C cSt	Visc 100°C cSt	Fuel %	Solids %
New Oil:	MOB	DSG	15W40							116.	14.81		
09/17–316	MOB	DSG	15W40	260	250	?	?	N	N	112.	14.76		
09/14–184	MOB	DSG	15W40	210	200	?	?	N	N	111.	14.23		
09/14–186	MOB	DSG	15W40	160	150	?	?	N	N	112.	14.43		
09/14–185	MOB	DSG	15W40	111	101	?	?	PR	N	107.	14.27		
09/07–355	MOB	DSG	15W40	60	50	?	?	N	N	104.	14.22		
09/07–356	MOB	DSG	15W40	20	10	?	?	N	N	104.	14.37		

Additional Tests

TBN D2896 (mgKOH/g)	TAN D664 (mgKOH/g)	NIT (A/cm)	OX (A/cm)
5.50	1.85		
3.85	4.19R	10.0	24.0R
		8.00	26.0U
3.26	4.85U	10.0	24.0R
		8.00	20.0R
		5.00	17.0
		1.00	17.0

Results

1) Iron = 12.2 ppm; copper = 71.1 ppm; chrome = 2.3 ppm.
2) Total Acid and Oxidation can cause dramatic reductions in component life. Also, note the flagged element Copper.

Chart B - Fluid Life Corp. laboratory oil analysis data sheet, Run-1

Recommendations

1) Flagged TAN (Total Acid Number) indicates additive consumption. Either monitor TAN regularly or change oil and filters.
2) Copper could be generated from an oil additive, oil cooler, oil pump, governor, thread seal or from component.

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2 RUTTER CRESCENT
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Unit Data

Unit # : AD5.9
Component : ENGINE
Location : MAIN
Manufacturer : CUMMINS
Serial # : 45406154
Model : G6B7A5.9

Lubricant

Manufacturer : MOBIL
Brand : D.S. GEO
Grade : 15W40

Sample : 10/04–300

Fluid Life
Oil Analysis

9321 - 48 Street
Edmonton, Alberta T6B 2R4
Phone: (780) 462-2400
Fax: (780) 462-2420

CODE: Y - Yes N - Negative P - Positive R - Reportable U - Unacceptable S - Severe I - Insufficient Sample > - More Than < - Less Than

Spectro-chemical (ppm)

Sample Number	Sample Date	Silicon	Sodium	Potassium	Iron	Chrome	Lead	Copper	Tin	Aluminum	Nickel	Silver	Titanium	Boron	Phosphorus	Zinc	Calcium	Barium	Magnesium	Molybdenum	Vanadium	Antimony	Lithium	Beryllium
New Oil:		2	0	3	0	0	1	0	0	2	0	0	0	1	579	629	1066	0	5	0	0	0	0	0
10/04–300	1999/10/01	6	0	1	7	2	7	33R	0	3	0	0	0	2	585	837	1479	0	7	0	0	0	0	0
09/30–170	1999/09/28	5	0	1	6	2	5	33R	1	3	0	0	0	3	542	783	1384	0	7	0	0	0	0	0
09/28–189	1999/09/26	5	0	6	5	2	2	29R	2	2	0	0	0	1	563	753	1342	0	7	0	0	0	0	0
09/28–188	1999/09/24	5	0	7	5	1	0	9	0	2	0	0	0	1	558	731	1293	0	7	0	0	0	0	0
09/21–344	1999/09/17	4	0	7	3	1	0	8	0	2	0	0	0	1	599	718	1260	0	6	0	0	0	0	0
09/17–317	1999/09/15	3	0	4	2	0	0	6	0	2	0	0	0	2	617	687	1200	0	6	0	0	0	0	0

Physical Tests

Sample Number	Oil Mfr.	Oil Brand	Oil Grade	Comp. Service	Oil Service	Units	Oil Chg	Water %	Glycol	Visc 40°C cSt	Visc 100°C cSt	Fuel %	Solids %
New Oil:	MOB	DSG	15W40							116.	14.81		
10/04–300	MOB	DSG	15W40	510	250	HR	?	N	N	113.	14.55		
09/30–170	MOB	DSG	15W40	457	197	HR	?	N	N	110.	14.59		
09/28–189	MOB	DSG	15W40	409	149	?	?	N	N	112.	15.00		
09/28–188	MOB	DSG	15W40	359	99	?	?	N	N	108.	14.55		
09/21–344	MOB	DSG	15W40	307	47	?	?	N	N	108.	14.29		
09/17–317	MOB	DSG	15W40	270	10	?	Y	N	N	108.	14.54		

Additional Tests

TBN D2896 (mgKOH/g)	TAN D664 (mgKOH/g)	NIT (A/cm)	OX (A/cm)		
5.50	1.85				
2.89	4.42	11.0	25.0U		
		10.0	25.0U		
3.53	2.92	11.0	23.0R		
		8.00	20.0R		
		5.00	17.0		
		3.00	17.0		

Results

1) Iron = 6.7 ppm; copper = 32.6 ppm; chrome = 1.8 ppm.
2) Oxidation can cause dramatic reductions in component life. Also, note the flagged element Copper.

Chart C - Fluid Life Corp. laboratory oil analysis data sheet, Run-2

Recommendations

1) Copper could be generated from an oil additive, oil cooler, oil pump, governor, thread seal or from component.
2) Resample next interval to monitor.

Table I- Summary of Indicated ICP oil analysis data for Cummins B5.9L engine.

Apparent Engine Wear Rates from Inductively Coupled Plasma (ICP) Spectrometry apply to prior time interval and are quoted in parts per million per 1,000 hours (ppm/khr)

Dynamometer Durability Testing conducted at Rated Horsepower and RPM by Bodycote ORTECH, Mississauga ON. Oil Analysis by Fluid Life Corp., Edmonton AB.

Sample Date	Lab. No.	Test No.	Engine Hours	Oil Hr.	Silicon Si ppm	Si Wear Rate ppm/khr	Iron Fe ppm	Fe Wear Rate ppm/khr	Chrome Cr ppm	Cr Wear Rate ppm/khr	Lead Pb ppm	Pb Wear Rate ppm/khr	Copper Cu ppm	Cu Wear Rate ppm/khr	Tin Sn ppm	Sn Wear Rate ppm/khr	Alum. Al ppm	Al Wear Rate ppm/khr	Neut. No's TBN	Neut. No's TAN	Infra-Red Nit.	Infra-Red Ox.	Viscosity 40°C cSt	Viscosity 100°C cSt
NEW OIL, MOBIL DELVAC SUPER GEO 15W-40																								
99/06/13	05/17-147	A-New	-	0	2		0.2		0.2		1		0		0		2		5.50	1.85	1	17	116	14.8
CONDITIONING/ FLUSH RUN																								
99/06/23	06/24-158	AP"0"	10	10	20	Flush	2.6		0.6		1		2.5		0		2				2	17	105	14.4
START, DURABILITY RUN 1																								
99/08/31	09/07-356	AR10	20	10	12	Ref.1	7.6	Ref.1	0.7	Ref.1	1	Ref.1	4.1	Ref.1	2	Ref.1	3	Ref.1	5.34	2.25	1	17	104	14.6
99/09/03	09/07-355	A50	60	50	16	100	9.2	40.0	1.2	12.5	1	0	7.0	73	2	0	3	0.0			5	17	104	14.2
99/09/07	09/14-185	A100	111	101	15	-20	10.8	31.4	1.9	13.7	1	0	21.7	288	1	-20	2	-20			8	20	107	14.3
99/09/10	09/14-186	A150	160	150	16	20	11.8	20.4	2.1	4.1	4	61	64.4	871	0	-20	2	0	3.26	4.85	10	24	112	14.4
99/09/12	09/14/184	A200	210	200	15	-20	12.5	14.0	2.3	4.0	7	60	78.5	282	0	0	3	20			8	26	111	14.2
99/09/15	09/17-316	A250	260	250	14	-20	12.2	-6.0	2.2	-2.0	8	20	71.1	-148	0	0	4	20	3.85	4.19	10	24	112	14.8
START, DURABILITY RUN 2																								
99/09/15	09/17-317	AR260	270	10	3	Ref.2	1.6	Ref.2	0.4	Ref.2	0	Ref.2	6.2	Ref.2	0	Ref.2	2	Ref.2			3	17	108	14.5
99/09/17	09/21-344	A300	307	47	4	27	2.6	27.0	0.6	5.4	0	0	7.6	38	0	0	2	0			5	17	108	14.3
99/09/24	09/28-188	A350	359	99	5	19	4.9	44.2	1.4	15.4	0	0	9.5	37	0	0	2	0			8	20	108	14.6
99/09/26	09/28-189	A400	409	149	5	0	5.4	10.0	1.5	2.0	2	40	28.6	382	2	40	2	0	3.53	2.92	11	23	112	15.0
99/09/28	09/30-170	A450	457	197	5	0	5.9	10.4	1.7	4.2	5	63	33.2	96	1	-21	3	21			10	25	110	14.6
99/10/01	99/04/300	A500	510	251	6	18	6.7	15.1	1.8	1.8	7	37	32.6	-11	0	-18	3	0	2.89	4.42	11	25	113	14.6

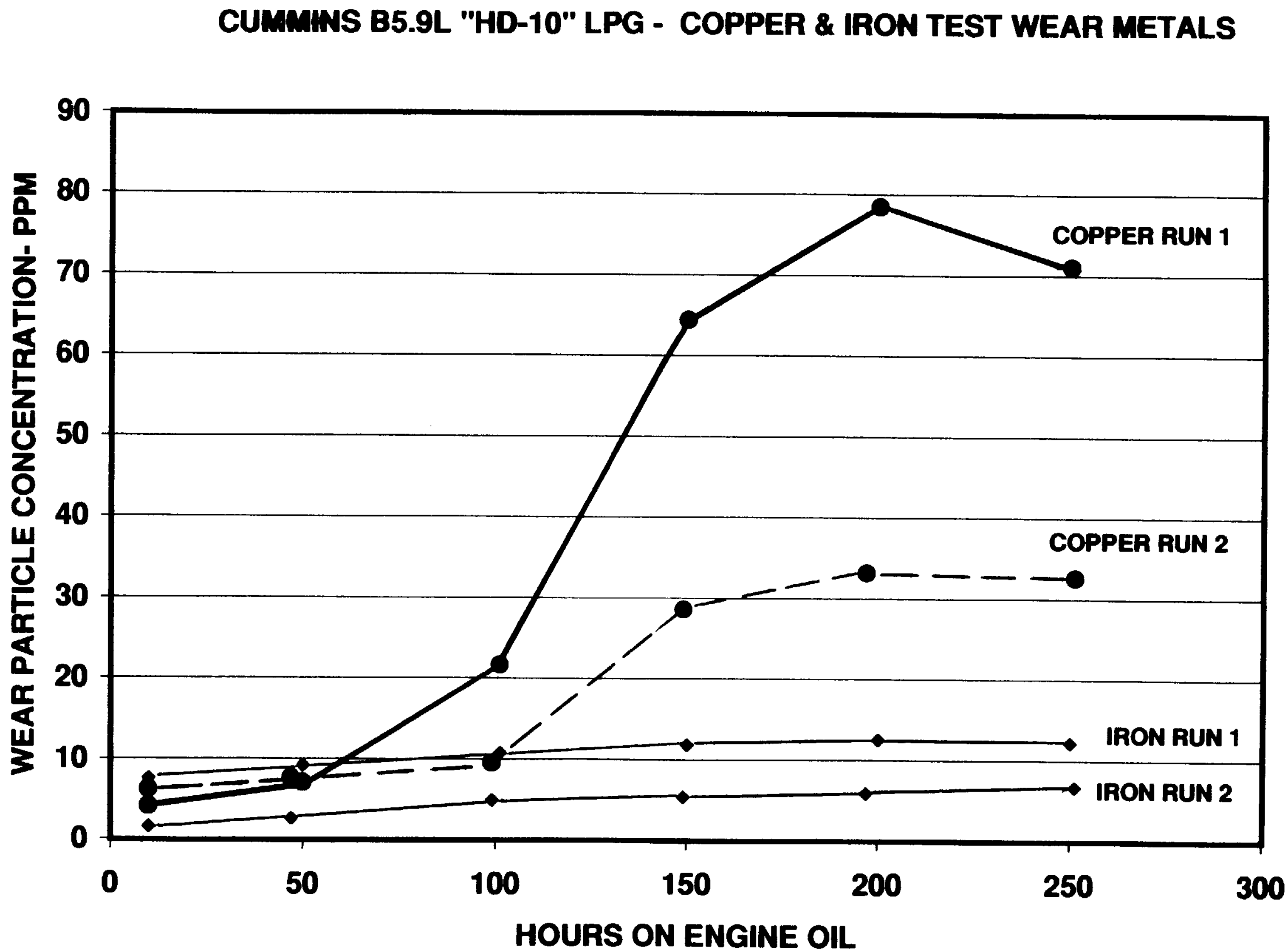


Figure 1- Graph of Spectrometry Copper and Iron concentrations for Runs 1 and 2.

Table II- Cummins B5.9 L LPG Engine Oil Consumption Summary

Date yy/mm/dd	Engine hrs	Consumption (Litres) Added	Consumption (Litres) Cumulative	Oil sample taken	Note
99-09-01	22:36	1.25	1.25		
99-09-02	37:02:00	0.55	1.80	99-09-03	
99-09-03	60:00:00	1.00	2.80		
99-09-04	87:00:00	1.00	3.80		
99-09-07	109:00:00	0.50	4.30	99-09-07	
99-09-09	134:45:00	1.00	5.30	99-09-10	
99-09-10	160:00:00	1.30	6.60		
99-09-11	175:44:00	0.50	7.10	99-09-12	
99-09-12	210:03:00	1.50	8.60		
99-09-13	225:00:00	0.50	9.10		
99-09-14	241:32:00	1.25	10.35	99-09-15	
99-09-15	260:00:00	0.00	0.00		oil & filter changed
99-09-15	269:43:00	0.00	0.00	99-09-15	
99-09-16	281:47:00	1.25	1.25	99-09-17	
99-09-17	307:19:00	1.00	2.25		
99-09-22	330:01:00	0.90	3.15		
99-09-23	342:22:00	0.50	3.65		
99-09-24	349:51:00	0.80	4.45	99-09-24	
99-09-25	373:00:00	1.00	5.45	99-09-26	
99-09-28	442:42:00	0.60	6.05	99-09-28	
99-09-28	456:00:00	0.75	6.80		
99-09-30	490:20:00	1.10	7.90		
99-10-04	510:00:00	1.65	9.55	99-10-04	

Summary:	Summary to last oil change (before 260 engine hours):		
	Total makeup oil	10.35	litres
	Total samples drawn:	1.80	litres
	Oil consumption:	8.55	litres
	Engine hours:	256.00	hours
	Oil consumption per hour	0.033	Litre/hour
	Oil consumption per day	0.802	Litre/day
	Summary since last oil change (after 260 engine hours):		
	Total makeup oil since last oil change:	9.55	litres
	Total samples drawn:	1.80	litres
	Oil consumption:	7.75	litres
	Engine hours:	255.50	hours
	Oil consumption per hour	0.030	Litre/hour
	Oil consumption per day	0.728	Litre/day
Average oil consumption for the 500 hrs. durability test (511.5 hours)		**0.032** **0.765**	**litres/hour** **litres/day**

5. TRUE WEAR RATE ANALYSIS DATA

The "True Wear" computer program was employed to determine the true wear rates of the four most significant wear metals, copper, iron, lead and chromium.

Table III - "True Wear" Copper particle wear-rates for Runs 1 and 2 adjusted for make-up oil. Note the high Cu wear rate of 1010 ppm/khr calculated between 100 and 150 test hours. A 63% decrease in these <5µm Cu particles in Run-2 was detected by ICPS.

Figure 2 - Graph of Copper True Wear Rate versus Engine Hours.
The high rate of generation of copper particles (>1000 ppm/khr) is alarming.

Table IV - "True Wear" Iron particle wear-rates for Runs 1 and 2.
Average Fe wear rate is normal (25 ppm/1000hr), and rises only slightly (3%) in the second run.

Figure 3 – Graph of Fe True Wear Rate versus Engine Hours.
Cylinder wall normal wear particles are the main source of ICPS iron.

Table V - "True Wear" Lead particle wear-rates for Runs 1 and 2. Lead ICPS detection is more difficult, but averaged about 35 ppm/khr dropping 7% in Run-2.

Figure 4 – Graph of Lead metal True Wear Rate versus Engine Hours.
Babbitt bearing metal would be the main source of this lead, only generated after 100 oil hours in both runs.

Table VI - "True Wear" Chrome particle wear-rates for Runs 1 and 2.
Chrome wear levels dropped 13%, from 8.0 ppm/khr in Run-1 to 7.0 ppm/khr in Run-2.

Figure 5 – Graph of Chromium true wear rate versus Engine Hours.
Upper piston compression rings are usually the main source of this chrome.

TABLE III - "TRUE WEAR " COPPER COMPUTATIONS CONSIDERING OIL LOSSES, ADDITIONS, AND LEVELS

Sample Number	Engine Start hrs	Engine End Hrs	OIL Test hr Run	OIL Test hr Interval	OIL Start Litres	Samp. Vol.	Add L Cumulative	L Low	Test L	Copper Test ppm	Ref. ppm	Net ppm Test - Ref.	Add ppm Dilution Cor.	Copper TRUE ppm	Interval True Wear Rate ppm/1000hr	Apparent WEAR Factor
RUN 1 - ADEPT HD-10 CUMMINS "TRUE WEAR RATE" COMPARED TO APPARENT WEAR FACTORS																
AR10	10	20	10	10	16.4	0.3	0.00	0.30	16.1	4.1	4.1	0.0	0.0	0.0	**0.0**	**0.0**
A50	20	60	50	40	16.1	0.3	1.80	1.00	15.4	7.0	4.1	2.9	3.2	3.0	**75.1**	**72.5**
A100	60	111	101	51	16.4	0.3	4.30	1.00	15.4	21.7	4.1	17.6	21.3	20.0	**333.9**	**288.2**
A150	111	160	150	49	16.4	0.3	5.30	1.30	15.1	64.4	4.1	60.3	75.0	69.5	**1009.9**	**871.4**
A200	160	210	200	50	16.4	0.3	7.10	1.50	14.9	78.5	4.1	74.4	96.9	88.8	**384.9**	**282.0**
A250	210	260	250	50	16.4	0.3	10.35	0.60	15.8	71.1	4.1	67.0	92.9	89.6	**17.7**	**-148.0**
Run Avg	10	260	250	250	16.4	1.8	10.35	0.60	15.8	71.1	4.1	67.0	92.9	89.6	**358.6**	**284.4**
RUN 2 - ADEPT HD-10 CUMMINS "TRUE WEAR RATE" COMPARED TO APPARENT WEAR FACTORS																
AR260	260	270	10	10	16.4	0.3	0.00	0.30	16.1	6.2	6.2	0.0	0.0	0.0	**0.0**	**0.0**
A300	270	307	47	37	16.1	0.3	1.25	1.00	15.4	7.6	6.2	1.4	1.5	1.4	**38.2**	**37.8**
A350	307	359	99	52	16.4	0.3	4.45	1.00	15.4	9.5	6.2	3.3	4.0	3.8	**45.4**	**36.5**
A400	360	409	149	50	16.4	0.3	5.45	0.60	15.8	29.0	6.2	22.8	28.5	27.5	**474.1**	**398.0**
A450	409	457	197	48	16.4	0.3	6.10	0.75	15.7	33.2	6.2	27.0	34.3	32.8	**111.2**	**87.5**
A500	457	510	250	53	16.4	0.3	9.55	1.65	14.8	32.6	6.2	26.4	36.1	32.8	**0.0**	**-11.3**
Run Avg	260	510	250	250	16.4	1.8	9.55	1.65	14.8	32.6	6.2	26.4	36.1	32.8	**131.26**	**105.60**
Copper Wear Reductions in second Run #2 compared to first Run #1															**63.4%**	**62.9%**

TABLE IV - "TRUE WEAR " IRON COMPUTATIONS CONSIDERING OIL LOSSES, ADDITIONS, AND LEVELS

Sample Number	Engine Start hrs	Engine End Hrs	OIL Test hr Run	OIL Test hr Interval	OIL Start Litres	Samp. Vol.	Add L Cumulative	L Low	Test L	Iron Test ppm	Ref. ppm	Net ppm Test - Ref.	Add ppm Dilution Cor.	Iron TRUE ppm	Interval True Wear Rate ppm/1000hr	Apparent WEAR Factor
RUN 1 - ADEPT HD-10 CUMMINS "TRUE WEAR RATE" COMPARED TO APPARENT WEAR FACTORS																
AR10	10	20	10	10	16.4	0.3	0.00	0.30	16.1	7.6	7.6	0.0	0.0	0.0	**0.0**	**0.0**
A50	20	60	50	40	16.1	0.3	1.80	1.00	15.4	9.2	7.6	1.6	1.8	1.7	**41.4**	**40.0**
A100	60	111	101	51	16.4	0.3	4.30	1.00	15.4	10.8	7.6	3.2	3.9	3.6	**38.9**	**31.4**
A150	111	160	150	49	16.4	0.3	5.30	1.30	15.1	11.8	7.6	4.2	5.2	4.8	**24.5**	**20.4**
A200	160	210	200	50	16.4	0.3	7.10	1.50	14.9	12.5	7.6	4.9	6.4	5.8	**20.1**	**14.0**
A250	210	260	250	50	16.4	0.3	10.35	0.60	15.8	12.2	7.6	4.6	6.4	6.2	**6.2**	**-6.0**
Run Avg.	10	260	250	250	16.4	1.8	10.35	0.60	15.8	12.2	7.6	4.6	6.4	6.2	**24.6**	**18.4**
RUN 2 - ADEPT HD-10 CUMMINS "TRUE WEAR RATE" COMPARED TO APPARENT WEAR FACTORS																
AR260	260	270	10	10	16.4	0.3	0.00	0.30	16.1	1.6	1.6	0.0	0.0	0.0	**0.0**	**0.0**
A300	270	307	47	37	16.1	0.3	1.25	1.00	15.4	2.6	1.6	1.0	1.1	1.0	**27.3**	**27.0**
A350	307	359	99	52	16.4	0.3	4.45	1.00	15.4	4.9	1.6	3.3	4.0	3.8	**53.2**	**44.2**
A400	360	409	149	50	16.4	0.3	5.45	0.60	15.8	5.4	1.6	3.8	4.7	4.6	**16.1**	**10.2**
A450	409	457	197	48	16.4	0.3	6.10	0.75	15.7	5.9	1.6	4.3	5.5	5.2	**13.5**	**10.4**
A500	457	510	250	53	16.4	0.3	9.55	1.65	14.8	6.7	1.6	5.1	7.0	6.3	**21.0**	**15.1**
Run Avg.	260	510	250	250	16.4	1.8	9.55	1.65	14.8	6.7	1.6	5.1	7.0	6.3	**25.4**	**20.4**
Iron Wear Increases in second Run #2 compared to first Run #1															**3.0%**	**10.9%**

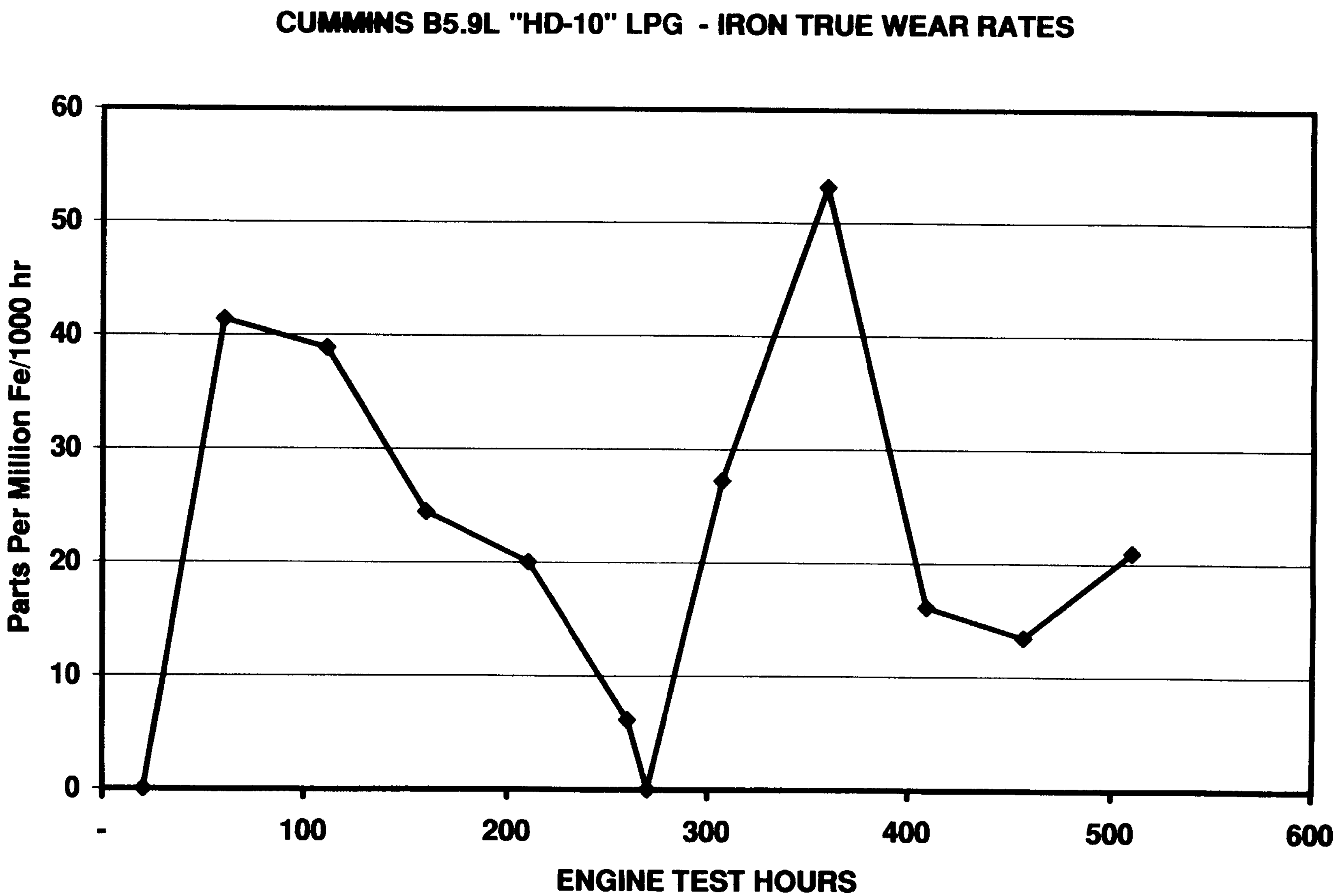


Figure 3 – Graph of Fe True Wear Rate versus Engine Hours.

TABLE V - "TRUE WEAR " LEAD COMPUTATIONS CONSIDERING OIL LOSSES, ADDITIONS, AND LEVELS

Sample Number	Engine Start hrs	Engine End Hrs	OIL Test hr Run	OIL Test hr Interval	OIL Start Litres	Samp. Vol.	Add L Cumulative	L Low	Test L	LEAD Test ppm	Ref. ppm	Net ppm Test - Ref.	Add ppm Dilution Cor.	LEAD TRUE ppm	Interval True Wear Rate ppm/1000hr	Apparent WEAR Factor
RUN 1 - ADEPT HD-10 CUMMINS "TRUE WEAR RATE" TO APPARENT WEAR FACTOR RATIOS																
AR10	10	20	10	10	16.4	0.3	0.00	0.30	16.1	1.0	1.0	0.0	0.0	0.0	**0.0**	**0.0**
A50	20	60	50	40	16.1	0.3	1.80	1.00	15.4	1.0	1.0	0.0	0.0	0.0	**0.0**	**0.0**
A100	60	111	101	51	16.4	0.3	4.30	1.00	15.4	1.0	1.0	0.0	0.0	0.0	**0.0**	**0.0**
A150	111	160	150	49	16.4	0.3	5.30	1.30	15.1	4.0	1.0	3.0	3.7	3.5	**70.6**	**61.2**
A200	160	210	200	50	16.4	0.3	7.10	1.50	14.9	7.0	1.0	6.0	7.8	7.2	**74.0**	**60.0**
A250	210	260	250	50	16.4	0.3	10.35	0.60	15.8	8.0	1.0	7.0	9.7	9.4	**44.2**	**20.0**
Run Avg.	10	260	250	250	16.4	1.8	10.35	0.60	15.8	8.0	1.0	7.0	9.7	9.4	**37.5**	**32.0**
RUN 2 - ADEPT HD-10 CUMMINS "TRUE WEAR RATE" TO APPARENT WEAR FACTOR RATIOS																
AR260	260	270	10	10	16.4	0.3	0.00	0.30	16.1	0.0	0.0	0.0	0.0	0.0	**0.00**	**0.00**
A300	270	307	47	37	16.1	0.3	1.25	1.00	15.4	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**
A350	307	359	99	52	16.4	0.3	4.45	1.00	15.4	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**
A400	360	409	149	50	16.4	0.3	5.45	0.60	15.8	2.0	0.0	2.0	2.5	2.4	**48.2**	**40.8**
A450	409	457	197	48	16.4	0.3	6.10	0.75	15.7	5.0	0.0	5.0	6.4	6.1	**76.4**	**62.5**
A500	457	510	250	53	16.4	0.3	9.55	1.65	14.8	7.0	0.0	7.0	9.6	8.7	**49.5**	**37.7**
Run Avg.	260	510	250	250	16.4	1.8	9.55	1.65	14.8	7.0	0.0	7.0	9.6	8.7	**34.80**	**28.00**
Copper Wear Reductions in second Run #2 compared to first Run #1															**7.1%**	**12.5%**

CUMMINS B5.9L "HD-10" LPG - LEAD TRUE WEAR RATES

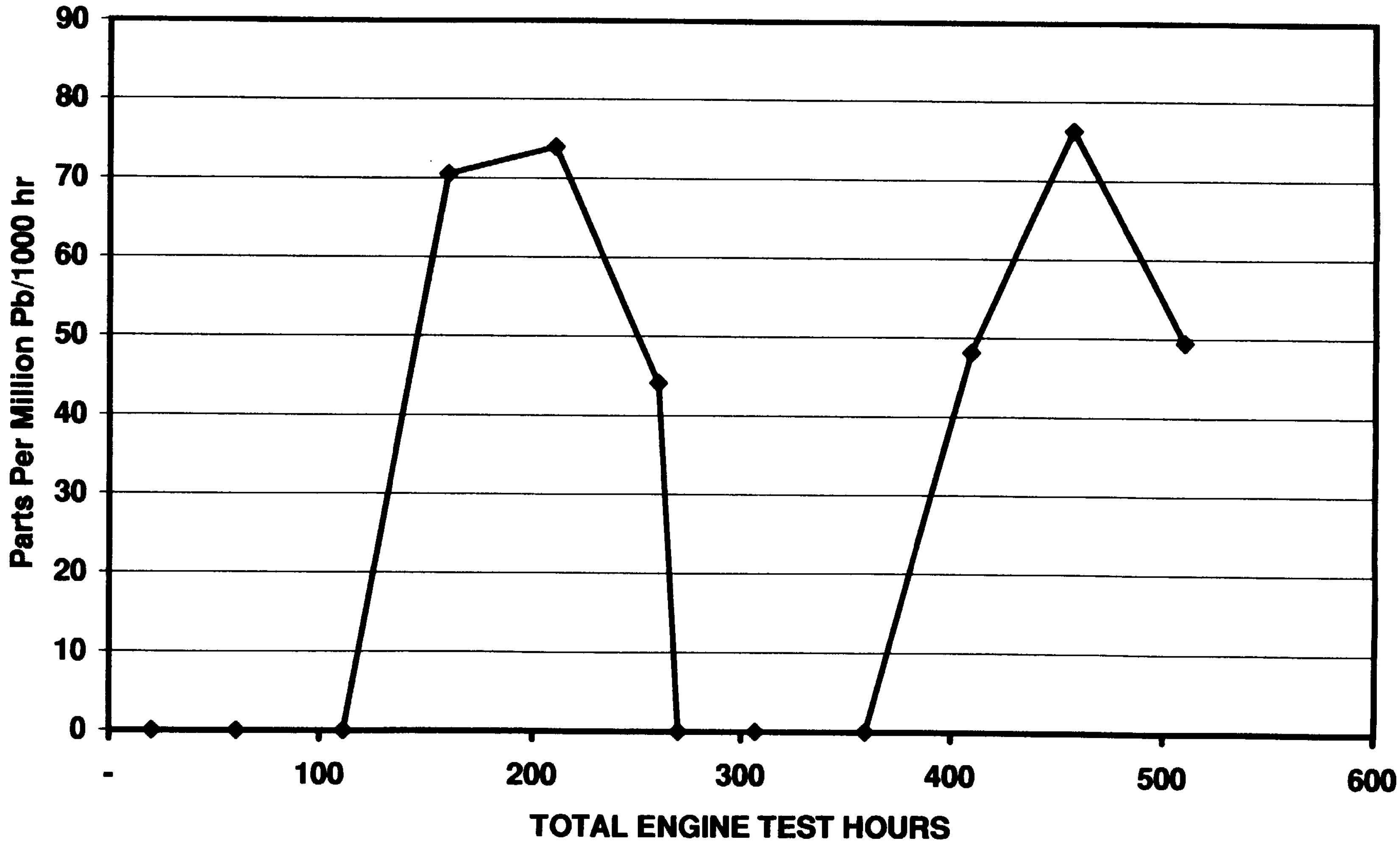


Figure 4 – Graph of Lead metal True Wear Rate versus Engine Hours.

TABLE VI - "TRUE WEAR " CHROME COMPUTATIONS CONSIDERING OIL LOSSES, ADDITIONS, AND LEVELS

Sample Number	Engine Start hrs	Engine End Hrs	OIL Test hr Run	OIL Test hr Interval	OIL Start Litres	Samp. Vol.	Add L Cumulative	L Low	Test L	Chrome Test ppm	Ref. ppm	Net ppm Test - Ref.	Add ppm Dilution Cor.	Chrome TRUE ppm	Interval True Wear Rate ppm/1000hr	Apparent WEAR Factor
RUN 1 - ADEPT HD-10 CUMMINS "TRUE WEAR RATE" COMPARED TO APPARENT WEAR FACTORS																
AR10	10	20	10	10	16.4	0.3	0.00	0.30	16.1	0.7	0.7	0.0	0.0	0.0	**0.0**	**0.0**
A50	20	60	50	40	16.1	0.3	1.80	1.00	15.4	1.2	0.7	0.5	0.6	0.5	**13.0**	**12.5**
A100	60	111	101	51	16.4	0.3	4.30	1.00	15.4	1.9	0.7	1.2	1.4	1.4	**16.6**	**13.7**
A150	111	160	150	49	16.4	0.3	5.30	1.30	15.1	2.1	0.7	1.4	1.7	1.6	**5.1**	**4.1**
A200	160	210	200	50	16.4	0.3	7.10	1.50	14.9	2.3	0.7	1.6	2.1	1.9	**5.9**	**4.0**
A250	210	260	250	50	16.4	0.3	10.35	0.60	15.8	2.2	0.7	1.5	2.1	2.0	**2.0**	**-2.0**
Run Avg.	10	260	250	250	16.4	1.8	10.35	0.60	15.8	2.2	0.7	1.5	2.1	2.0	**8.0**	**8.8**
RUN 2 - ADEPT HD-10 CUMMINS "TRUE WEAR RATE" COMPARED TO APPARENT WEAR FACTORS																
AR260	260	270	10	10	16.4	0.3	0.00	0.30	16.1	0.4	0.4	0.0	0.0	0.0	**0.0**	**0.0**
A300	270	307	47	37	16.1	0.3	1.25	1.00	15.4	0.6	0.4	0.2	0.2	0.2	**5.5**	**5.4**
A350	307	359	99	52	16.4	0.3	4.45	1.00	15.4	1.4	0.4	1.0	1.2	1.1	**18.1**	**15.4**
A400	360	409	149	50	16.4	0.3	5.45	0.60	15.8	1.5	0.4	1.1	1.4	1.3	**3.6**	**2.0**
A450	409	457	197	48	16.4	0.3	6.10	0.75	15.7	1.7	0.4	1.3	1.7	1.6	**5.3**	**4.2**
A500	457	510	250	53	16.4	0.3	9.55	1.65	14.8	1.8	0.4	1.4	1.9	1.7	**3.0**	**1.9**
Run Avg.	260	510	250	250	16.4	1.8	9.55	1.65	14.8	1.8	0.4	1.4	1.9	1.7	**7.0**	**5.6**
Chrome Wear Reductions in second Run #2 compared to first Run #1															**13.3%**	**36.4%**

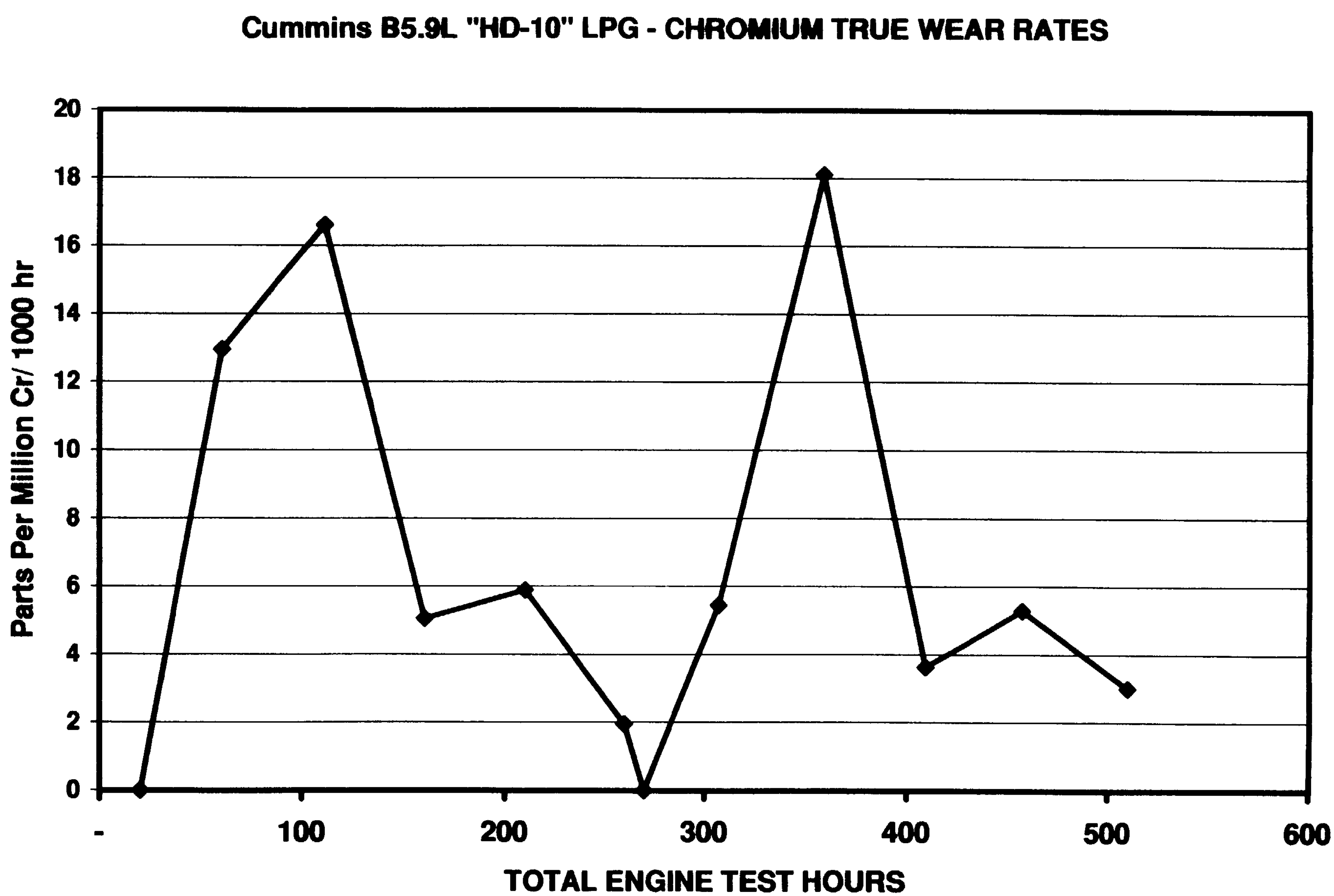


Figure 5 – Graph of Chromium true wear rate versus Engine Hours.

6. FERROGRAPHY and MAGNETIC IRON

The following five figures present the ferrography and magnetic iron concentration data for the larger wear particles generated during this durability study.

Figure 6 – Ferrographic Analysis of used oil at "0" hours, after 10-hr run-in. Note photographs of low and medium alloy steel debris aligned with magnetic field. Traces of copper/copper alloy particles up to 65 µm (0.0026 in.) in size were detected. Magnetic Iron was at 0.2 ug/mL. Morphology of other wear and contaminant particle classes and concentrations are shown by the centrally located bar graphs.

Figure 7- Ferrographic Oil Analysis during Run-1 at 150 hrs under full load. Normal wear particles of low and medium alloy steel show rubbing/sliding, rated at level 5 (moderate). Traces of bearing babbitt up to 30 µm in size were found. Magnetic iron was now measured at 1.17 ug/mL.

Figure 8 – Ferrographic Analysis at 250 hrs, end of Run-1. Debris morphology is similar to 150 hr, mostly low and medium alloy steel. Normal wear still rated moderate at level 5. Magnetic iron has dropped to 0.33 ug/mL, possibly due to oxidation.

Figure 9 – Ferrographic Analysis at 400 engine test hr or 150 Run-2 oil hours. Normal wear is at level 4, identified as mostly rubbing/sliding low and medium alloy steel. Traces of 20 µm babbitt particles were also present.

Figure 10 – Ferrographic Analysis at 500 engine test hr, 250 oil hours, end of Run-2. Normal wear at level 5, mostly steel showing the usual rubbing/sliding, magnetic iron at 1.0 ug/mL with no large (>100 µm) magnetic particles. Some copper particles, up to 20 µm in size were present as shown in the lower microphotograph.

HERTZ ENGINEERING
2 RUTTER CRESCENT
SASKATOON, SASKATCHEWAN
S7H 3B7
Attention : BARRY HERTZ
Phone : (306) 373–2754
Fax : (306) 955–5548

Unit Data

Unit # : AD5.9
Component : ENGINE
Location : MAIN
Manufacturer : CUMMINS
Serial # : 45406154
Model : G6B7A5.9

Lubricant

Manufacturer : MOBIL
Brand : D.S. GEO
Grade : 15W40

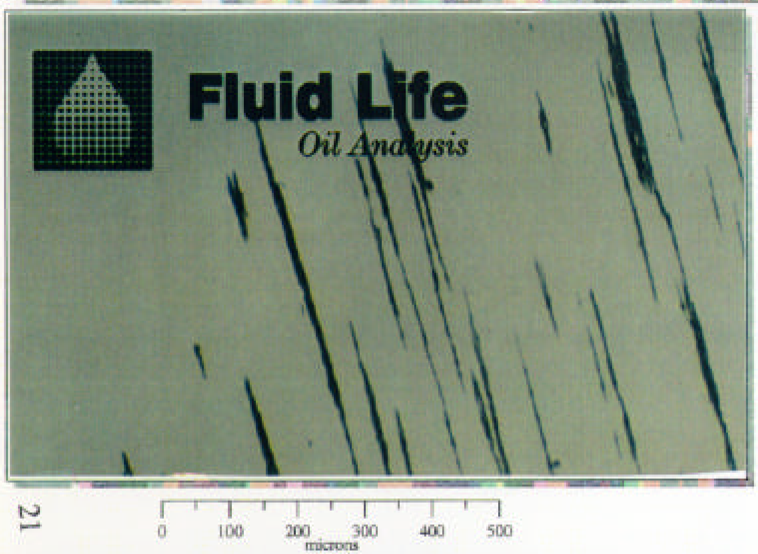
Sample : 06/24–158

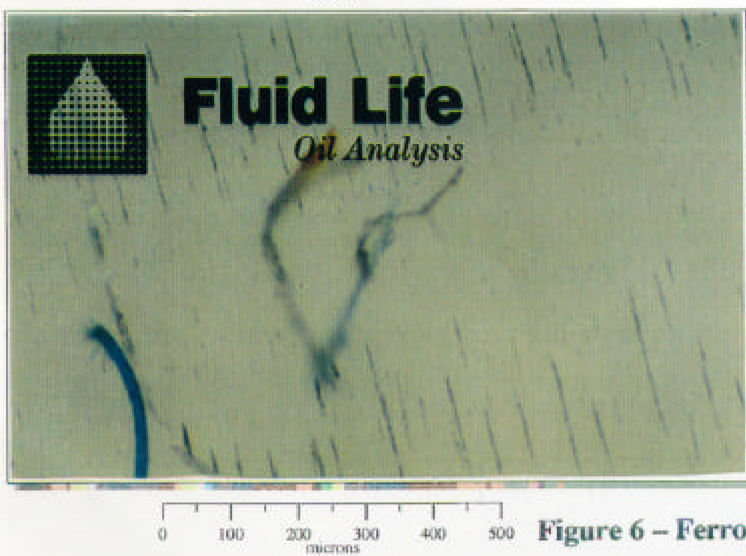
Fluid Life
Ferrography

9321 - 48 Street
Edmonton, Alberta T6B 2R4

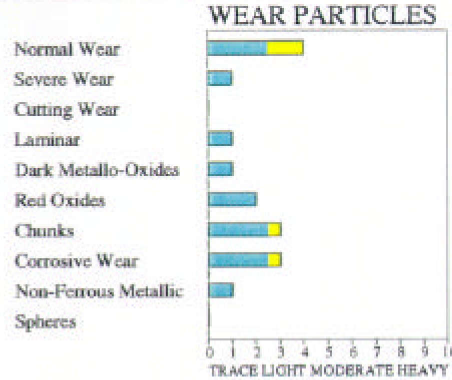
Phone: (780) 462-2400
Fax: (780) 462-2420

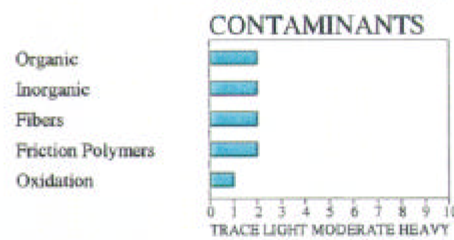
CODE: Y - Yes N - Negative P - Positive R - Reportable U - Unacceptable S - Severe I - Insufficient Sample > - More Than < - Less Than





Particle Description





Comments

Most metal particles are low and medium alloy steel showing rubbing/sliding wear.

Traces of copper/copper alloy particles (up to 65 microns) present in sample.

Magnetic Iron

Sample Date	Small ug/ml	Large ug/ml	Total ug/ml
1999/06/23	0.10	0.10	0.20

Magnetic Iron Trend

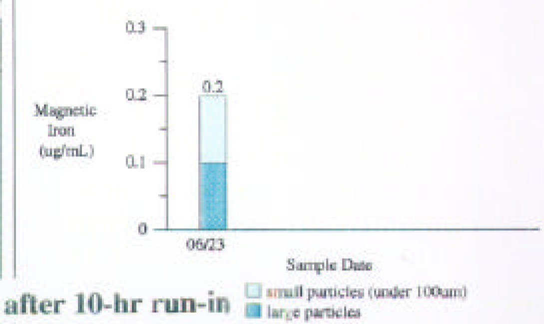


Figure 6 – Ferrographic Analysis of used oil at "0" hours, after 10-hr run-in

HERTZ ENGINEERING
2 RUTTER CRESCENT
SASKATOON, SASKATCHEWAN
S7H 3B7
Attention : BARRY HERTZ
Phone : (306) 373–2754
Fax : (306) 955–5548

Unit Data

Unit # : AD5.9
Component : ENGINE
Location : MAIN
Manufacturer : CUMMINS
Serial # : 45406154
Model : G6B7A5.9

Lubricant

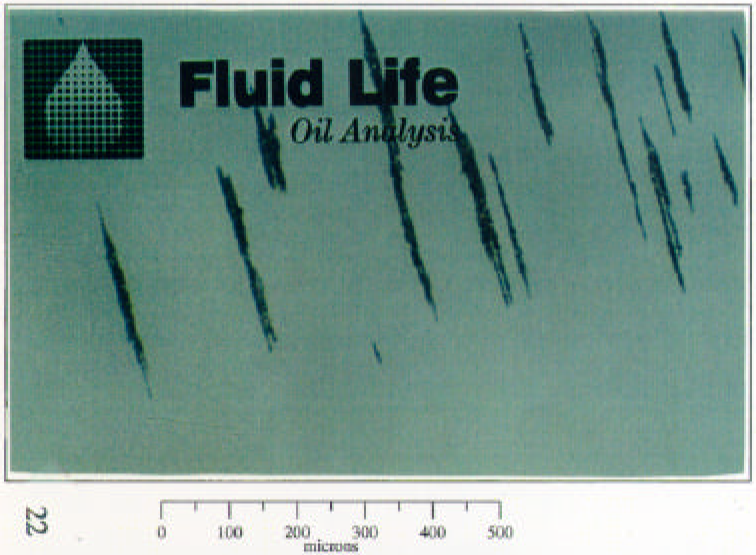
Manufacturer : MOBIL
Brand : D.S. GEO
Grade : 15W40

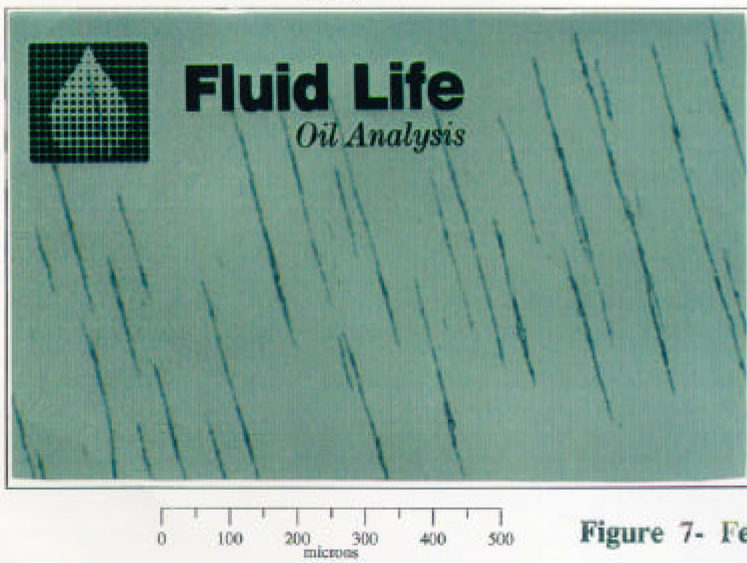
Sample : 09/14–186

Fluid Life *Ferrography*

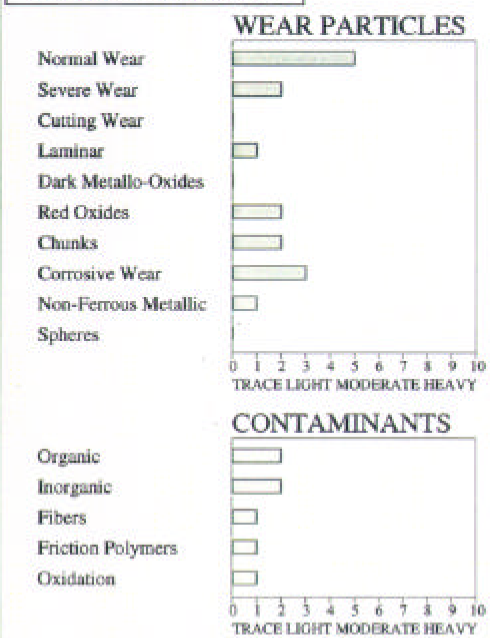
9321 - 48 Street
Edmonton, Alberta T6B 2R4
Phone: (780) 462-2400
Fax: (780) 462-2420

CODE: Y - Yes N - Negative P - Positive R - Reportable U - Unacceptable S - Severe I - Insufficient Sample > - More Than < - Less Than





Particle Description



Comments

Most metal particles are low and medium ally steel showing rubbing/sliding wear.

Traces of babbitt (up to 30 microns) found in debris.

Magnetic Iron

Sample Date	Small ug/ml	Large ug/ml	Total ug/ml
1999/09/10	1.00	0.17	1.17
1999/09/07			
1999/09/03			
1999/08/31			
1999/06/23	0.10	0.10	0.20

Magnetic Iron Trend

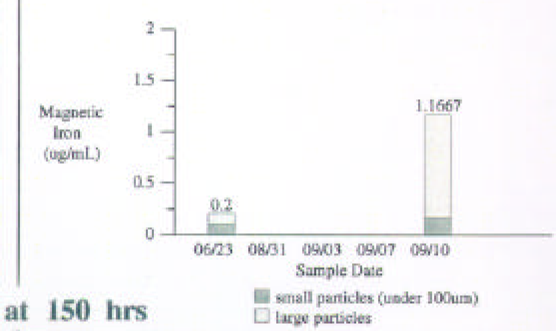


Figure 7- Ferrographic Oil Analysis during Run-1 at 150 hrs

HERTZ ENGINEERING
2 RUTTER CRESCENT
SASKATOON, SASKATCHEWAN
S7H 3B7
Attention : BARRY HERTZ
Phone : (306) 373-2754
Fax : (306) 955-5548

Unit Data

Unit # : AD5.9
Component : ENGINE
Location : MAIN
Manufacturer : CUMMINS
Serial # : 45406154
Model : G6B7A5.9

Lubricant

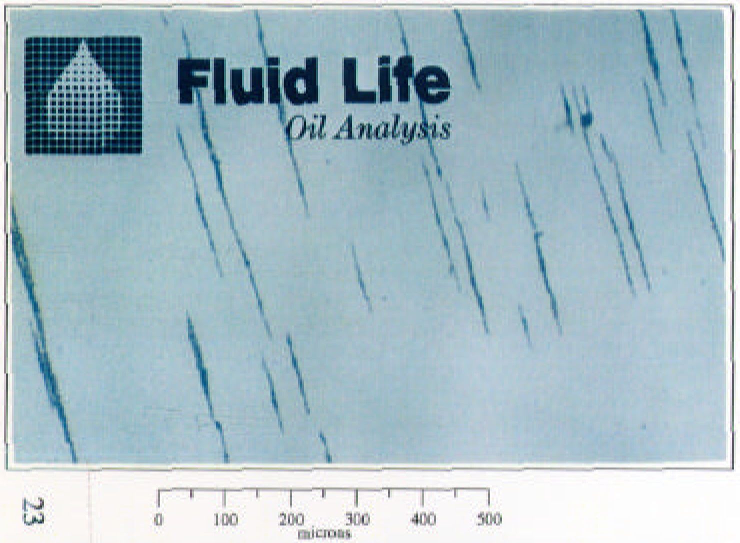
Manufacturer : MOBIL
Brand : D.S. GEO
Grade : 15W40

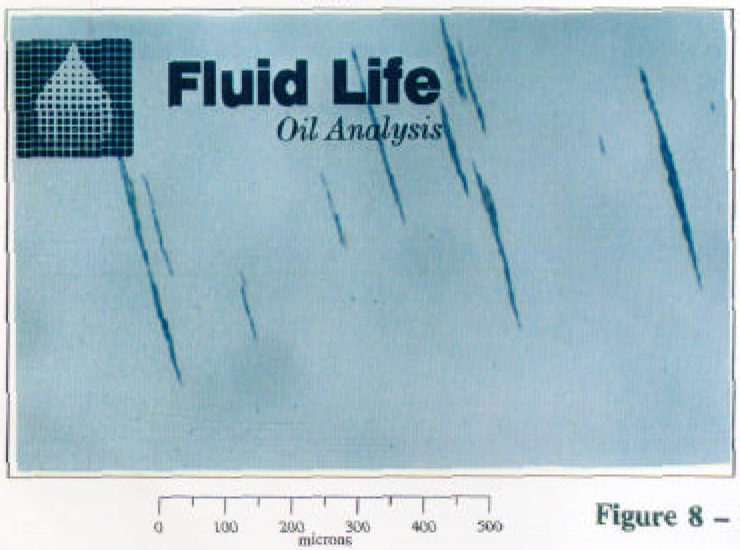
Sample : 09/17-316

Fluid Life *Ferrography*

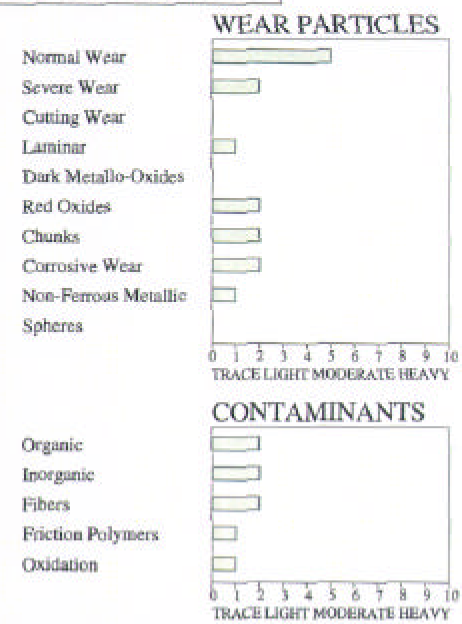
9321 - 48 Street
Edmonton, Alberta T6B 2R4
Phone: (780) 462-2400
Fax: (780) 462-2420

CODE: Y - Yes N - Negative P - Positive R - Reportable U - Unacceptable S - Severe I - Insufficient Sample > - More Than < - Less Than





Particle Description



Comments

Most metal particles are low and medium alloy steel showing rubbing/sliding wear.

Magnetic Iron

Sample Date	Small ug/ml	Large ug/ml	Total ug/ml
1999/09/15	0.17	0.17	0.33
1999/09/12			
1999/09/10	1.00	0.17	1.17
1999/09/07			
1999/09/03			

Magnetic Iron Trend

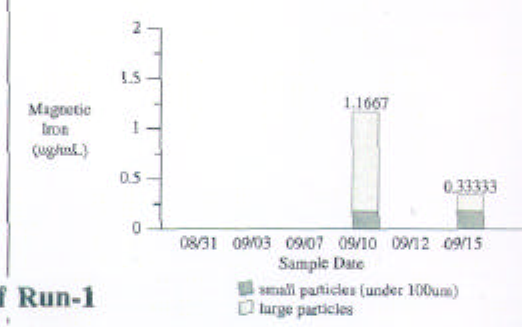


Figure 8 – Ferrographic Analysis at 250 hrs, end of Run-1

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2 RUTTER CRESCENT
SASKATOON, SASKATCHEWAN
S7H 3B7
Attention : BARRY HERTZ
Phone : (306) 373–2754
Fax : (306) 955–5548

Unit Data

Unit # : AD5.9
Component : ENGINE
Location : MAIN
Manufacturer : CUMMINS
Serial # : 45406154
Model : G6B7A5.9

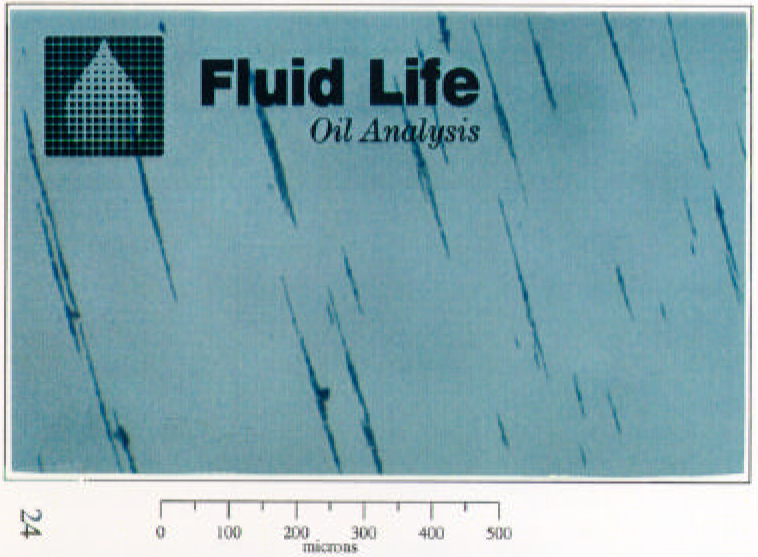
Lubricant

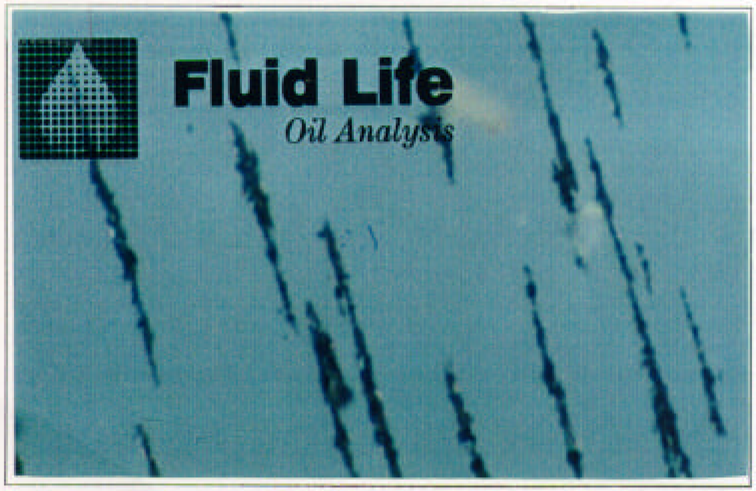
Manufacturer : MOBIL
Brand : D.S. GEO
Grade : 15W40

Sample : 09/28–189

Fluid Life *Ferrography*
9321 - 48 Street
Edmonton, Alberta T6B 2R4
Phone: (780) 462-2400
Fax: (780) 462-2420

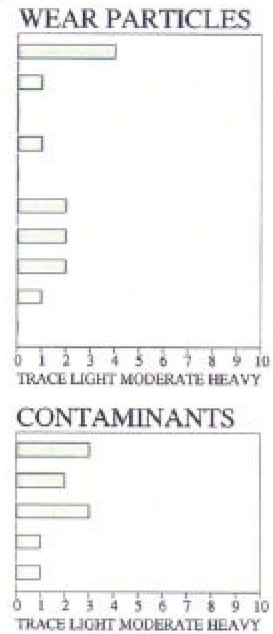
CODE: Y - Yes N - Negative P - Positive R - Reportable U - Unacceptable S - Severe I - Insufficient Sample > - More Than < - Less Than





0 100 200 300 microns

Particle Description



Comments

Most metal particles are low and medium alloy steel showing rubbing/sliding wear.

Traces of babbitt material to 20 microns found in debris.

Magnetic Iron

Sample Date	Small ug/ml	Large ug/ml	Total ug/ml
1999/09/26	0.33	0.00	0.33
1999/09/24			
1999/09/17			
1999/09/15			
1999/09/15	0.17	0.17	0.33

Magnetic Iron Trend

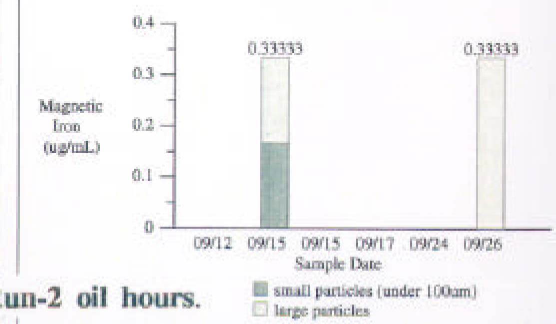


Figure 9 – Ferrographic Analysis at 400 engine test hr or 150 Run-2 oil hours.

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2 RUTTER CRESCENT
SASKATOON, SASKATCHEWAN
S7H 3B7
Attention : BARRY HERTZ
Phone : (306) 373-2754
Fax : (306) 955-5548

Unit Data

Unit # : AD5.9
Component : ENGINE
Location : MAIN
Manufacturer : CUMMINS
Serial # : 45406154
Model : G6B7A5.9

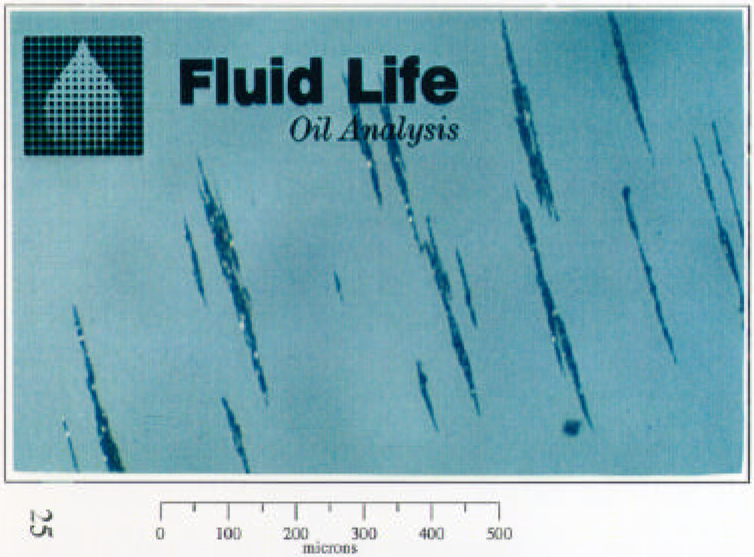
Lubricant

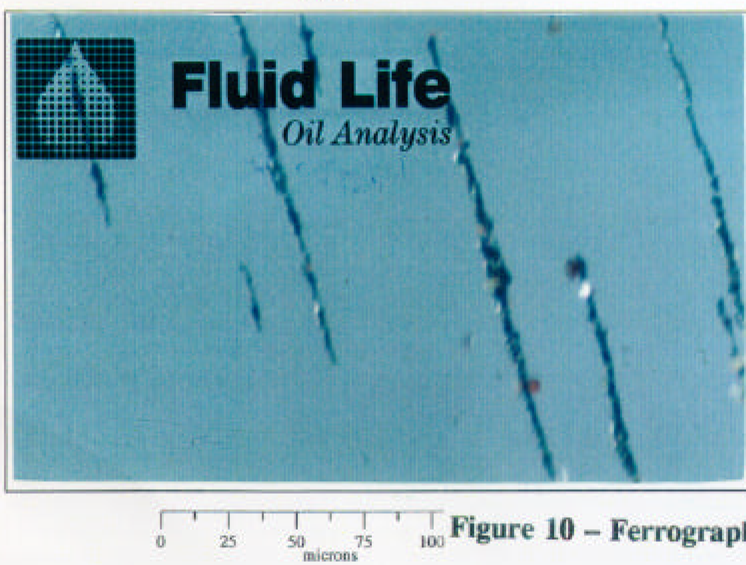
Manufacturer : MOBIL
Brand : D.S. GEO
Grade : 15W40

Sample : 10/04-300

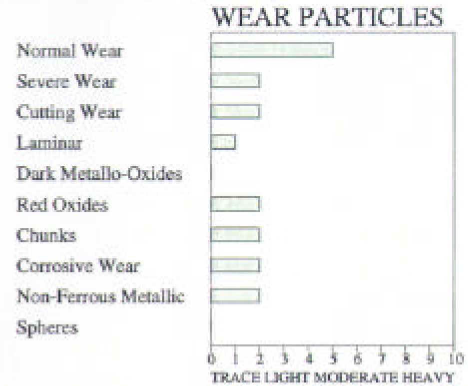
Fluid Life
Ferrography
9321 - 48 Street
Edmonton, Alberta T6B 2R4
Phone: (780) 462-2400
Fax: (780) 462-2420

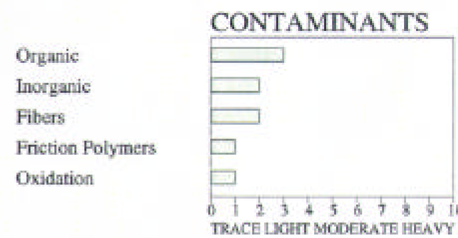
CODE: Y - Yes N - Negative P - Positive R - Reportable U - Unacceptable S - Severe I - Insufficient Sample > - More Than < - Less Than





Particle Description





Comments

Most of the metal particles are low and medium alloy steel showing rubbing/sliding wear.

Some copper/copper alloy particles to 20 microns present.

Traces of cutting wear also found in sample.

Magnetic Iron

Sample Date	Small ug/ml	Large ug/ml	Total ug/ml
1999/10/01	1.00	0.00	1.00
1999/09/28			
1999/09/26	0.33	0.00	0.33
1999/09/24			
1999/09/17			

Magnetic Iron Trend

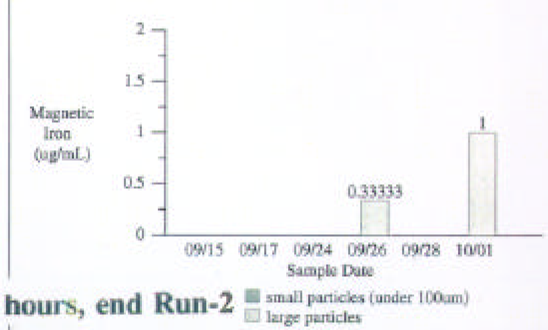


Figure 10 – Ferrographic Analysis at 500 engine test hr, 250 oil hours, end Run-2

7. OIL FILTER ANALYSES

Photographs of the trapped oil filter debris are reported for a new filter and used filters removed after the 10 hour run-in and at the 250 and 500-hour engine test hour oil change points.

Figure 11 – Filter report and debris photos for new Fleetguard LF 3349 oil filter. Only minor dirt, dust and fibers are present.

Figure 12 – Filter report and debris photos for "0" hours, after 10 hour run-in. Note presence of 180 μm size iron and 25 μm copper particles, with dirt, fibers, and rust.

Figure 13 – Filter report and debris photos for 250 hours, end of Run-1. Note major dirt/dust, carbon/soot, iron debris up to 220 μm and copper particles up to 85 μm in size.

Figure 14 – Filter report and debris photos for 500 hours, end of Run-2. Note dirt/dust, higher carbon/soot deposits, and darker brown coloration. Iron particles up to 250 μm, some chrome indicating potential ring wear, more iron particles but no large copper particles.

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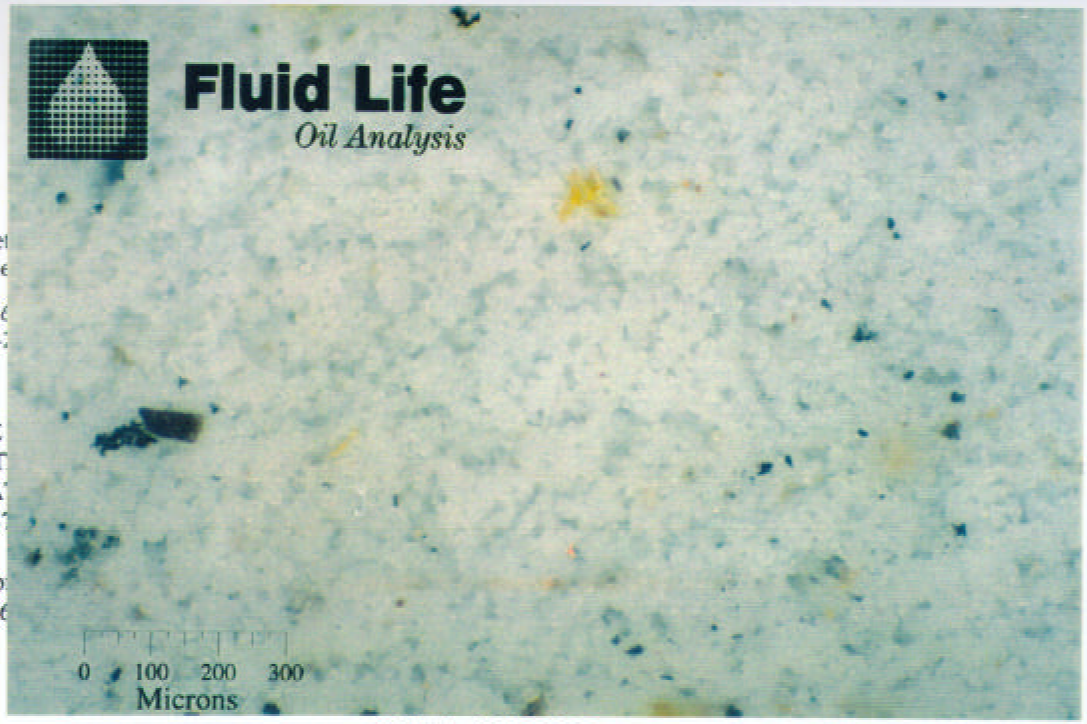

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S7H 3B

Attentio
Fax (306

FILTER ANALYSIS

SAMPLE ID: New filter; 1999/06/24-268

SAMPLE DATE: June 23, 1999

MAJOR CONTAMINATION: Dirt/dust
Fibers

SPECTROGRAPHIC ANALYSIS: n/a

COMMENTS: Filter debris consists of some dirt and a few fibers.

Figure 11 – Filter report and debris photos for new Fleetguard LF 3349 oil filter.

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FILTER ANALYSIS

SAMPLE ID:	AD 5.9 filter; 1999/06/24-158
SAMPLE DATE:	June 23, 1999
MAJOR CONTAMINATION:	Dirt/dust Fibers Dark metallo-oxides
MINOR CONTAMINATION:	Iron particles up to 180 microns Copper/copper alloy particles up to 25 microns Rust
SPECTROGRAPHIC ANALYSIS:	Silicon, iron, and traces of aluminum, copper and tin. Additive type metals include zinc, phosphorous and calcium.

COMMENTS: Most of the filter debris is typical of reservoir contamination.

The fibers in debris matched those found in new filter debris.

Debris is normal for a new system flush.

Figure 12 – Filter report and debris photos for "0" hours, after 10 hour run-in

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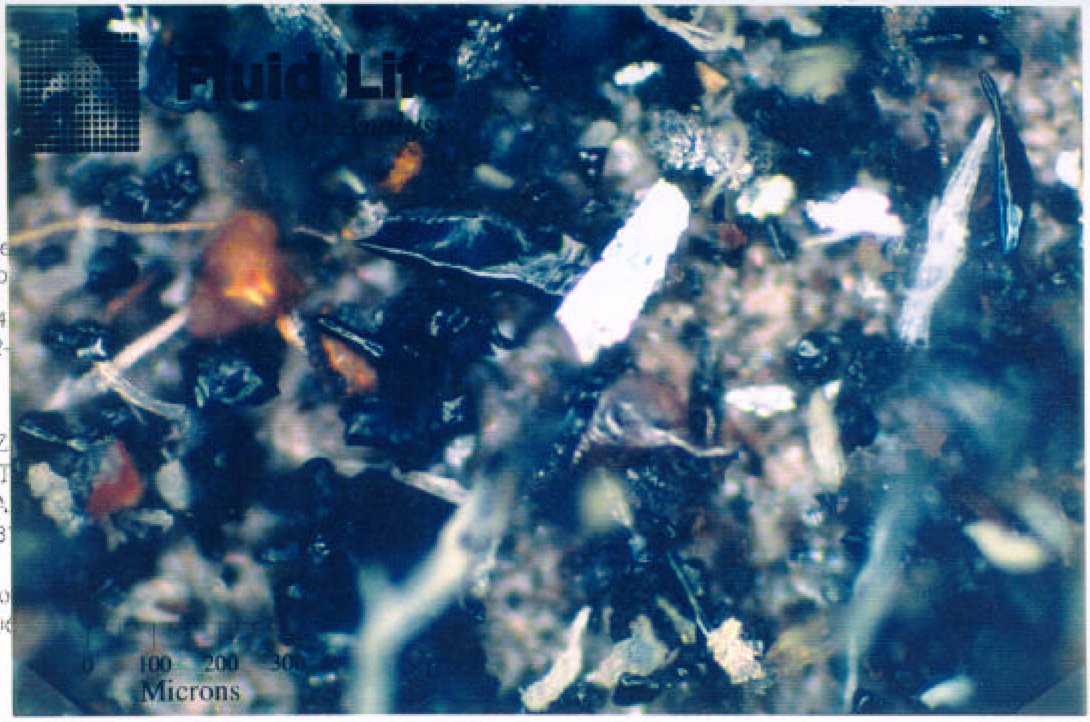

FILTER ANALYSIS

SAMPLE ID:	AD 5.9 filter, 250 hrs; 1999/09/17-320
SAMPLE DATE:	September 17, 1999
MAJOR CONTAMINATION:	Dirt/dust Carbon/soot deposits
MINOR CONTAMINATION:	Iron particles up to 220 microns Copper/copper alloy particles up to 85 microns Fibers
SPECTROGRAPHIC ANALYSIS:	Silicon, iron, copper and traces of lead and tin. Additive type metals include zinc, phosphorous and calcium.

COMMENTS: Dirt/dust and carbon compounds make up most of the debris.

Iron particles (up to 220 microns) show both sliding and laminar wear.

Several large copper/copper alloy (up to 85 microns) show laminar wear.

Figure 13 – Filter report and debris photos for 250 hours, end of Run-1

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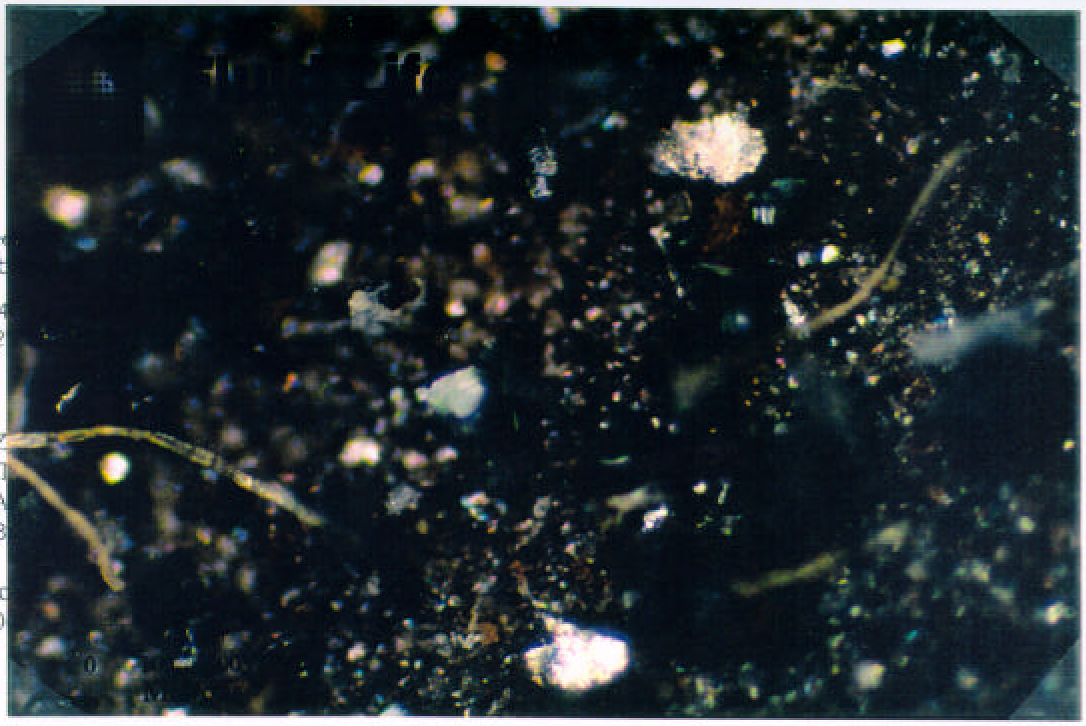

HERTZ
2 RUTT
SASKA
S7H 3B

Attentio
Fax (30

FILTER ANALYSIS

SAMPLE ID: AD 5.9 filter, 500 hrs; 1999/10/08-425

SAMPLE DATE: October 7, 1999

MAJOR CONTAMINATION: Dirt/dust
Carbon/soot deposits

MINOR CONTAMINATION: Iron particles up to 250 microns
Fibers

SPECTROGRAPHIC ANALYSIS: Silicon, iron, copper and traces of lead,tin, and chrome. Additive type metals include zinc, phosphorous and calcium.

COMMENTS: Dirt/dust and carbon compounds make up most of the debris. The carbon type deposits are greater than the last sample.

Iron particles (up to 250 microns) show both sliding and laminar wear. Chrome is detected in latest filter possibly indicating ring wear.

The number of iron particles has increased while large copper/copper alloy particles were not found in this filter.

Figure 14 – Filter report and debris photos for 500 hours, end of Run-2

8. ENGINE OIL CONDITION

Plots of Infrared oxidation and nitration levels are provided along with oil neutralization ability changes as the engine oil accumulated test hours.

Figure 15 – Graph of Oil Infrared Oxidation and Nitration versus Engine Hours. Note the rise in IR absorption with oil hours. The oxidation levels above 25 A/cm are considered unacceptable, but are mitigated by additions of fresh make-up oil.

Figure 16 – Graph of Engine Oil TAN and TBN Neutralization Ability. The Total Base Numbers are depressed with time after each oil change while the oil acidity (TAN) rises to unacceptable high levels beyond 150 oil hours.

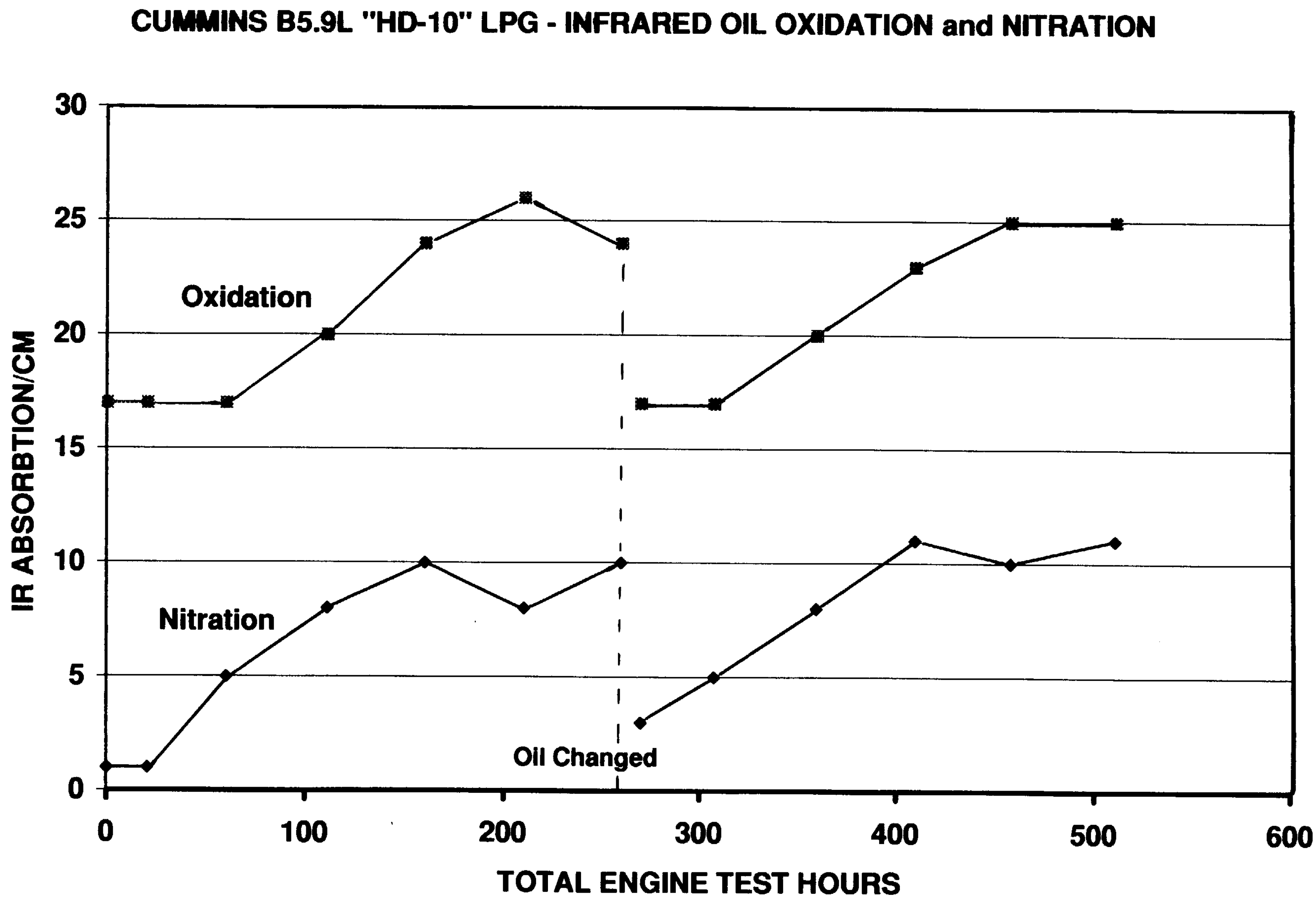

Figure 15 – Graph of Oil Infrared Oxidation and Nitration versus Engine Hours

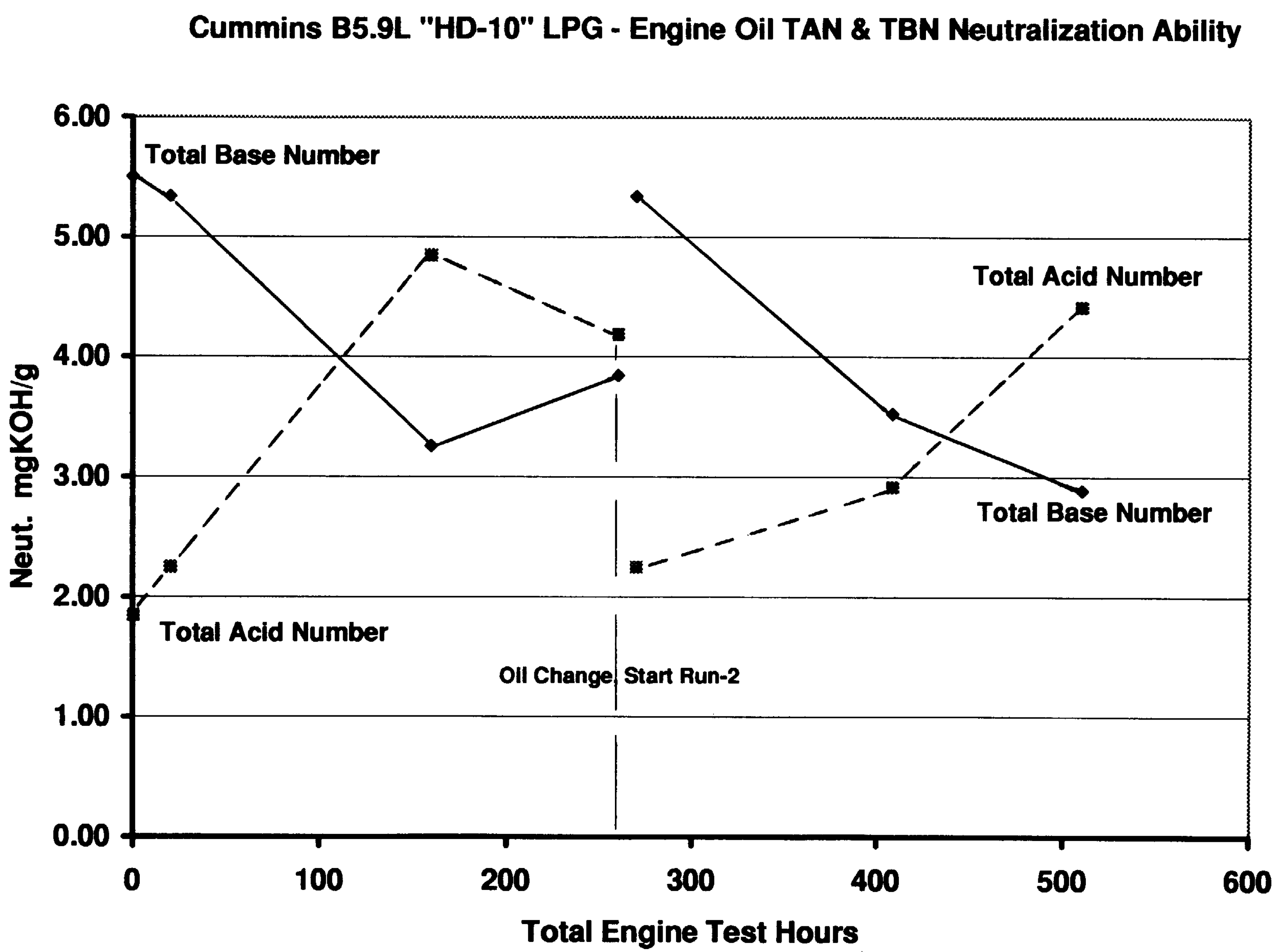

Figure 16 – Graph of Engine Oil TAN and TBN Neutralization Ability

be generated from these sources. Other copper wear component sources could be explored in a more detailed internal engine examination of the camshaft and oil pump bushings. Lacking other evidence, the spark plug ground bars are the most likely source of the larger copper wear debris particles and high ICPS Cu levels observed.

Other wear metal wear rates were normal but somewhat sporadic during these durability tests. The true iron wear-rate averaged 25 ppm Fe/khr which is typical. Chromium averaged 7.5 ppm/khr, while lead indicated 36 ppm/khr. These levels are well within accepted wear-rates for their respective main sources such as cylinder walls, piston rings, and babbitt-coated bearings. Some evidence of cylinder wall scratching was reported in addition to the main bearing abrasion, presumably from hard upper-cylinder introduced debris. The release of internal spark plug porcelain insulator fragments or burned copper fragments could explain the misfiring and account for the abrasion grooves in the cylinder walls and bearings. Pieces of hard chromium from the top-rings could also cause this damage but larger chrome particles were not observed until near the end of the last run.

During both runs the engine oil indicated signs of oxidation by infrared analysis. Oxidation absorbency increased from 17 A/cm in the new oil to just unacceptably high levels of 25-26 A/cm. Oil nitration levels also climbed from 1.0 A/cm to 11 A/cm after 250 oil hours, but up to 30 A/cm nitration is considered tolerable. The lubricant was not contaminated with glycol, water, or fuel, and remained close to its initial viscosity of 14.8 cSt@100°C throughout both 250-hr test runs. The acid neutralization ability of the used oil was depleted by about one-half after 250 hr. The total acid number (TAN) measured in mgKOH/g by ASTM D664 rose from 1.8 in the new oil to an unacceptable 4.8 as the tests proceeded. Cummins oil contamination guidelines (Service Bulletin No. 3810340-01) limit the TAN increase to 2.5 above new oil value, or 4.3 instead of 4.8 in this case. The total base number (TBN) in mgKOH/g by ASTM D2896 started at 5.5 and dropped to 2.9. Cummins guidelines suggest a minimum TBN of 2.5 or, one-half the new oil value or, equal to the TAN. Since the TBN of 2.9 became lower than the TAN of 4.8, it too was grounds for oil condemnation. Average oil consumption was 0.032 L/hr during this durability test series, which would be equivalent to 3000 km per liter at 100 km/hr.

10. TRIBOLOGICAL OIL ANALYSIS CONCLUSIONS

Based on the tribological oil and filter analysis data, it would appear that the unusually high copper wear rates observed were the result of copper ground bar erosion of the Champion "Premium Gold 2095" spark plugs. Although the copper wear rates were becoming stable and lower as the tests proceeded, this was probably due to the installation of a new set of similar plugs. The 2095 plugs used were the coldest heat-range available. The abrasion scratches on cylinder walls and main bearings can be related to debris from the spark plug failures. Other wear metals including iron, lead and chromium were well within acceptable ranges for this type of engine under continuous full-load.

In hindsight, a more durable set of spark plugs based on platinum construction such as Champion "Double-Platinum 7346" could have alleviated the early failures observed in these tests and eliminated the most probable cause of elemental copper oil contamination. The Mobil Delvac Super Geo SAE 15W-40 oil change frequency at 250 hours should not be exceeded under the full-load test conditions employed in this study. Oil oxidation and acid neutralization ability begins to deteriorate after 150 hours and depends on make-up oil additions to avoid exceeding condemnation limits.

The application of ARB LPG "HD-10" fuel did not appear to contribute to abnormal wear of this engine. The high temperature attack of the spark plugs was probably not a function of the fuel type based on relative heating values of ideal fuel/air mixtures. Comparative tribological tests with other fuels was not within the scope of the present durability test series, but could shed light on this spark plug failure phenomenon in future testing. The tribological oil analysis procedures employed in this study provided a continuous insight into overall engine durability and wear without the need for engine disassembly prior to test completion.