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BENCH WEAR AND SINGLE-CYLINDER ENGINE EVALUATIONS OF HIGH-TEMPERATURE LUBRICANTS FOR U.S. ARMY GROUND VEHICLES

INTERIM REPORT
BFLRF No. 291

By

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High-temperature lubricant (HTL) requirements for future U.S. Army ground vehicles were investigated. A single-cylinder diesel engine (SCE-903) was successfully modified to operate at increased cylinder liner temperatures and to serve as an evaluation tool for HTLs. Oil D, one of six lubricants evaluated, completed 200 test hours at an average cylinder wall temperature of 247°C and an oil sump temperature of 166°C with only minor oil degradation. However, improved piston cleanliness is desired. A wide range of bench scale wear techniques have been developed to highlight different lubricant performance characteristics, with particular emphasis on high-temperature operation and oxidation. Based on the bench tests, Oil D would be expected to have inadequate high-temperature, long-term wear protection. Oil D passed the Allison C-4 graphite clutch friction test.

14. SUBJECT TERMS

Lubricant	Low-Heat Rejection Engine	Scuffing	Deposits
Diesel Engine	Tribology	Friction Coefficient	Wear Rate
Adiabatic Engine	Bench Test	Wear Volume	Piston Rings
High-Temperature Oil	C-4 Friction	Ester	Oxidation
Synthetic Oil			

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EXECUTIVE SUMMARY

Problems and Objectives: Future engines for powering U.S. Army ground equipment are expected to require improved or even novel lubricants. Engine oil will be exposed to severe high-temperature environments. Current engine lubricant technology (MIL-L-2104F) is inadequate for future low-heat rejection (LHR) engine requirements. The program objective was to develop lubrication requirements for future U.S. Army ground vehicle engine and transmission systems.

Importance of Project: A key limiting technology in the development of future LHR engines for the U.S. Army is the ability of the engine oil to function at elevated temperatures. Requirements for high engine oil temperature exceed the ability of current generation oils in the areas of thermal/oxidative stability and low-deposition rates.

Technical Approach: The approach is to develop requirements for high-temperature lubricants (HTL) that will encourage industry to develop improved HTLs. A single-cylinder simulated LHR engine (Cummins SCE-903) was used to investigate HTL requirements and to screen candidate HTLs. Concurrently, bench-scale tribology investigations were conducted.

Accomplishments: A single-cylinder diesel engine was installed in a test cell and modified to simulate a low-heat rejection engine. It was used to evaluate candidate HTLs for future U.S. Army LHR diesel engines. Six high-temperature lubricant candidates were evaluated, and only Oil D completed the scheduled 200 hours. Oil D still needs improved piston deposition performance. Oxidation and friction-wear bench test investigations were conducted. A microlubrication wear bench test and an oxidative/wear coupled bench test were developed.

Military Impact: Development of adequate high-temperature lubricants will allow all the benefits and payoffs of minimum-cooled diesel engines to be realized. The payoffs include improved specific fuel consumption, increased vehicle power density, reduced engine size, and reduced cooling maintenance requirements.

FOREWORD/ACKNOWLEDGMENTS

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The contribution of experimental lubricants by Lubrizol Corporation and NIST is greatly appreciated.

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I. INTRODUCTION AND BACKGROUND

Low-heat rejection (LHR) diesel engines--also referred to as adiabatic engines--and other high-temperature, high-output diesel engines are being considered by the U.S. Army as powerplants for future ground vehicles. Normally, efficiency in an engine is increased by reducing heat loss to the environment. The ultimate objective of the U.S. Army is to produce an engine that approaches adiabatic operation. However, projected temperatures in such equipment exceed those experienced in conventional applications, and are beyond the usable range for conventional liquid petroleum lubricants. As indicated in the Bibliography at the end of this report, many researchers have been involved in attempting to solve the technical challenges of developing adiabatic diesel engines. The insulated LHR engine configuration affords many important advantages of military interest. These advantages include compact engine size, lower engine weight/power output, less smoke, and improved specific fuel consumption.(1–14)* An LHR engine that can operate without a conventional liquid cooling system would also offer the Army the advantages of reduced combat vulnerability and decreased maintenance requirements.

By retaining thermal energy within the engine, LHR engines produce a greater thermal stress on the liquid lubricant. Top ring reversal (TRR) temperatures in an LHR engine can vary from 370°C to more than 560°C.(9–13, 15) In previous Belvoir Fuels and Lubricants Research Facility (BFLRF) work (16–17), reviews of the technical literature were conducted to identify potential lubricant delivery systems for high-temperature use. We concluded that few solutions are viable alternatives in long-term applications. In particular, regardless of the materials and lubricant selected, a continuous lubricant delivery system is necessary, i.e., sufficiently durable solid lubricant coatings and composite materials are not currently available. BFLRF has evaluated a wide range of petroleum and synthetic liquid lubricants at elevated operating temperatures in two different single-cylinder, simulated LHR engines.(7, 14) The following engine oil deficiencies were observed when operating at 316° to 343°C (600° to 650°F) average cylinder wall temperature (CWT): excessive oil oxidation, which caused severe oil thickening and even oil solidification within 50 hours; corrosive attack of engine bearings; very high oil consumption;

* Underscored numbers in parentheses refer to the list of references at the end of this report.

and unacceptable engine deposits that resulted in ring sticking. Advanced HTL candidates will be evaluated in the current work.

The piston ring-cylinder bore interface is among the most critical areas in the development of advanced displacement engines. High temperatures combine with a large number of sliding cycles to make effective lubrication and wear prevention difficult. Current lubrication delivery systems use oil from the crankcase supplied to the cylinder wall via throw-off from the crankshaft or by spray jets on the connecting rods. Relative motion between the piston and cylinders forms a hydrodynamic film over much of the cycle. However, the piston is stationary for an instant at both top and bottom dead center. At this point, the lubrication mechanism depends on squeeze film effects and, ultimately, boundary lubrication.(18)

Results from experimental work with insulated compression-ignition (CI) engines have shown temperatures between 150° to 600°C at the top ring reversal point.(9–13, 15) In the near future, it is expected that oils will be required to operate for short periods in the region of 300° to 350°C.(19) Carbonaceous deposits that form on diesel engine piston surfaces have been shown to be largely lubricant derived.(20) As a result, lubricant development has emphasized increased thermal stability and improved deposit ratings.(10) Fully formulated lubricants derived from synthetic base stocks have been available for a number of years (11) and tend to be superior to petroleum oils in specific performance areas. Many exhibit higher viscosity index, better thermal and oxidation stability, and low volatility. However, the optimum deposit characteristics are commonly achieved in oils that contain few metal-based antiwear additives and so are susceptible to increased wear. A need exists to develop a laboratory bench scale friction and wear methodology to assist in HTL development.

II. OBJECTIVE AND APPROACH

One objective was to evaluate the potential effectiveness of advanced lubricants formulated to minimize oxidation and oil-related deposits in a low-heat rejection diesel engine. Candidate HTLs were evaluated in a single-cylinder, low-heat rejection diesel engine (SCE-903). Many laboratory tests are available to characterize both the oxidation and deposit characteristics of a given oil, i.e., the ASTM coking method (21), the panel coker test (22), the ashing test (23), and the Thin Film Oxygen Update Test (TFOUT).(24) Similarly, a wide range of standard and nonstandard laboratory wear tests are available. The objective of the present wear study is to determine the interrelated efforts of oxidation resistance/deposit formation on wear resistance, as well as the basic wear resistance of high-temperature lubricants (HTLs). A final objective was to determine powershift transmission fluid performance of a candidate HTL.

III. ENGINE EVALUATIONS

A. Hardware

1. Engine Description

Cylinder Block – A SCE-903 engine was used as the screening tool for evaluating HTL candidate engine performance. The SCE-903 is manufactured by Cummins Engine Company and is one-quarter of a vee-configured, eight-cylinder Cummins VTA-903T. The resulting two-cylinder engine has one active, or firing, cylinder and one cylinder utilized primarily for inertial balance. The SCE-903 block consists of Cylinder Nos. 7 and 8 separated from an 8-cylinder block at the midplane of Cylinder No. 5. This configuration allows for two main bearing webs, two camshaft bearing webs, the rear-mounted camshaft gear train, rear engine cover, flywheel, and flywheel housing to remain. The front of the engine is closed off with 16-mm (0.625-in.) steel plate fastened to the cylinder block with socket head cap screws.

Cylinder Heads – The cylinder head for the left bank, which contains the active cylinder, is sliced through the midplane of Cylinder No. 5, and has the coolant passages between the head and cylinder block plugged. The head is modified to operate on a separate coolant circuit from the block. The coolant inlet is placed in a core plug on the exhaust side of the head, which is the lowest point of the head coolant passages when the head is installed on the engine. The coolant outlet at the rear of the head is one of the coolant passage outlets of the standard VTA-903T. The fuel enters the head from the rear through the stock fuel inlet rail, and returns via the stock fuel return rail. The fuel rails are plugged between Cylinder No. 7 and five injector bores. A

Cummins PT fuel injector, modified for increased fuel metering and fuel injection rate was utilized with a 4.699-mm (0.185-in.) injector plunger lift setting. The four-valve head--two intake and two exhaust--utilizes stock exhaust valves in all locations and stock rocker levers. The cylinder head has also been modified to accept a 10-mm diameter cylinder pressure transducer. The front of the left cylinder head is closed off with 16-mm (0.625-in.) steel plate. The cylinder head for the right bank, which contains the inertial balance cylinder, consists of a 16-mm (0.625-in.) flat steel plate bolted to the cylinder block.

Crankshaft – The SCE-903 crankshaft is machined from a VTA-903T crankshaft. The fourth crank throw, rear main bearing journal, and the flywheel mounting flange from the VTA-903T were retained. The stock crankshaft was cut just after the third crank throw before the fourth main bearing journal to make the SCE-903 crankshaft. The crankshaft was then machined at the fourth main bearing journal to accept a pressed fit crankshaft extension. The crankshaft extension included room for additional balance mass and a running surface for the front crankshaft seal. The SCE-903 was designed as a research engine for component testing, thus additional crankshaft balance mass can be added to compensate for variations in reciprocating component mass.

Camshaft – The SCE-903 camshaft is separated from a VTA-903T camshaft, and is the portion from just before the fourth bearing journal to the rear of the engine, including the cam gear. The cam gear has a modified two-piece web, which enables timing changes by means of the machined adjustment slots on the gear web. The stock camshaft intake and exhaust valve lift and duration are retained, but a slightly modified injection cam profile is utilized. The SCE-903 fuel injection cam, compared to the VTA-903T fuel injection cam, has a longer metering duration and an increased fuel injection rate. Roller followers activate the valve and injector rocker levers through short push tubes.

Cylinders – The cylinder components for the SCE-903 consist of the stock connecting rods, bearings, piston pins, piston pin bushings, and piston rings. The firing cylinder utilizes a gallery-cooled aluminum alloy 14.5:1 compression ratio trunk-style piston, with a ni-resist top ring groove insert. The piston cooling oil is supplied through an orifice and a P-tube located on the main oil gallery. The balance piston consists of a stock VTA-903T aluminum trunk-style piston modified by removal of the ring grooves, leaving a hole in the crown to eliminate compression, and machined to accept a balance mass. The balance mass is sized such that the balance cylinder components equate the piston and ring mass of the firing cylinder.

2. Test Bed Installation

The SCE-903 engine is installed in a test cell and coupled to a Midwest 175-hp dry gap eddy current dynamometer through a flexible coupling. The engine speed is controlled with a Digilog dynamometer controller, magnetic pickup, and 60-tooth gear. Engine load feedback is via a 91-kg (200-pound) Lebow electronic load cell. The SCE-903 engine was designed to operate with external accessories to reduce parasitic loads. The fuel system, cooling system, air system, and lubrication system functions are external to the engine.

Fuel System – The fuel system consists of a Cummins PT fuel pump, an AC synchronous motor, a three-way valve, a heat exchanger, a regulator, a standpipe, and a Micro Motion model 6D vibrating tube mass flowmeter. The PT fuel pump, taken from a VTA-903T engine, is driven by the synchronous motor to supply the fuel rail pressure to the engine. The fuel rail pressure is set utilizing an air cylinder to actuate the fuel pump rack. The overcapacity of the PT fuel pump compared to the single-cylinder engine fuel requirements compensates for variations in fuel demand due to engine speed changes. The three-way valve is utilized on the outlet of the PT pump to avoid pumping fuel into the engine when it has stopped and to route fuel away from the engine in an over-speed emergency. The heat exchanger is utilized on the fuel return line to the standpipe in order to keep the fuel inlet temperature within the recommended operating range. The regulator maintains a constant head in the standpipe accounting for the difference in mass flow between the fuel to the engine and the return fuel from the engine. The vibrating tube mass flowmeter measures the make-up fuel, which the regulator flows to maintain the constant head.

Coolant System – The cooling system consists of a centrifugal pump, tube and shell heat exchanger, standpipe with 15 psi pressure cap, and a 70/30 ethylene glycol/water coolant. The centrifugal pump is mounted below the coolant inlet to the cylinder head, and the standpipe is mounted above the coolant outlet from the cylinder head. The standpipe serves as the expansion tank, with the breather line from the pressure cap routing to an overflow tank. The engine coolant is on the shell side of the heat exchanger, and laboratory cooling water on the double pass configured tube side. Temperature control is by means of a Type J thermocouple, an electronic PID controller, an I/P convertor, and an air operated globe valve located on the tube side outlet of the heat exchanger. The 70/30 ethylene glycol/water coolant and the 15 psi pressure cap allow operation at a 121°C (250°F) coolant outlet temperature.

Air System – The engine intake air system incorporates two air compressors, a back pressure regulator, a 5-cm (2-in.) regulator, a pilot regulator, an air dryer, a vortex shedding flowmeter, and an intake plenum with heating elements. The air system provides compressed and heated air to the SCE-903 to simulate turbocharged engine conditions. The two compressors, one high-volume/low-pressure and one high-pressure/low-volume, fill an air tank maintained at 70 psig by the back pressure regulator. The outlet of the air tank goes to the 5-cm (2 in.) regulator, which maintains the line pressure equal to the pressure setting of the pilot regulator located at the engine operator control panel. The regulated air flows through the 1.7°C (35°F) dew point air dryer to maintain constant humidity, then through the vortex shedding flowmeter. The temperature and pressure of the air at the flowmeter are measured to calculate the mass flow of air to the engine. The inlet air then flows into the intake plenum, which contains resistance heaters to maintain the air at the temperature required for the engine operating condition. Temperature control utilizes a Type J thermocouple, an electronic PID controller, and an SCR to power the resistance heaters. The intake plenum is sized to dampen engine-induced pressure pulsations so stable measurements and control of the inlet pressures can be achieved. The inlet air temperatures and pressures utilized for SCE-903 operation are the same values as measured on a VTA-903T engine.

The exhaust system can be considered part of the air system, because it utilizes a 1:1 automatic proportioning regulator to maintain a back pressure on the engine equal to the engine inlet air pressure. The exhaust pressure is measured in a sized exhaust plenum, and controlled via a butterfly valve in the exhaust line going to the laboratory exhaust system. The back pressure specifications for the SCE-903 were also determined from a VTA-903T.

Lubrication System – The lubrication system comprises an AC synchronous motor, a cast iron gear pump, a plate-type oil cooler, an oil filter, a turbine flowmeter, and Teflon®-lined stainless steel braided hoses. The AC motor and gear pump are mounted on the bed plate below the engine oil sump, to maintain a positive head at the inlet to the pump. A globe valve is on the outlet of the pump to regulate the oil pressure while the lubricant is approaching operating temperatures. A plate-type oil cooler is utilized to lower the 171°C (340°F) oil sump temperature to a main oil gallery temperature of 159°C (318°F). Laboratory cooling water is pressurized to 100 psig and utilized on the coolant side of the plate oil cooler, before being aftercooled and returned to the laboratory cooling system. Temperature control is by means of a Type J thermocouple, an electronic PID controller, an I/P convertor, and an air-operated globe valve on the outlet of the cooling water aftercooler. The lubricant then enters the oil filter, the turbine flowmeter, and the engine main oil gallery. The oil flow measurement is used to calculate the heat rejection to the lubricant by the engine. The utilization of Teflon®-lined stainless steel braided hoses were required to withstand the elevated lubricant temperatures of the HTL candidate evaluations.

3. Engine Modifications

Several modifications to the SCE-903 were made to augment the HTL candidate evaluations. These modifications included elimination of the cylinder block cooling, oil pan modifications, cylinder liner temperature, bearing temperature, and oil jet temperature instrumentation, and top ring zone oil sampling.

Cylinder Block – The SCE-903 was designed such that the cylinder block and cylinder head cooling circuits could be separated. For the HTL evaluations, it was decided to operate the engine without cylinder block cooling in order to maximize the cylinder liner temperatures. The cylinder block coolant passages to the cylinder head were sealed with pipe plugs in the head, and the coolant inlet on the cylinder block side plate was used as the pass through for the cylinder liner temperature instrumentation. Due to the absence of coolant in the water jacket, the cylinder liner seal would become brittle and fail, allowing the lubricant to migrate into the block cooling passages. Special high-temperature sealants were utilized to augment the sealing around the cylinder liner and retain the engine oil in the sump.

Oil Pan – The oil pan for the SCE-903 was a shortened VTA-903T pan and had an original capacity of approximately 19 L (5 gallons). Due to the limited quantity of several of the candidate lubricants, and the time required for the single-cylinder engine to raise the lubricant to operating temperature, the oil pan volume was reduced to approximately 8 L (2 gallons). To achieve this reduced volume, the depth of the pan was decreased and aluminum blocks were bolted inside the pan. The aluminum blocks were installed in the pan so that rod heaters could be inserted into the blocks to bring the lubricant up to operating temperature in a more timely manner. The blocks and heaters were sized such that the watt density was roughly 0.003 W/mm^2 (2 W/in.^{2}), low enough to avoid stressing the oil. The outlet to the external oil pump was from the bottom center of the oil pan, and the return line from the pressure regulating valve was installed in the pan below the block/pan parting line and at the lubricant fill level.

Temperature Instrumentation – To obtain a better understanding of the environment in which the lubricants must perform, thermocouples were installed in the cylinder liner of the firing cylinder. The axial locations of the piston lands and the thrust side cylinder liner thermocouples are both shown in Fig. 1 for the SCE-903 piston at top dead center. For several of the tests, the third thermocouple from the top was removed, and an additional thermocouple was added at top ring reversal on the antithrust side. The angular orientation of the thermocouples with respect to the thrust and antithrust sides of the cylinder are shown in Fig. 2. The cylinder liner temperature measurements were made with 0.7-mm (0.028-in.) diameter wire chromel-alumel thermocouples with a high-temperature woven fiberglass sheathing. The cylinder liner thermocouples were installed by drilling a 2-mm diameter hole through the liner at the designated locations, then spot welding the twisted thermocouple leads on the cylinder liner inside diameter. After the thermocouple junctions were formed, the cylinder liner was plateau honed to a factory consistent surface finish to remove any excess spot weld material. After installation of the thermocouples, the cylinder liner was placed in an oven and the thermocouples calibrated in the range from 204°C (400°F) to 343°C (650°F).

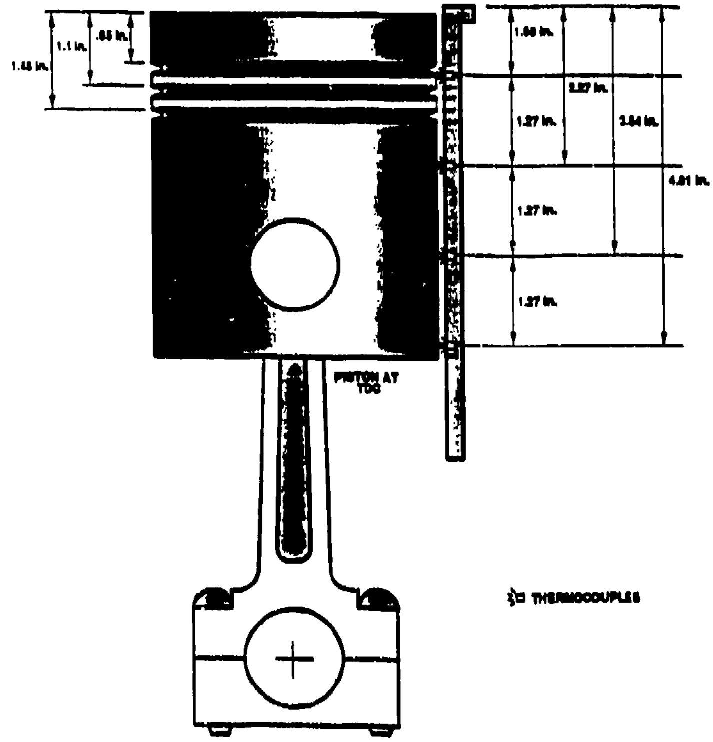


Figure 1. Axial locations of cylinder liner thermocouples

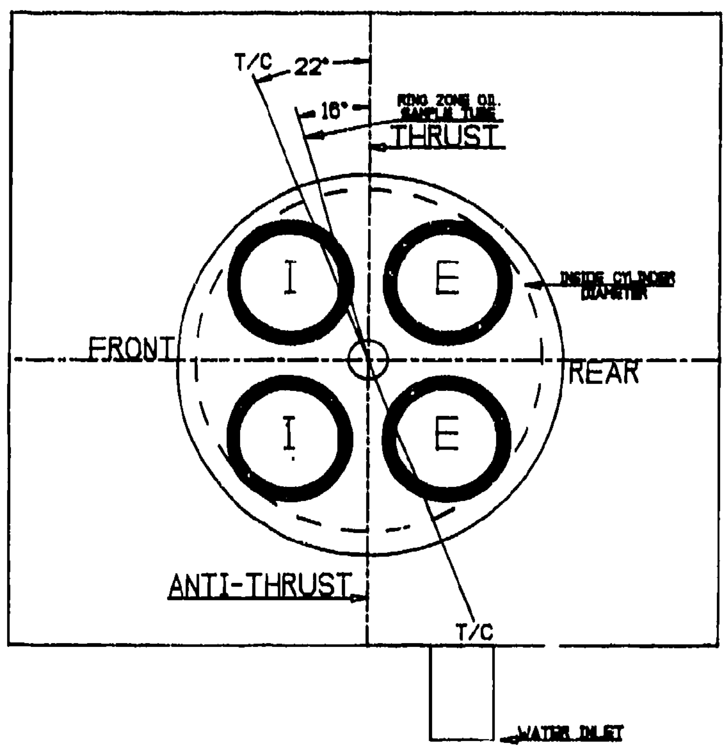


Figure 2. Angular orientation of thermocouples with respect to the cylinder liner thrust/antithrust axis

For several of the latter high-temperature lubricant candidate evaluations, modifications were made to enable observation of the lubricant temperatures in other areas of the engine. One of the thermocouples was installed in the tube for the piston oil cooling jet for obtaining temperature data to be utilized for piston thermal modeling. A thermocouple was installed through a 0.85-mm (0.033-in.) hole in the main bearing cap. The thermocouple was positioned to touch the backside of the rear main bearing shell to obtain the bearing temperature. In order to obtain the thermal conditions at which the lubricant is exposed in the bearings, a thermocouple was installed that slightly protruded into the oil groove of the upper rear main bearing shell via a groove machined in the bearing cap. All described measurement locations utilized 0.8-mm (0.032-in.) diameter Type K thermocouples with inconel sheaths.

Ring Zone Oil Sampling – The condition of the lubricant in the proximity of the top ring, at top ring reversal, was considered essential for determining the expected performance of the candidate HTLs with respect to ring/liner wear and piston cleanliness. At an axial location corresponding to the top edge of the second land (Fig. 1), a 1.85-mm (0.073-in.) hole was drilled through the engine block and liner at the angular orientation noted in Fig. 2. The sample port was drilled while the liner was installed in the engine block to maintain proper alignment. The hole through the engine block was enlarged to 9.5 mm (0.375 in.) to the coolant jacket depth. The sampling port was then enlarged from the backside of the liner as installed in the engine block with a 2.6-mm (0.104-in.) diameter bit to a depth of 5.7 mm (0.225 in.) and tapped to accept a M3.2x.6 (5-44) thread. A threaded 3.175-mm (0.125-in.) tube was utilized to transport the ring zone oil sample from the cylinder liner out to the external sample line. The ring zone oil sample was collected in a sample trap immersed in an ice bath. Typically 25 hours of engine operation were required before enough of the ring zone oil sample could be collected for analysis. The ring zone oil samples were used in the bench wear evaluations discussed in a later section of this report.

4. Operating Conditions

When the SCE-903 installation was completed (Fig. 3), power curves were generated to verify engine operation and to determine attainable oil sump and cylinder liner temperatures.

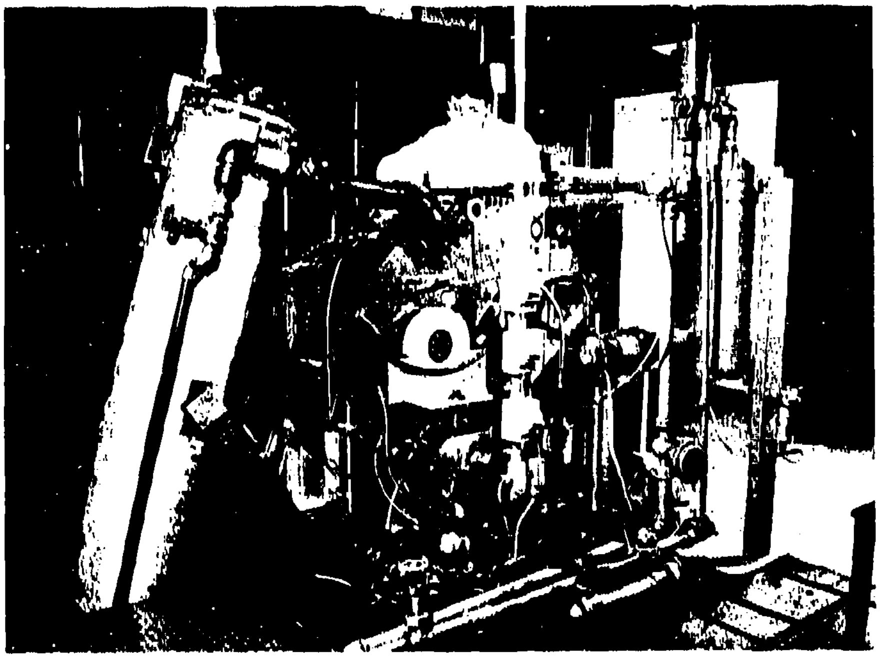


Figure 3. Test cell installation of the SCE-903 engine utilized for the high-temperature lubricant candidate evaluations

Sustainable engine operation at controllable air/fuel (A/F) ratios was achieved at engine speeds above 2,000 rpm, as shown in Fig. 4 for a 30:1 A/F ratio. The test conditions utilized for the HTL candidate screening were based on the targeted operating parameters of a LHR diesel engine under development and standard VTA-903T operating conditions. The thermal conditions, engine speed, and A/F ratio were determined by the targeted advanced LHR engine operating parameters. The combustion air conditions (pressure and temperature) and the exhaust back pressure were selected from VTA-903T full rack operating performance. The cylinder head coolant outlet temperature was chosen to maintain the durability of the cylinder head. The target operating conditions for the SCE-903 HTL candidate evaluations are shown in TABLE 1.

Also shown in TABLE 1 are the overall average and standard deviations of the operating conditions for all seven of the HTL evaluations. With the exception of the cylinder liner and oil sump temper. .ures, the targeted operating conditions were achieved. Although an increase of the fuel flow rate to the engine would have increased both the oil sump and cylinder liner temperatures, it was decided to perform the evaluations at the target A/F ratio. It was felt an

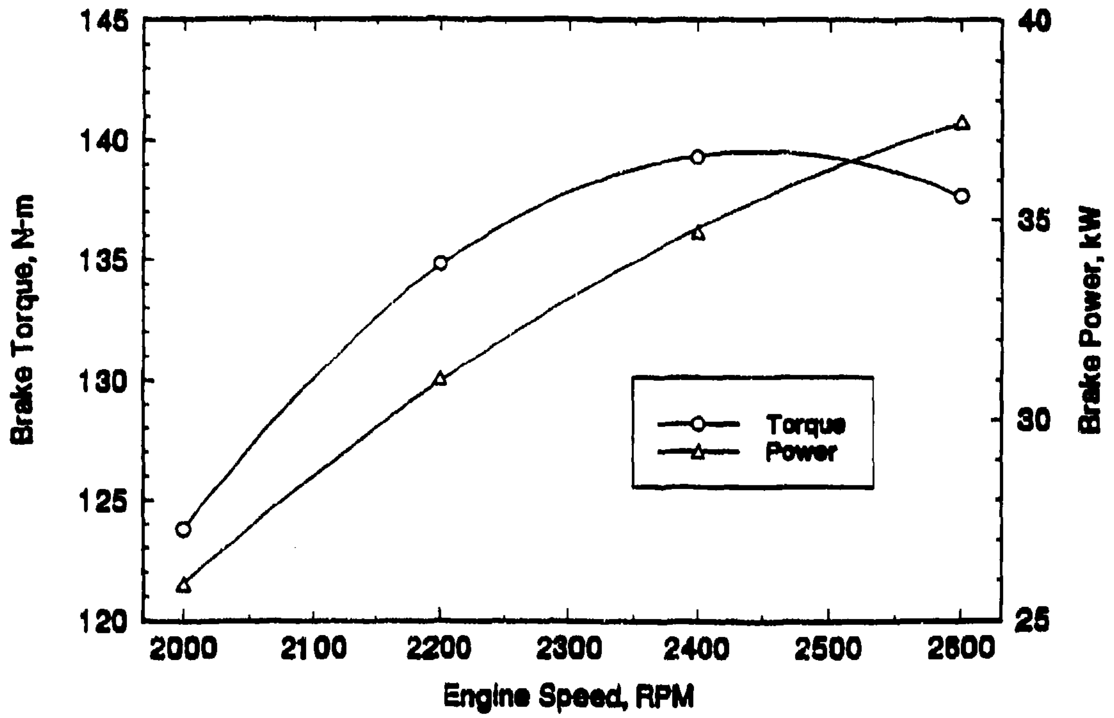


Figure 4. Brake torque and brake power curves for the SCE-903 engine at a 30:1 A/F ratio

TABLE 1. Operating Condition Summary and Targets for the SCE-903 High-Temperature Lubricant Evaluations

Parameter	Target	Overall Average	Overall Standard Deviation
Engine Speed, rpm	2600	2601	4
Brake Torque, ft-lb	112	115	3
Fuel Flow, lb/hr	21	20.7	0.2
Air/Fuel Ratio	28:1	28.4:1	0.75
Oil Sump Temperature, °C (°F)	171 (340)	167 (333)	1 (2)
Oil Gallery Temperature, °C (°F)	159 (318)	158 (316)	1 (2)
Head Coolant Outlet Temperature, °C (°F)	121 (250)	121 (249)	1 (2)
Average Cylinder Liner Temperature, °C (°F)	260 (500)	246 (475)	14 (25)
Top Ring Reversal Temperature, °C (°F)	288 (550)	252 (485)	23 (42)
Manifold Air Pressure, psig	15	15.6	0.2
Exhaust Back Pressure, psig	15	14.9	0.6

increased fuel rate could lead to: (1) unrealistic soot levels in the lubricant, affecting piston deposition and ring sticking; (2) possible fuel dilution of the lubricant; and (3) elevated exhaust valve temperatures, which could have affected engine durability.

Discounting the variation in the cylinder liner temperatures, the engine was consistently controlled throughout the HTL candidate evaluations. The deviations in the cylinder liner temperatures were most likely influenced by a strong axial component of heat transfer in the cylinder liner. With the uncooled cylinder block, the empty coolant jacket was effectively functioning as air gap insulation, serving to reduce the radial component of heat transfer within the cylinder liner. The relatively cool (121°C) cylinder head acts as a heat sink and governs the direction of the heat transfer paths.

To some extent, the deviations of cylinder liner temperatures may have also been affected by differing rates of evaporation of the various lubricants from the cylinder liner walls. Some indication of this effect is the similar cylinder liner temperature distributions in evidence for the candidate lubricant on which a repeat evaluation was performed.

B. Test Fuel

The base fuel was Reference No. 2 diesel fuel supplied by a local refinery in San Antonio, TX. The specification requirements for this fuel, commonly referred to as "Cat fuel," are set forth in Section 5.2, Methods 354 and 355 of Federal Test Method Standard (FTMS) 791C and described in Appendix F of ASTM STP 509A, Part I and II.(25) This test fuel is a straight-run, mid-range natural sulfur fuel manufactured under closely controlled refinery operation to minimize batch-to-batch compositional and physical property deviations. Properties of the test fuel are given in TABLE 2.

TABLE 2. Test Fuel Analysis

Properties	ASTM Method No.	Reference No. 2 DF Test Fuel	Specification*
Gravity, API°	D 287	34.5	Record
Viscosity, cSt, 38°C (100°F)	D 445	3.3	1.6 to 4.5
Flash Point, °C (°F)	D 93	85 (185)	37.8 (100) min
Cloud Point, °C (°F)	D 2500	-2.0 (+28)	Record
Pour Point, °C (°F)	D 97	-12 (+10)	-6.7 (+20) max
Water and Sediment, vol%	D 1796	0.0	0.5 max
Carbon Residue, wt%	D 524	0.10	0.20 max
Sulfur, wt%	D 129	0.41	0.35 min
Acid No., mg KOH/g	D 664	0.0	Record
Aniline Point, °C (°F)	D 611	63 (145)	Record
Copper Corrosion	D 130	1A	No. 2 max
Distillation, °C (°F)	D 86		
Initial Boiling Point		207 (405)	Record
10%		241 (465)	Record
50%		273 (524)	260 (500) min
90%		317 (603)	316 to 338 (600 to 640)
End Point		348 (658)	343 to 366 (650 to 690)
Cetane No.	D 613	52	0 to 45
Net Heat of Combustion			
MJ/kg (Btu/lb)	D 240	42.13 (18,130)	Record
Ash, wt%	D 482	0.006	0.01 max

* ASTM STP 509A, Part I and II, Appendix F.

C. Lubricants

Six different lubricants were evaluated during this program in the SCE-903 engine. Five of the oils were synthetic based, and one SAE 15W-40 viscosity grade petroleum-based oil (Oil B) was included as a baseline. The physical and chemical characteristics of the test oils are presented in TABLE 3. Oils A, B, and C are commercially available, heavy-duty diesel engine oils, with Oils A and C containing synthetic base stock blends of polyolester and polyalphaolefin material. Oils D and E are experimental HTLs that contain different polyolester base stocks, and were formulated with the same high stability additive package that was selected to minimize high-temperature deposit formation. Oil F contained an unknown blend of synthetic components. As

TABLE 3. Summarized Lubricant Properties

Oil Code		A	B	C	D	E	F
AL No.		8924	19372	19371	19346	19347	19902
AIPS Test No.		A-1	A-2, A-6	A-3	A-4	A-5	A-7
Properties	Method						
K. Vis, cSt, at	D 445						
40°C		56	97.9	64.77	63.89	105.39	75.33
100°C		10	14.59	10.08	9.83	14.50	10.94
Viscosity Index	D 2270	167	155	141	138	141	134
HTHS Vis, 150°C, cP	D 4624	3.1	3.9	3.7	3.7	5.1	4.5
Flash Point, °C	D 92	224	221	265	288	286	212
Pour Point, °C	D 97	−39	−19	−38	−36	−33	−33
Total Acid No.	D 664	3.6	3.2	1.9	0.4	0.8	2.5
Total Base No.	D 664	5.7	6.3	10.2	6.2	6.1	7.8
Sulfated Ash, wt%	D 874	1.10	0.91	0.97	0.86	0.83	1.43
TFOUT, minutes	D 4742	183	200	258	>300	>300	>300
Nitrogen, wt%	D 4629	0.14	0.098	0.081	0.029	0.03	0.189
Elements, wt%	XRF						
S		0.33	1.1	0.28	0.21	0.20	ND*
Ca		0.25	0.18	0.07	0.27	0.27	ND
P		0.13	0.12	0.08	NIL	NIL	ND
Zn		0.13	0.15	0.09	NIL	NIL	ND
Elements, ppm	ICP						
B		2	8	167	<1	<1	<1
Mg		5	4	1385	13	10	13
P		1334	1029	1029	6	2	9136
Zn		1421	1431	1203	3	<1	939
Ca		2259	ND	895	2706	2962	2921
HPDSC, 500 psi O_2, minutes, at							
180°C		80	57	140	>300	>300	ND
190°C		43	34	63	172	172	>300
200°C		22	20	52	95	85	ND
210°C		13	10	28	63	51	ND

* ND = Not Determined.

shown in Fig. 5, the sulfated ash contents of the oils, which are indicative of metallic additive content, ranged from 0.83 to 1.43 wt%. All the oils contained calcium as an additive element, and Oil C also contained magnesium. Oils D and E did not contain zinc or phosphorus, which indicates that zinc dithiophosphate was not used in these formulations. High-Pressure Differential Scanning Calorimetry (HPDSC) determinations were conducted on each oil to indicate oxidation stability. Fig. 6 shows the HPDSC minutes to be a breakpoint for oils evaluated at 190°C isothermal conditions, and 500 psi oxygen pressure. The HPDSC breakpoint minutes at 190°C ranged from 34 to greater than 300, with Oil F having the best HPDSC performance.

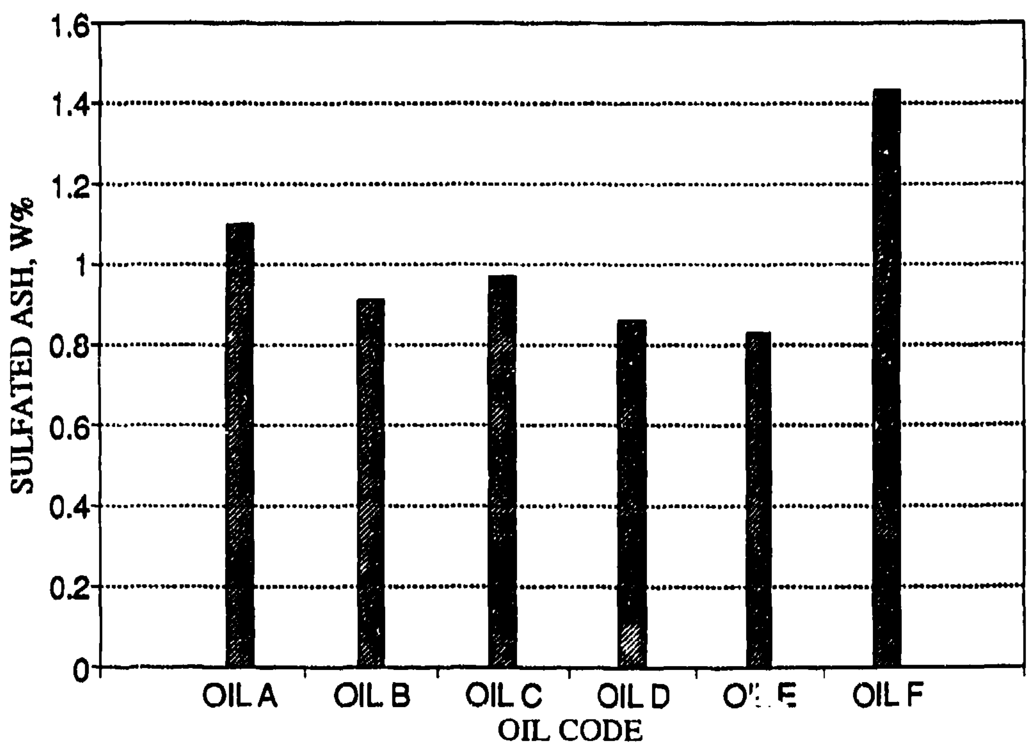


Figure 5. __Sulfated ash contents__

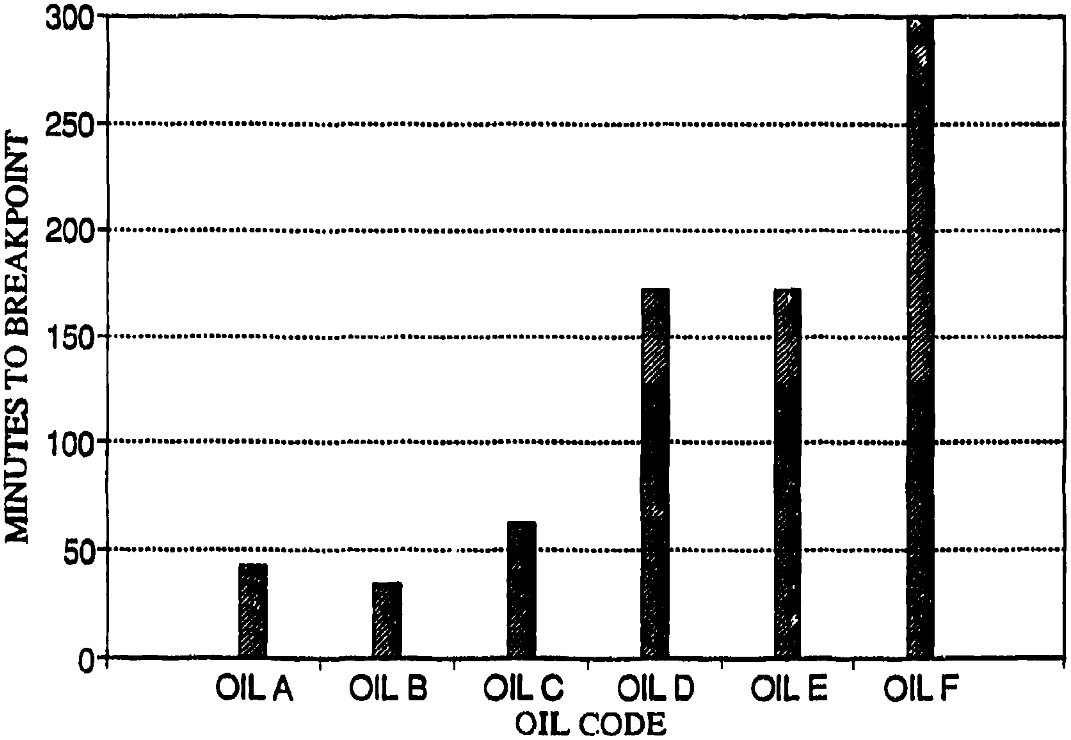


Figure 6. HPDSC, 190°C, 500 psi oxygen

D. Discussion of Results

Seven SCE-903 high-temperature engine evaluations were conducted in which six different lubricants were evaluated (Oil B was run twice). TABLE 4 shows the summarized engine operating conditions, end-of-test (EOT) inspections and ratings, and EOT used oil properties. Evaluation durations ranged from 40 hours (Oil B) to 200 hours (Oil D). Engine trials were stopped before the scheduled 200 hours because of mechanical problems, oil viscosity increase, or excessive wear metal accumulation in the used oil. Each oil evaluation is discussed individually. Complete engine-lubricant performance reports are included in Appendices A through G.

Candidate Oil A was a commercially available SAE 10W-30 viscosity grade, synthetic diesel engine oil. The lubricant evaluation lasted 75 hours, after which time the engine was disassembled for parts rating and inspection. The engine operation was stopped because of significant leakage from the rear crankshaft seal. The ratings revealed slight front-to-back

TABLE 4. High-Temperature SCE-903 Engine Tests

Test No.	A-1	A-2	A-3	A-4	A-5	A-6	A-7
Oil ID	AL-8924-L	AL-19372-L	AL-19371-L	AL-19346-L	AL-19347-L	AL-19372-L	AL-19902-L
SAE Vis Grade	10W-30	15W-40	15W-30	30	40	15W-40	XW-30
Oil Code	A	B	C	D	E	B	F
Operating Conditions							
Test Hours	75	40	90	200	100	49	75
rpm	2597	2598	2599	2599	2608	2600	2599
Obs Bhp	56	58	60	57	56	56	60
BMEP, psi	150	156	162	155	150	151	162
A/F Ratio	28.2	28.8	28.2	27.1	28.6	28.2	28.2
BSFC, lb/Bhp-hr	0.373	0.356	0.345	0.361	0.371	0.369	0.345
Oil Sump Temp., °F (°C)	330 (166)	332 (167)	332 (167)	331 (166)	331 (166)	332 (167)	332 (167)
Average Cylinder Liner Temp., °F (°C)	527 (275)	472 (244)	456 (236)	477 (247)	451 (233)	470 (243)	456 (236)
BSOC, lb/Bhp-hr	0.007	0.007	0.0021	0.0015	0.0015	0.0064	0.002
EOT Inspections							
Rings	Free	Free	Free	Free	Free	Free	No. 3-20%
Ring Distress Demerits	0.5	0	0	0	0	0	Cold Stuck
Cylinder Scuffing, %	10.5	0	0	0	0	0	0
Bore Polishing, %	2.5	0	0	0.5	5.0	2.5	2
Piston Deposits							
TGF, %	69	53	99	98	13	41	57
2GF, %	38	43	3	7	14	53	76
WDK WTD	558	477	460	414	482	485	1876
Bearing Distress							
Main Front	3% Cu	0	1% Cu	1% Cu	--*	--*	--*
Con Rod Top	1% Cu	0	0	1% Cu	--*	--*	--*
EOT Used Oil Properties							
K. Vis, cSt, at 100°C	26.2	45.8	15.48	10.69	28.14	26.89	27.55
K. Vis, cSt, at 100°C, % Increased	162	214	54	9	94	84	152
TAN	7.6	8.0	6.8	2.0	20.9	5.0	1.6
TAN Change	+4.0	+4.8	+4.9	+1.6	+20.1	+1.8	−0.9
TBN	2.8	3.4	3.0	2.4	0	2.5	4.8
TBN Change	−2.9	−2.9	−7.2	−3.8	−6.1	−3.8	−3.0
Insolubles, wt%							
Pentane B	0.09	0.13	0.07	0.04	1.02	0.02	1.00
Toluene B	0.09	0.08	0.06	0.03	0.40	0.01	0.66
Soot, wt%, by TGA	1.1	1.6	0.8	0.5	3.7	1.6	0.9
Elements, ppm, ICP							
Fe	100	26	55	72	112	38	48
Cu	82	41	38	32	97	32	197
Pb	50	14	468	71	119	19	131

* Bearing distress not determined.

cylinder liner scuffing, slight piston skirt scuffing, and very mild ring face distress. All three rings were free with moderate groove and land deposits. The connecting rod piston pin bushing revealed distress due to the high-temperature operation, and the connecting rod and main bearings revealed exposed copper. The EOT lubricant inspection revealed substantial oil degradation, with both large viscosity and Total Acid Number (TAN) increases. As shown in Fig. 7, the kinematic viscosity measured at 100°C increased steadily throughout the test, as did the iron and copper wear metals as shown in Fig. 8. Used oil wear metal contents as determined by inductively coupled plasma (ICP) emission spectroscope were 100 ppm of iron and 82 ppm of copper, which were relatively high considering the duration of the test. The high silicone content observed in the used oil for this and other SCE-903 tests is believed to be from the silicone sealants and gaskets used to build the engines.

HPDSC was used to determine the time in minutes to a breakpoint for both new and used oils. The breakpoint time is indicative of oil oxidation stability. HPDSC operating conditions were 180°C isothermal and 500 psi oxygen pressure. Unused Oil A had a breakpoint time of 80 minutes, while the 50- and 75-hour used oil samples had breakpoint times of <10 minutes, which indicates that these used oils had no reserve antioxidant capacity remaining.

Oil B, a commercially available SAE 15W-40 viscosity grade petroleum-based diesel engine, served as the baseline oil. Oil B was evaluated in Test A-2 and again in Test A-6. Test A-2 lasted 40 hours, after which time the engine was disassembled for parts rating and inspection. The engine operation was halted because of viscosity increase, leakage from the rear crankshaft seal, and blowby increase. The blowby increase was caused by the alignment of the three ring gaps of the power cylinder. The ratings revealed no cylinder liner scuffing or bore polish, and no ring face distress. All three rings were free with moderate groove and land deposits. The connecting rod piston pin bushing appeared to be free of distress. No bearing distress was evident, likely due to the short test duration. The EOT lubricant inspection revealed substantial oil degradation, with a 200-percent viscosity increase and a TAN increase of 4.8. As shown in Fig. 9, used oil viscosity increased steadily throughout the test. Fig. 10 shows the wear metal accumulation determined by X-Ray Fluorescence (XRF) during the test. EOT used oil wear metal contents determined by ICP were 26 ppm of iron and 41 ppm of copper.

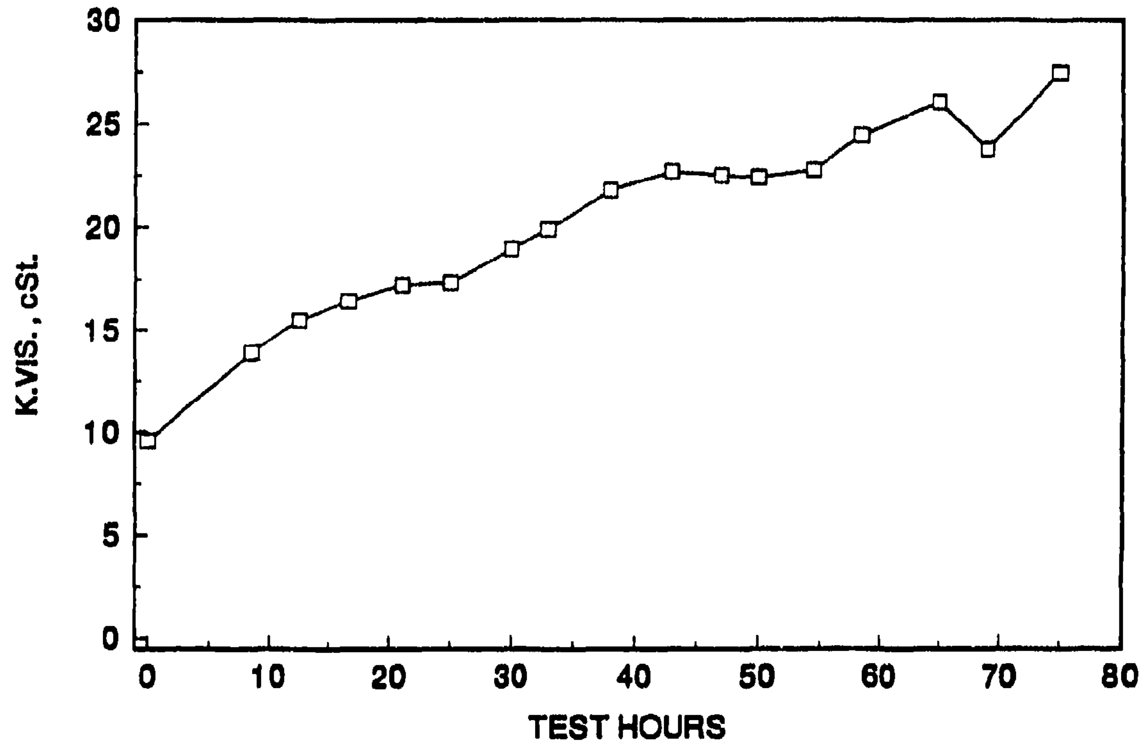


Figure 7. Test A-1, Oil A, K. Vis at 100°C

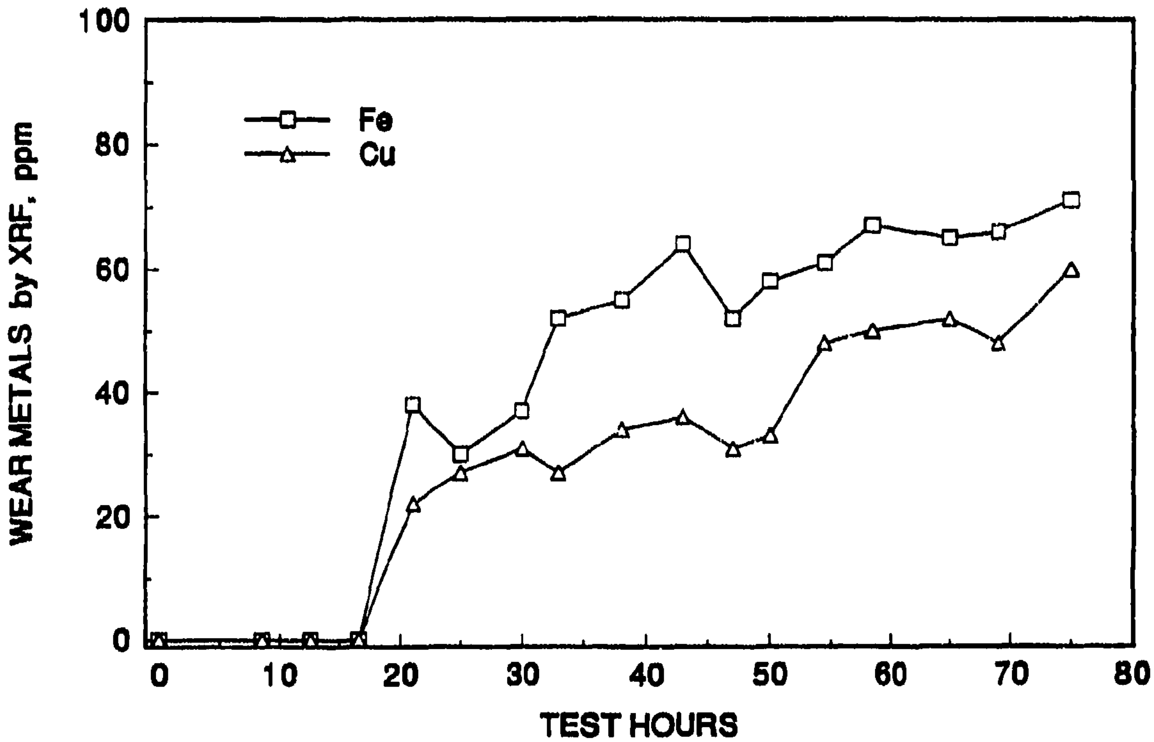


Figure 8. Test A-1, Oil A, wear metals

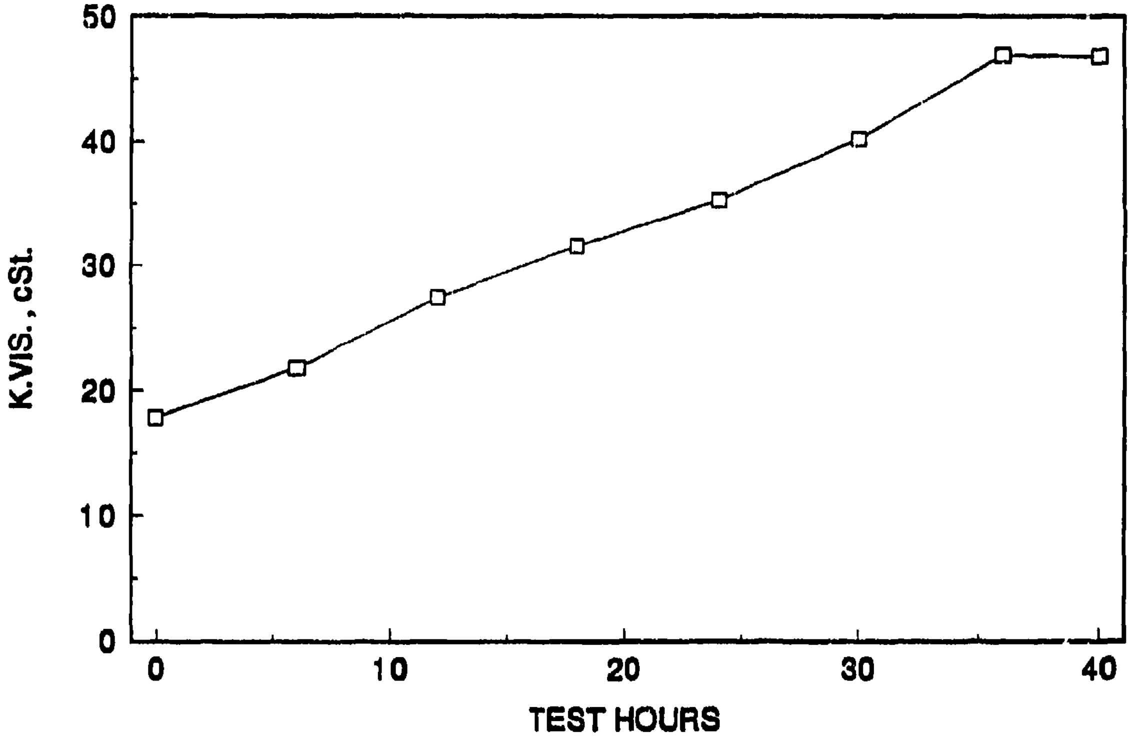


Figure 9. Test A-2, Oil B, K. Vis at 100°C

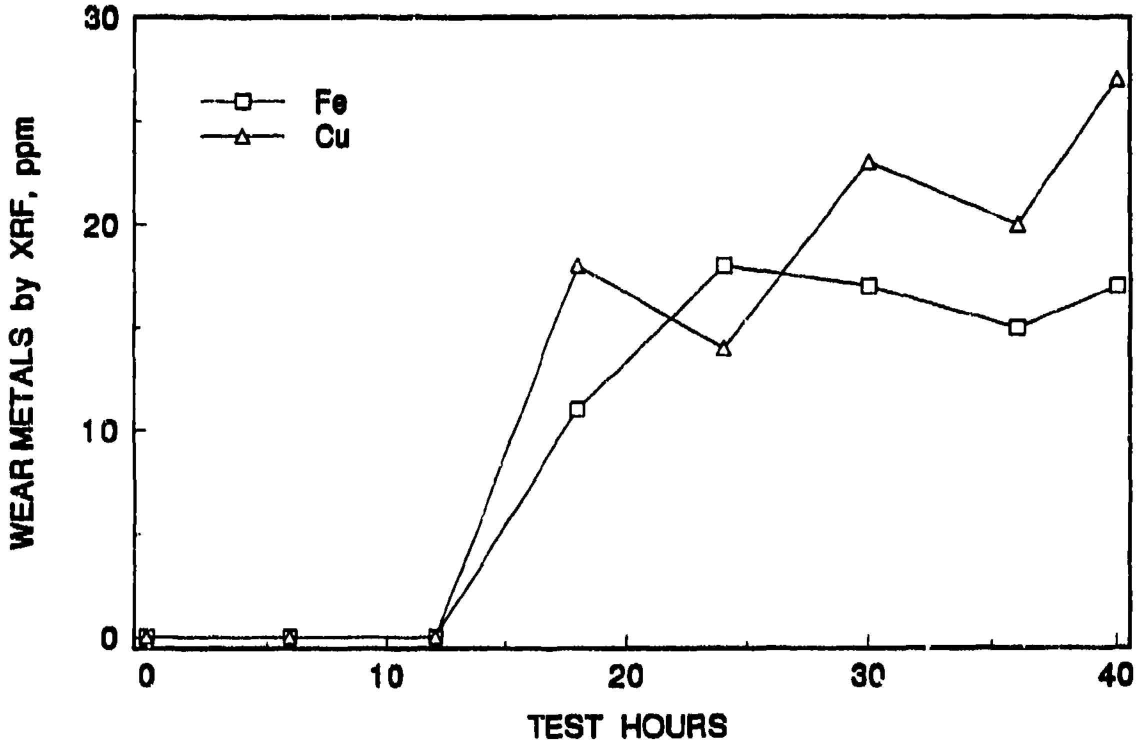


Figure 10. Test A-2, Oil B, wear metals

Oil B had an HPDSC breakpoint at 180°C isothermal of 57 minutes while the 40-hour used oil had a breaktime of 12 minutes. This short breaktime indicated that the oil had little reserve antioxidant capacity at the end of the test.

Test A-6 was run to check the baseline using Oil B, the petroleum-based SAE 15W-40 oil. This evaluation lasted 49 hours, and the engine was disassembled for parts rating and inspection. The ratings revealed no cylinder liner scuffing, 2.5-percent bore polish, and no ring face distress. All three rings were free, with moderate to heavy groove and land deposits. The connecting rod piston pin bushing appeared to have some distress. No bearing distress was again evident, likely due to the short test duration. The EOT lubricant inspection revealed oil degradation, with a 84-percent viscosity increase and a TAN increase of 1.8. This test, which was a repeat of Test A-2, revealed oil degradation rates similar to the earlier test until later in the test (hour 40) when oil leaks caused large additions of makeup oil. Fig. 11 shows the viscosity increase during the test, while Fig. 12 shows the plot of accumulated wear metals determined by ICP during the test. Both plots reflect the large addition of makeup oil at 40 hours.

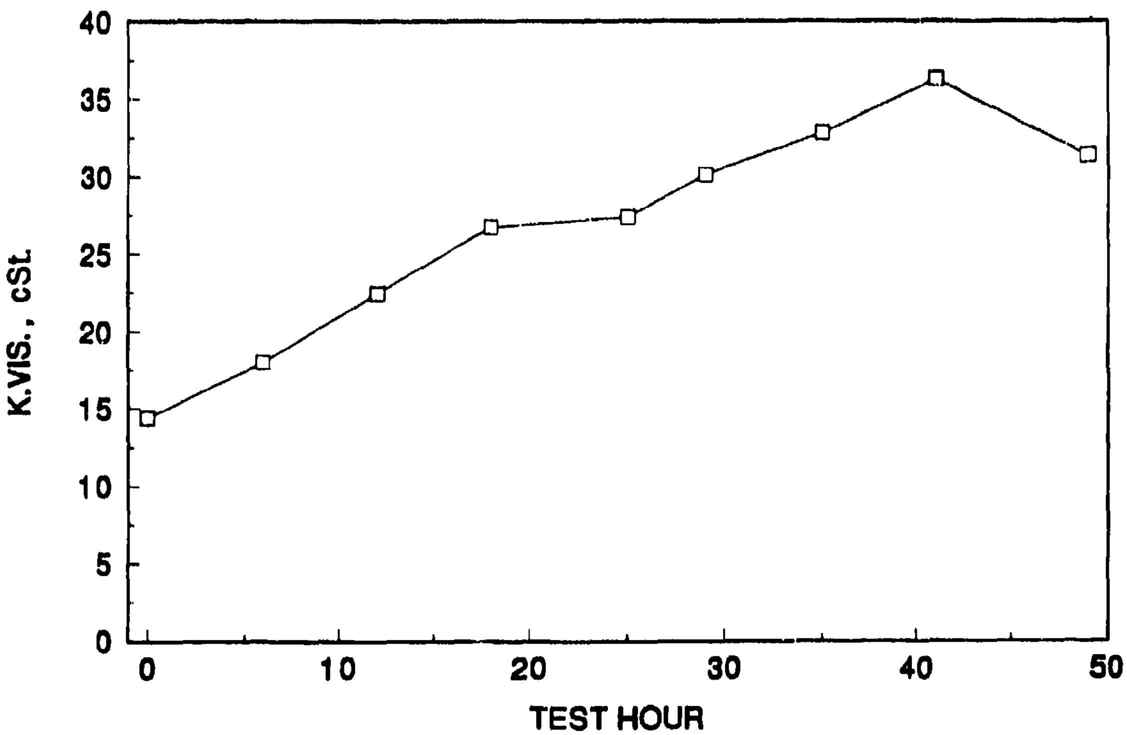


Figure 11. Test A-6, Oil B, K. Vis at 100°C

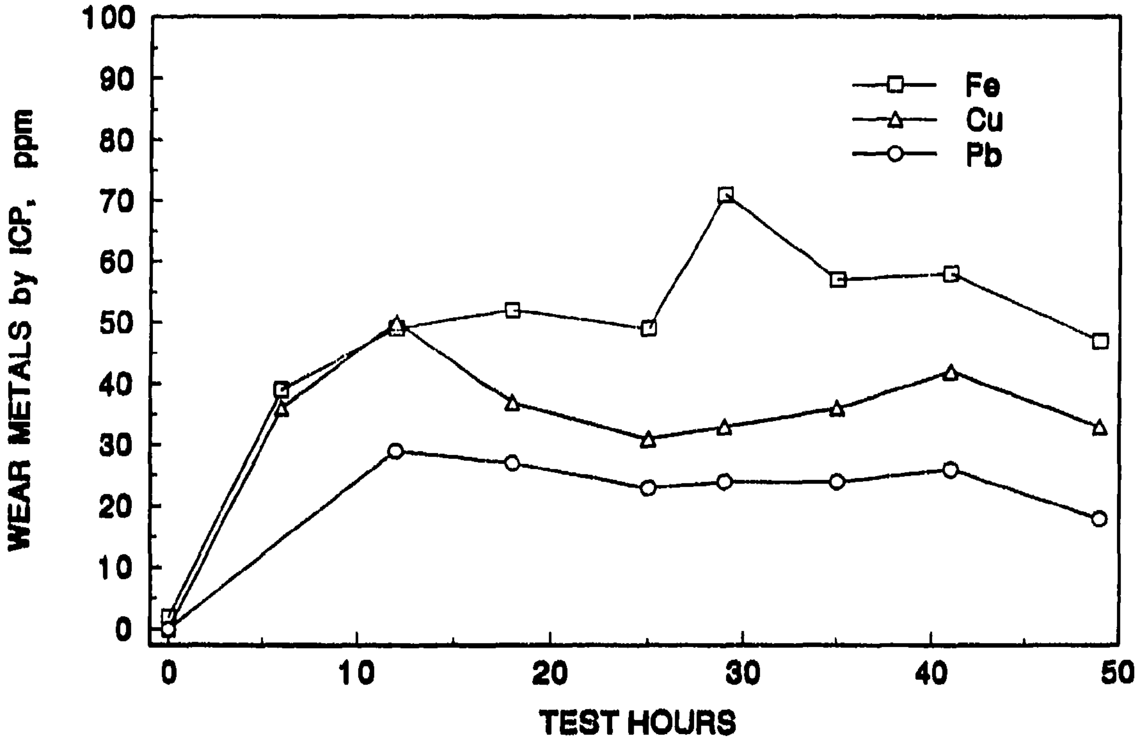


Figure 12. Test A-6, Oil B, wear metals

Oil C (Test A-3) was a commercially available SAE 15W-30 viscosity grade, synthetic diesel engine oil. This lubricant evaluation lasted 90 hours, after which time the engine was disassembled for parts rating and inspection. The reason for test termination was excessive oil loss from the rear crankshaft seal. It was determined that the rear seal leakage was caused by the seal rotating in the cast aluminum rear engine cover. This problem was solved for future tests by pinning the seal in place and coating the periphery of the seal with a high-temperature silicone-based sealant. The ratings revealed no cylinder liner scuffing or bore polish, and no ring face distress. All three rings were free with moderate to heavy groove and land deposits. The connecting rod piston pin bushing, the main bearings, and connecting rod bearings appeared to be free of distress. The EOT lubricant inspection revealed moderate oil degradation, with a viscosity increase of 54 percent and a TAN increase of +4.9. Fig. 13 shows the viscosity increase during the test, and Fig. 14 shows the accumulation of wear metals at 50, 75, and 90 test hours. Used oil wear metal contents by ICP at EOT were 55 ppm iron, 38 ppm copper, and 468 ppm lead.

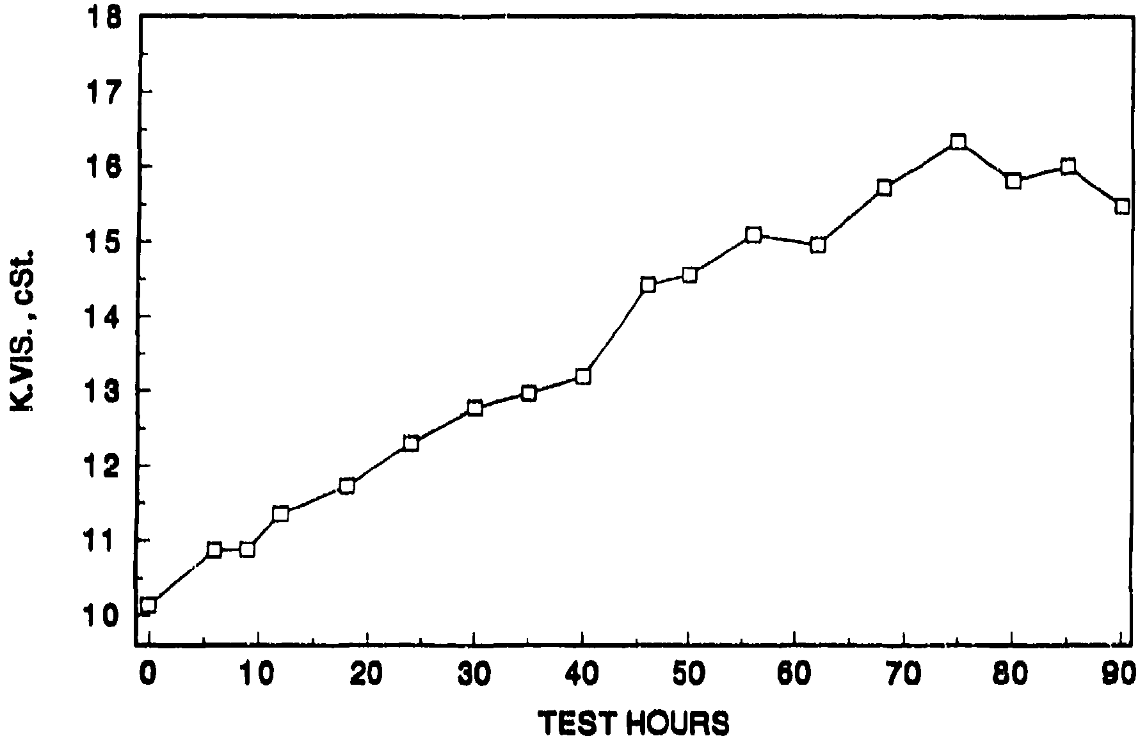


Figure 13. Test A-3, Oil C, K. Vis at 100°C

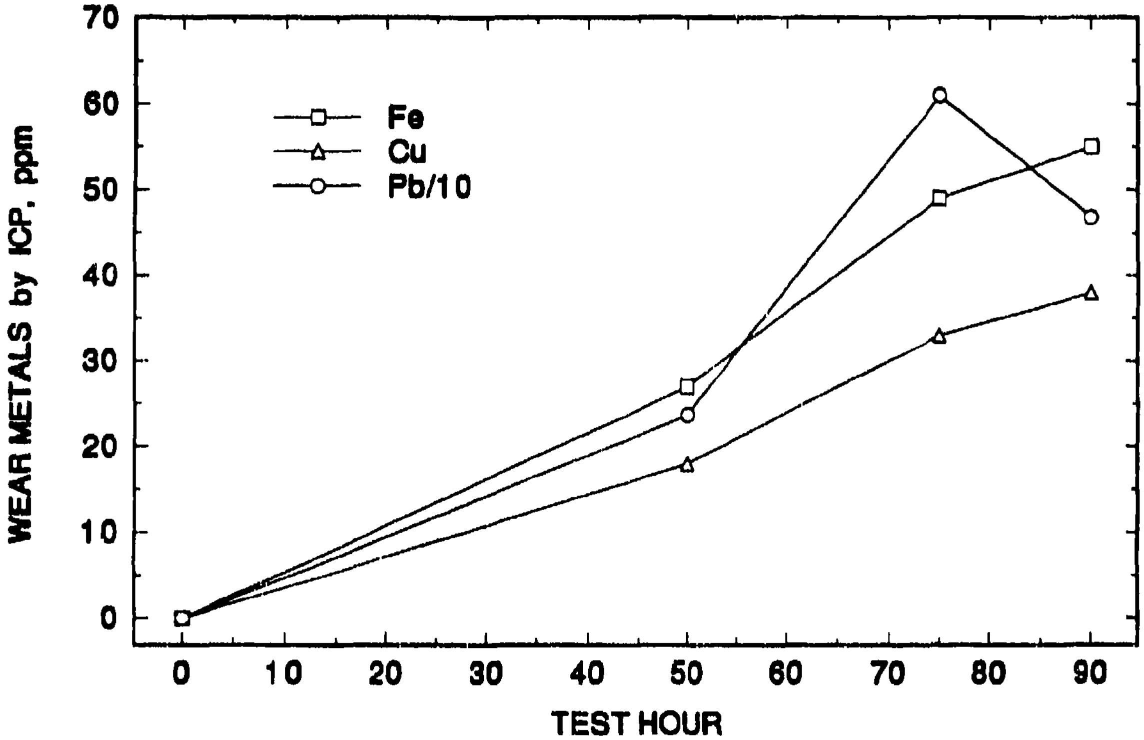


Figure 14. Test A-3, Oil C, wear metals

Unused Oil C had an HPDSC breakpoint at 180°C isothermal of 142 minutes while the used oil breakpoints at 50, 75, and 90 hours were <10 minutes, indicating that these used oils had no reserve antioxidant remaining.

High-temperature candidate Oil D (Test A-4) was an experimental SAE 30 viscosity grade, synthetic diesel engine oil. This lubricant evaluation completed the scheduled 200 hours, and the engine was disassembled for parts rating and inspection. The ratings revealed no cylinder liner scuffing or bore polish, and no ring face distress. All three rings were free with moderate to heavy groove and land deposits. The heaviest deposits were in the top groove and on the top land and also on the third groove and land. The connecting rod piston pin bushing, the main bearings, and connecting rod bearings appeared to be free of distress. The EOT lubricant inspection indicated reserve alkalinity was remaining, and very little oil degradation. Fig. 15 shows the plot of oil viscosity with test hours, and Fig. 16 shows the accumulation of iron and copper wear metals in the used oil during the test. The variations in the copper plot are because 20 ppm was the lower detection limit for copper on the XRF instrument that was used. The EOT kinematic viscosity at 100°C had increased by only 9 percent, and used oil wear metal contents by ICP were 72 ppm iron, 32 ppm copper, and 71 ppm lead.

Because HPDSC breaktime at 180°C isothermal was greater than 300 minutes for this oil, the temperature was increased to 190°C, which produced a breakpoint of 172 minutes. EOT HPDSC breakpoint at 190°C was 44 minutes, which indicated that the oil still had reserve antioxidant remaining.

High-temperature candidate Oil E (Test A-5) was an experimental SAE 40 viscosity grade, synthetic diesel engine oil. The lubricant evaluation was stopped at 100 hours because of sudden increases in wear metals and viscosity, and the engine was disassembled for parts rating and inspection. The ratings revealed no cylinder liner scuffing, 5-percent cylinder liner bore polish, and no piston ring face distress. All three rings were free, with moderate to heavy groove and land deposits. The heaviest deposit ratings were in the third groove and on the third land. The connecting rod piston pin bushing, the main bearings, and connecting rod bearings all revealed

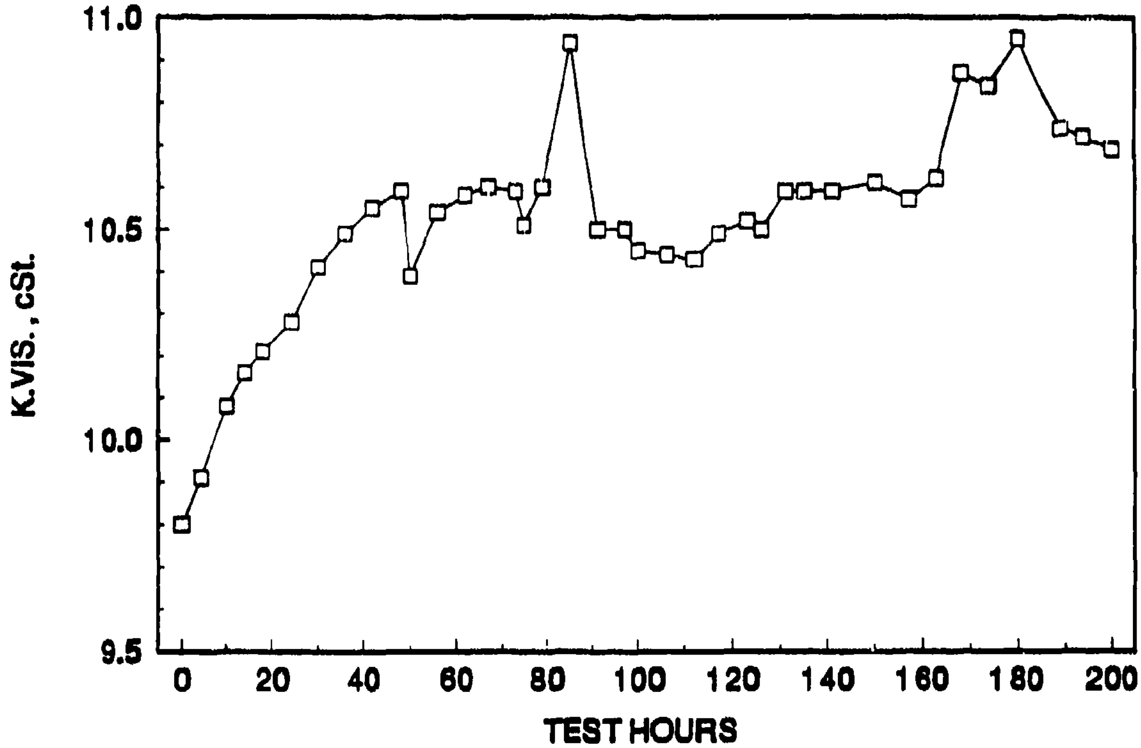


Figure 15. Test A-4, Oil D, K. Vis at 100°C

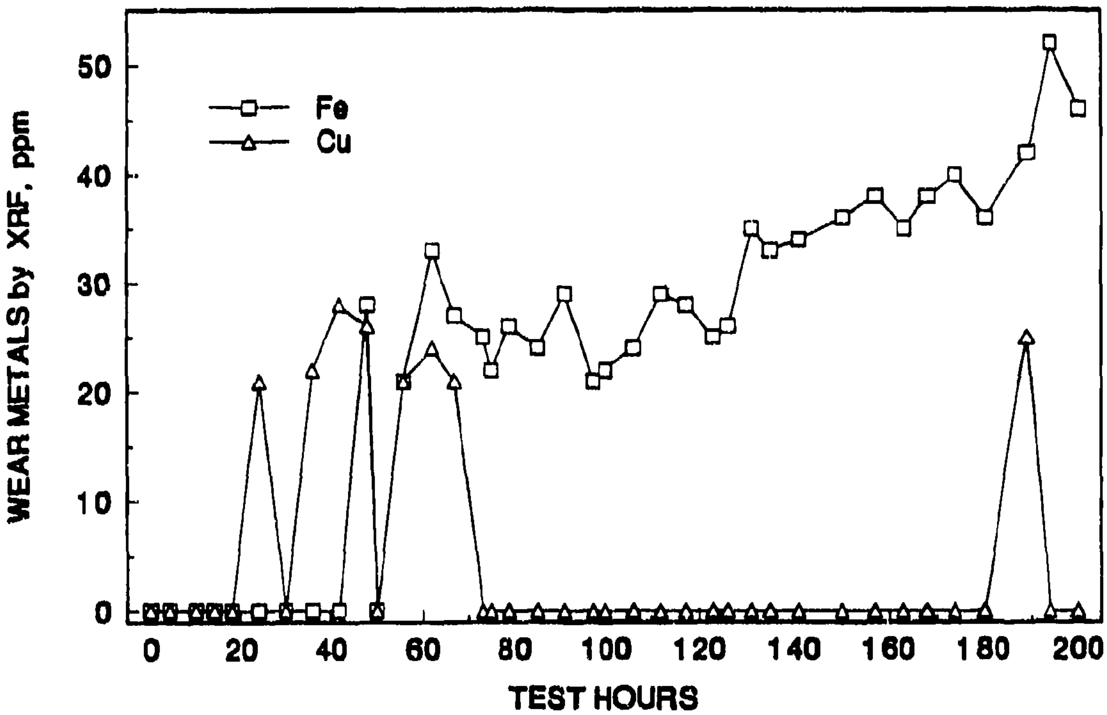


Figure 16. Test A-4, Oil D, wear metals

signs of distress and exposed copper. Of particular interest was the near catastrophic failure of the slipper piston pin bushing and the slipper piston connecting rod bearing shell. The EOT lubricant inspection indicated that substantial oil degradation had occurred, apparently catalyzed by the copper from the bearings. This test showed a 100-percent increase in lubricant viscosity and an extremely high TAN of 20. Fig. 17 shows the plot of viscosity increase during the test. The viscosity increased slowly throughout the test until between 94 and 100 hours, at which point it had a large increase. Fig. 18 shows the wear metal accumulations during the test. Substantial increases in both iron and copper occurred between 94 and 100 hours. EOT used oil wear metal contents by ICP were 112 ppm iron, 97 ppm copper, and 119 ppm lead. Also in evidence was 323 ppm zinc, in a lubricant that does not contain a zinc additive. It is speculated that the zinc originated from the bearing material.

High-temperature candidate Oil F evaluated in Test A-7 was an experimental SAE XW-30 (undetermined low-temperature properties) viscosity grade, synthetic-based diesel engine oil. This lubricant evaluation was stopped at 74 hours, at which time the engine was disassembled for parts rating and inspection. The evaluation was terminated due to a 66 cSt viscosity at 100°C at 73 hours. The ratings revealed no cylinder liner scuffing, 2.0-percent cylinder liner bore polish, and no piston ring face distress. The compression ring and scraper ring were free, while the oil control ring was 20-percent cold stuck. All three rings had moderate to heavy groove and land deposits. The connecting rod piston pin bushing had 10-percent exposed copper on the top half and 90-percent heat fatigue with flaking and pitting on the bottom half. No significant bearing distress was evident, other than 5-percent flaking of the overlay on the bottom half of the active connecting rod bearing. Fig. 19 shows the plot of the used oil kinematic viscosity at 100°C with test hours. A gradual viscosity increase was observed until between 66 and 73 test hours when a large viscosity increase occurred. However, viscosity of the 75-hour sample from the oil sump was reduced. Viscosity was determined for used oil residues found in the oil pan and valve deck at EOT. In each case, the viscosity was greater than the 75-hour sump used oil sample. It appears that the 75-hour used oil sample had stratified or broken into phases of different viscosities.

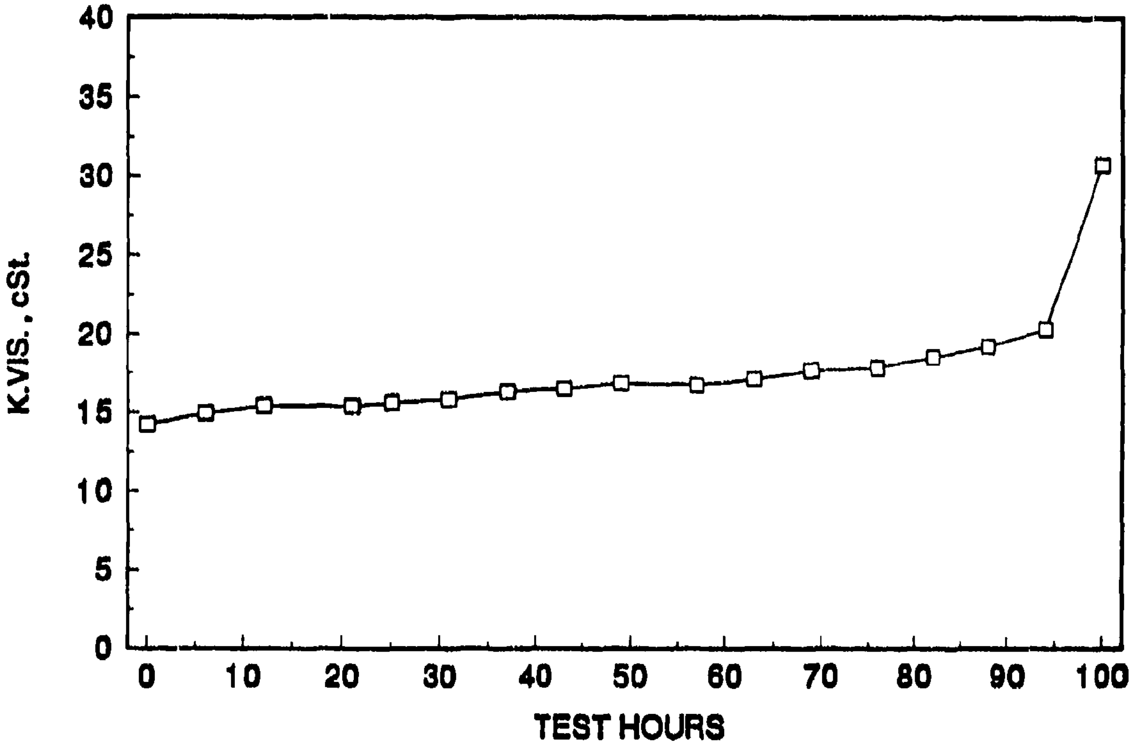


Figure 17. Test A-5, Oil E, K. Vis at 100°C

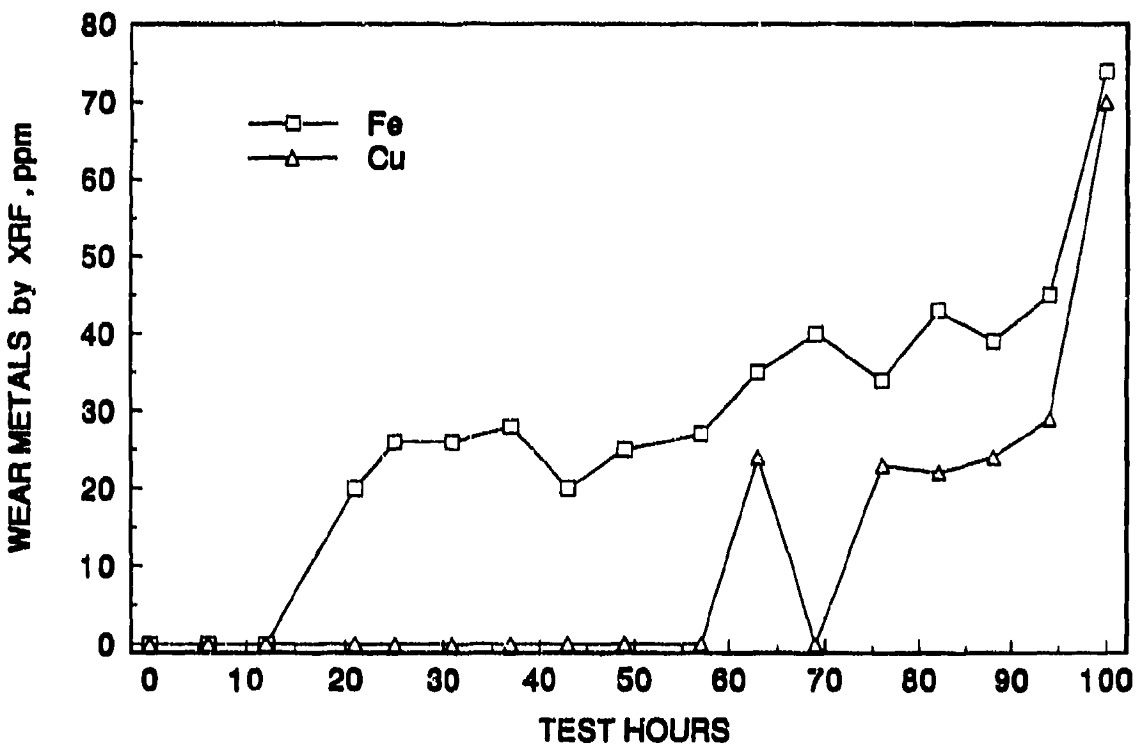


Figure 18. Test A-5, Oil E, wear metals

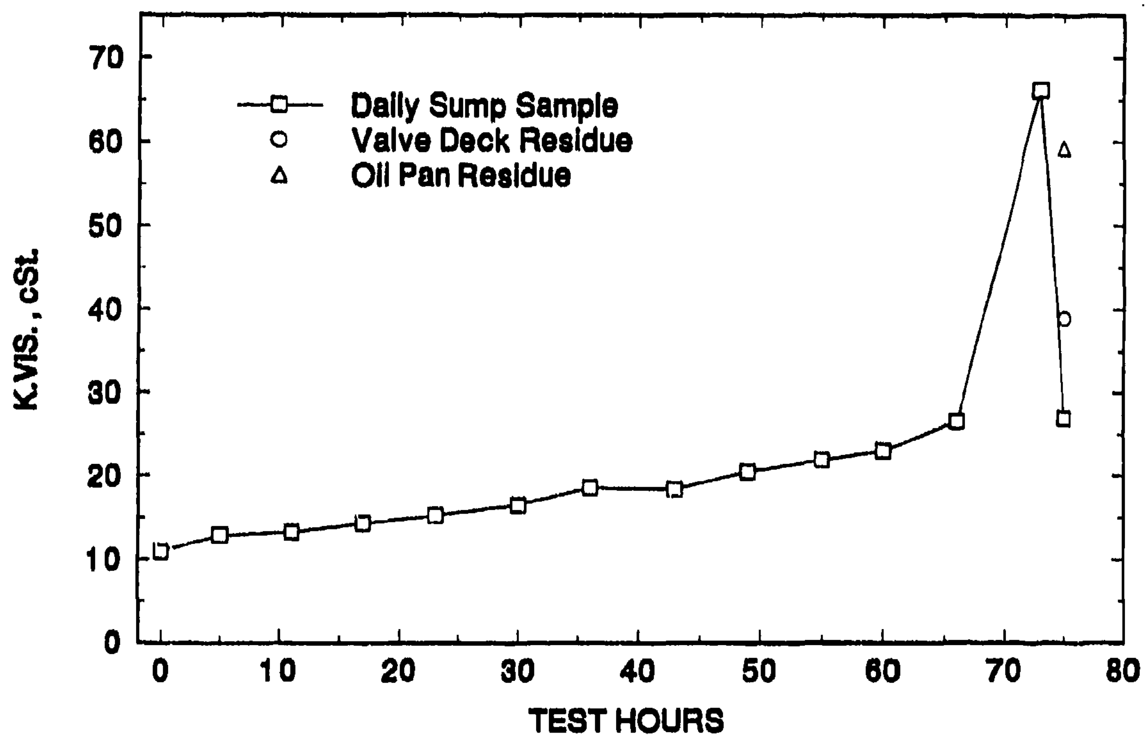


Figure 19. Test A-7, Oil F, K. Vis at 100°C

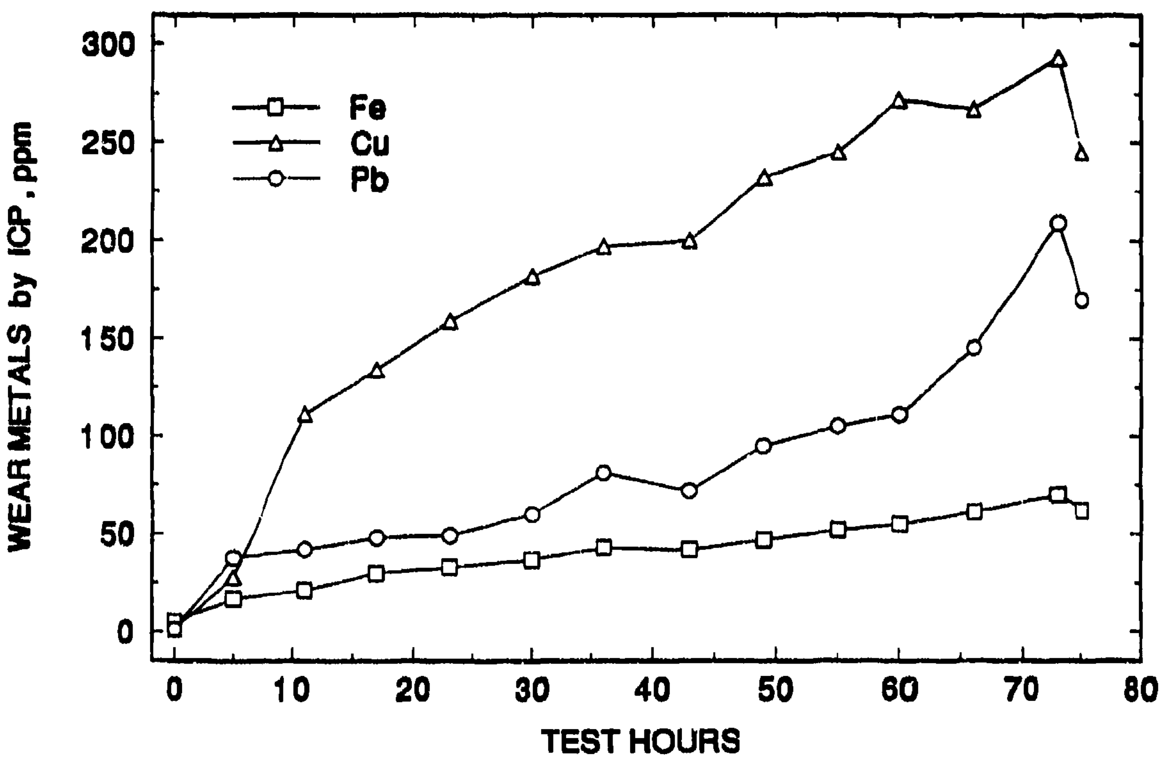


Figure 20. Test A-7, Oil F, wear metals

Fig. 20 shows the build up of used oil iron, copper, and lead with test hours. As with viscosity, the wear metals reached their maximum at 73 hours and were reduced at 75 hours (EOT). Used oil copper increased dramatically between 5 and 11 test hours and continued to increase throughout the remainder of the test. The lead content increased substantially between 60 and 66 test hours. EOT used oil wear metal contents by ICP were 62 ppm iron, 245 ppm copper, and 170 ppm lead. The high values of copper and lead are evidence of possible bearing corrosion.

HPDSC breaktime at 190°C isothermal conditions was greater than 300 minutes for the unused oil and was reduced to 33 minutes for the EOT used oil. This indicates that the used oil still had some reserve antioxidancy.

E. Lubricant Performance Comparisons

Comparisons of candidate high-temperature lubricant performance are difficult because the test durations vary. Viscosity increase at 100°C was normalized by test hour to get a value for cSt increase/test hour, with the results shown in Fig. 21. It should be noted that the data for Oil B in Figs. 21 through 25 are the average of two engine tests. Oil D clearly had the lowest normalized viscosity increase rate. This is indicative of low oxidation rate, low soot accumulation, and low loss of light ends. Fig. 22 shows the brake specific oil consumption (BSOC) in lb/Bhp-hr for each test. Oils D and E had the best performance with respect to specific oil consumption. Oil B, the petroleum-based oil, had a specific oil consumption rate 4.5 times higher than that of Oils D and E. Comparative piston deposition performance of these six lubricants is presented in Fig. 23, which shows the total piston deposit rating (WDK) for each oil. Each bar graph showing total WDK deposit rating also shows the contribution of each piston area to the total deposit rating. The very high deposit rating obtained with Oil F was the result of heavily weighted deposits lower down the piston such as the third land. In overall WDK rating, Oil D had the best performance. Fig. 24 shows the grouped locational deposit ratings for these pistons. The "upper" grouping, which represented the higher temperature regions of the piston, included the top land and groove and second land. The balance of the piston rating areas was grouped in the "lower" piston temperature area. This analysis shows that Oils C and D had

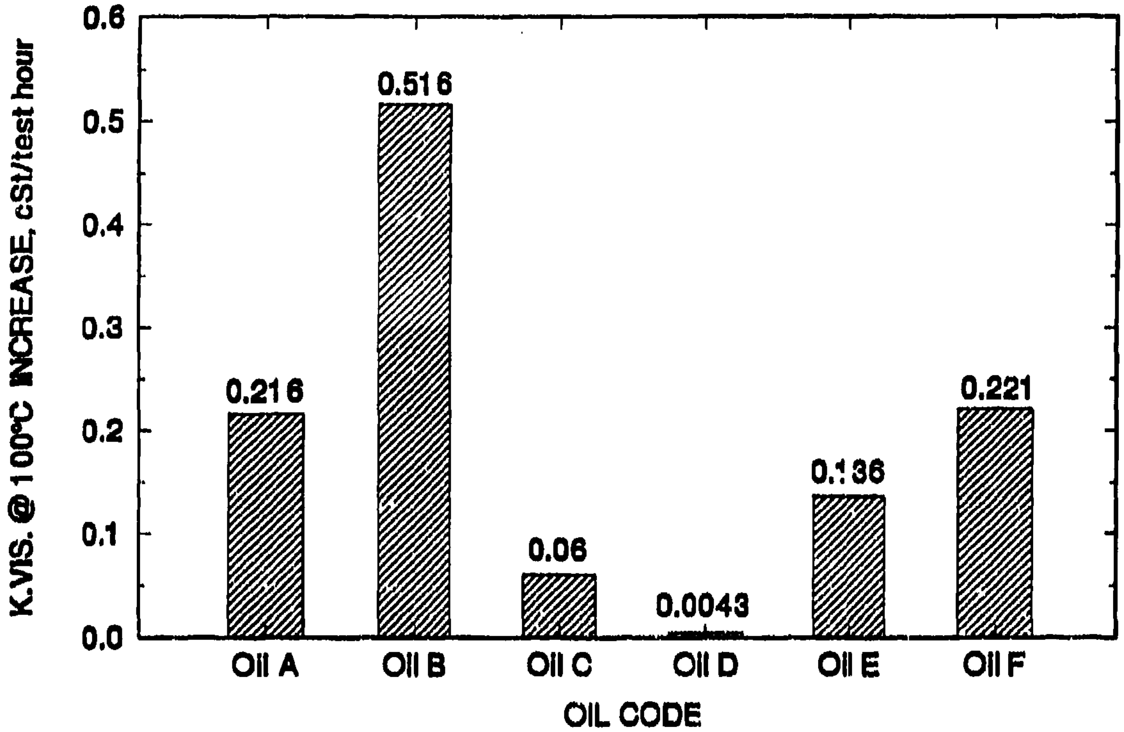


Figure 21. K. Vis at 100°C increase, cSt/test hour

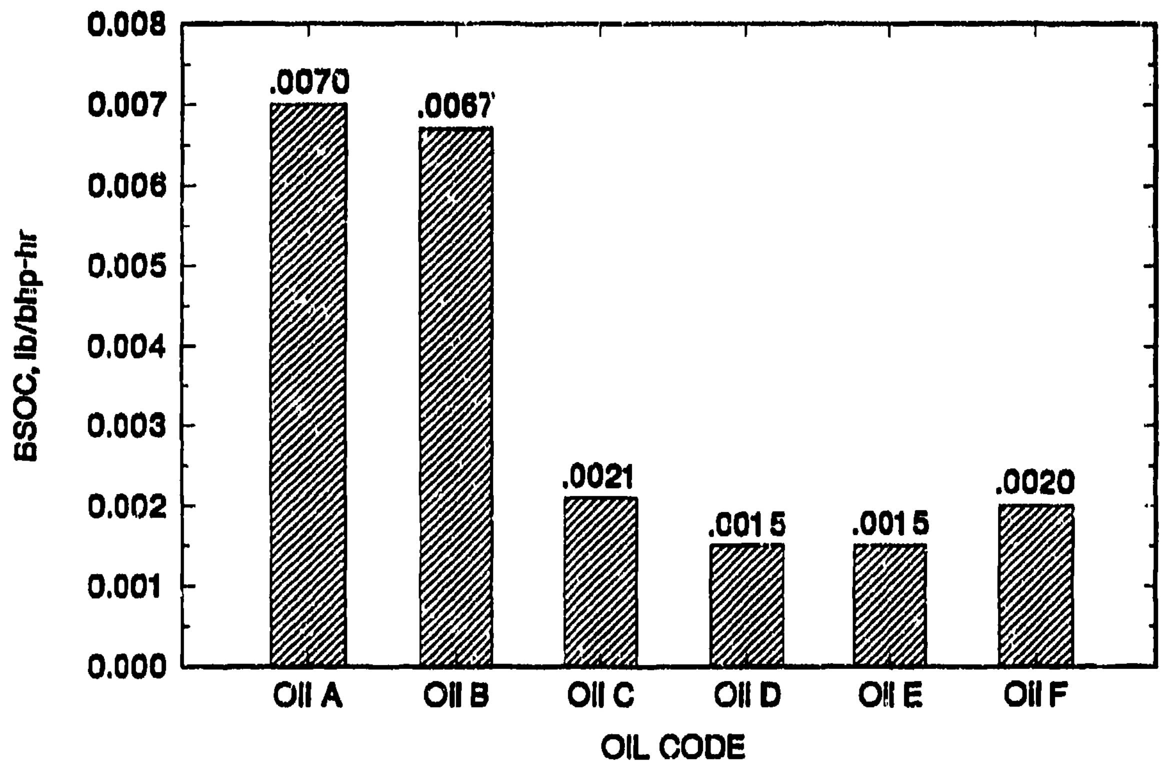


Figure 22. BSOC, lb/Bhp-hr

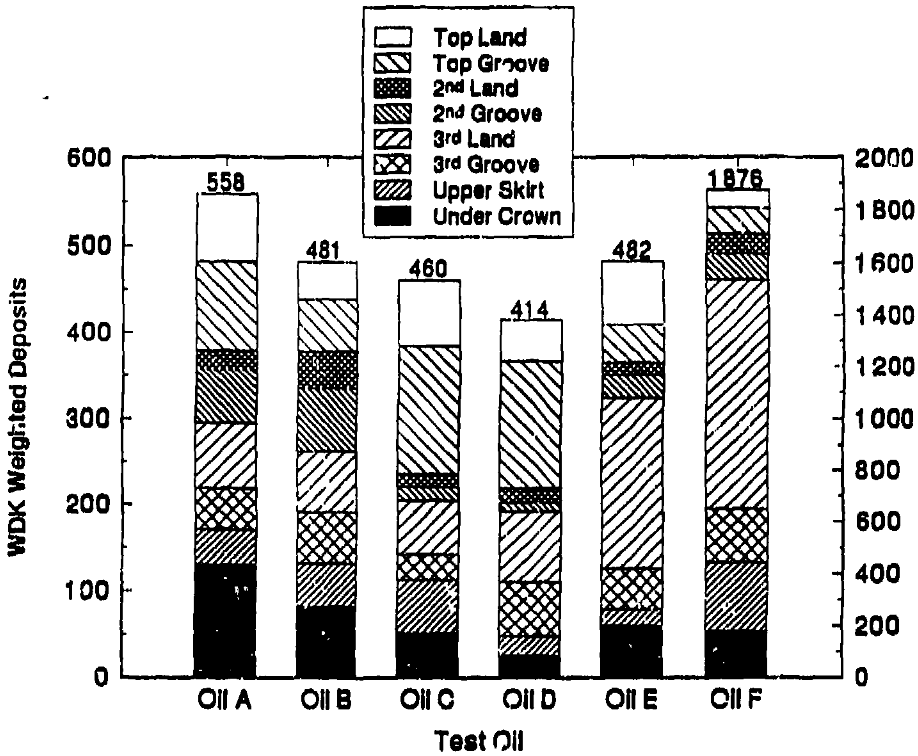


Figure 23. Total piston deposit rating (WDK) for each oil

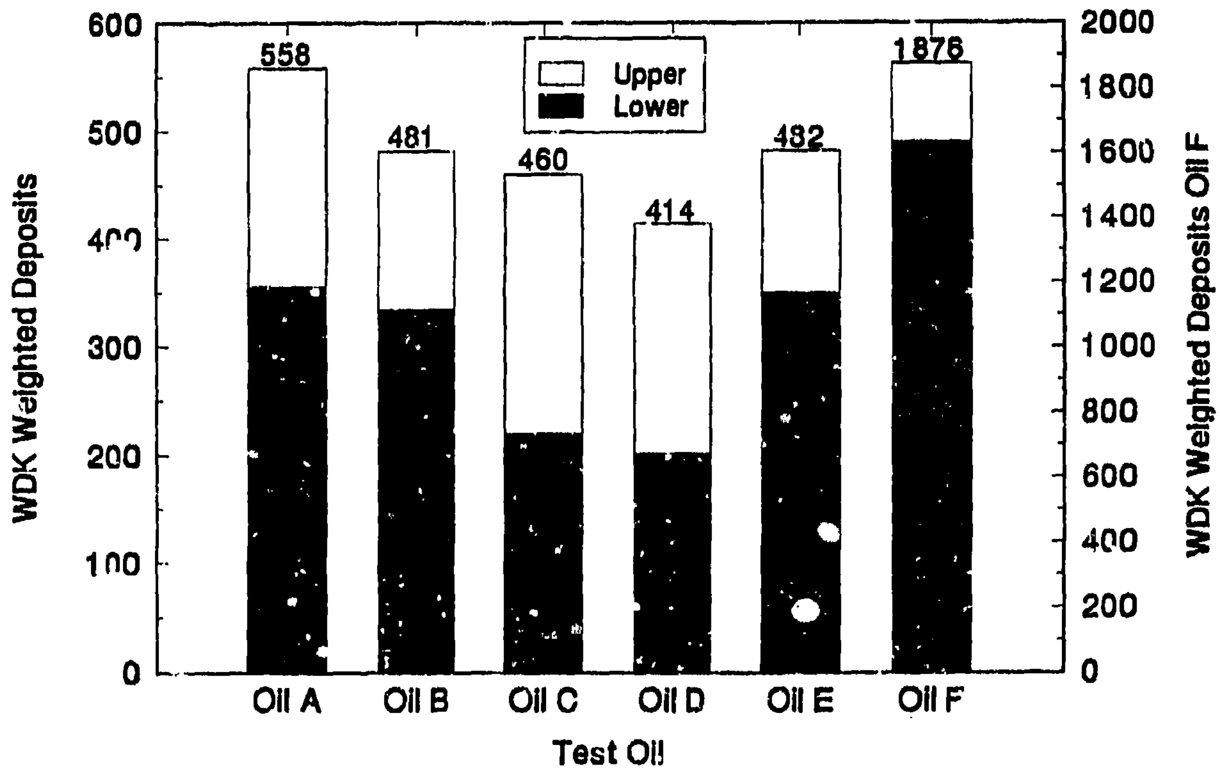


Figure 24. Grouped locational deposit ratings for pistons

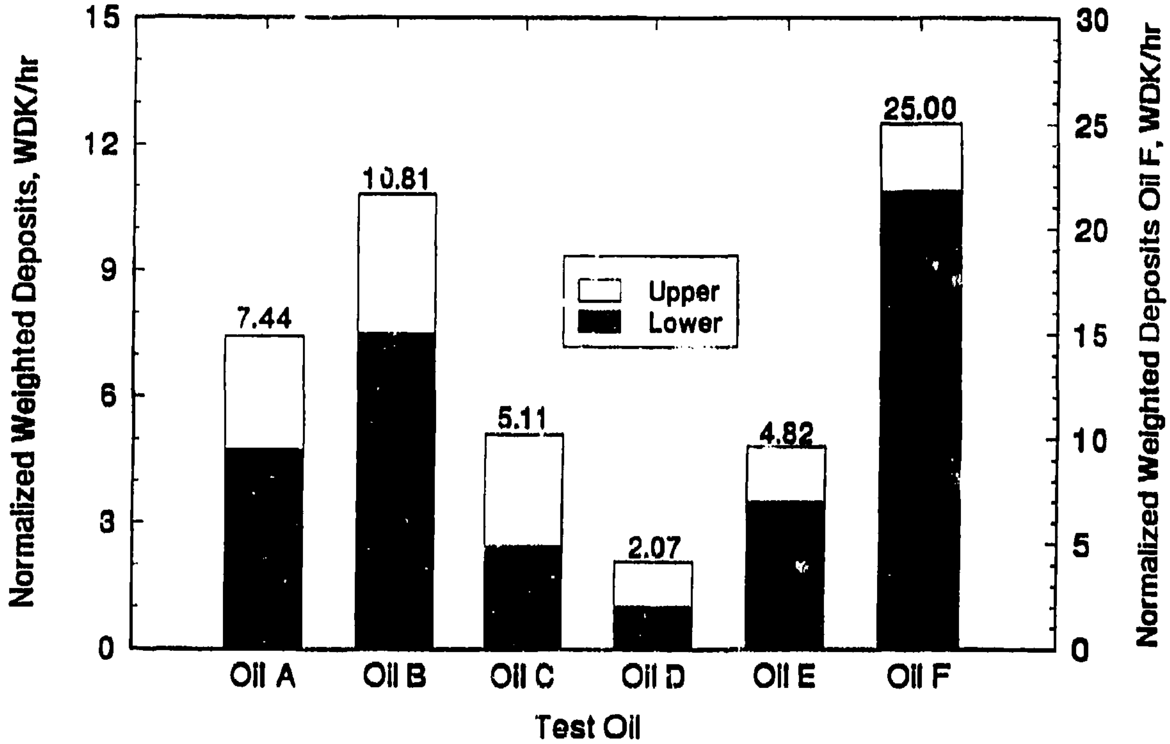


Figure 25. WDK piston deposit ratings normalized by test hour

the least lower area deposits, yet still had substantial upper area deposits. Finally, Fig. 25 shows the WDK piston deposit ratings normalized by test hour to give a WDK/hour value, which is presented in bar graph format with upper and lower piston area groupings. By this analysis, Oil D had the least deposits per hour of operation. Overall, Oil D had the best performance; however, improved deposit control in upper piston areas is needed.

IV. BENCH WEAR EVALUATIONS

A. Contact Conditions at Ring/Liner Interface

Previously, a single-cylinder engine test performed with each of the lubricants was described. The measured top ring reversal temperature in this partially cooled engine was approximately 240°C, which is somewhat higher than normal. Little wear and no obvious trends were evident in physical measurements of wear prone cylinder liner components in this test (see Appendix H). However, if thick film lubrication is maintained between the piston ring and liner, virtually no wear can be expected. In an attempt to define the level of interasperity contact and also the effects of increasing temperature on overall film thickness, the hydrodynamic film thickness around the piston ring liner interface was modeled.

Simple consideration of the dynamic film formation predicts that no film should exist at both top and bottom dead center, due to the lack of relative motion at this point. However, the rapid decrease in film thickness required for intermetallic contact is normally prevented by squeeze film action. A simple analysis by Furahama (26) predicts that a significant oil film is temporarily maintained at both top and bottom dead center, as shown in Fig. 26. The predicted film thickness is in general agreement with practical measurements performed by Lux using a quartz window fitted to a similar engine.(27) However, detailed comparison is not possible due to incomplete information relating to the test conditions used in the full-scale tests.

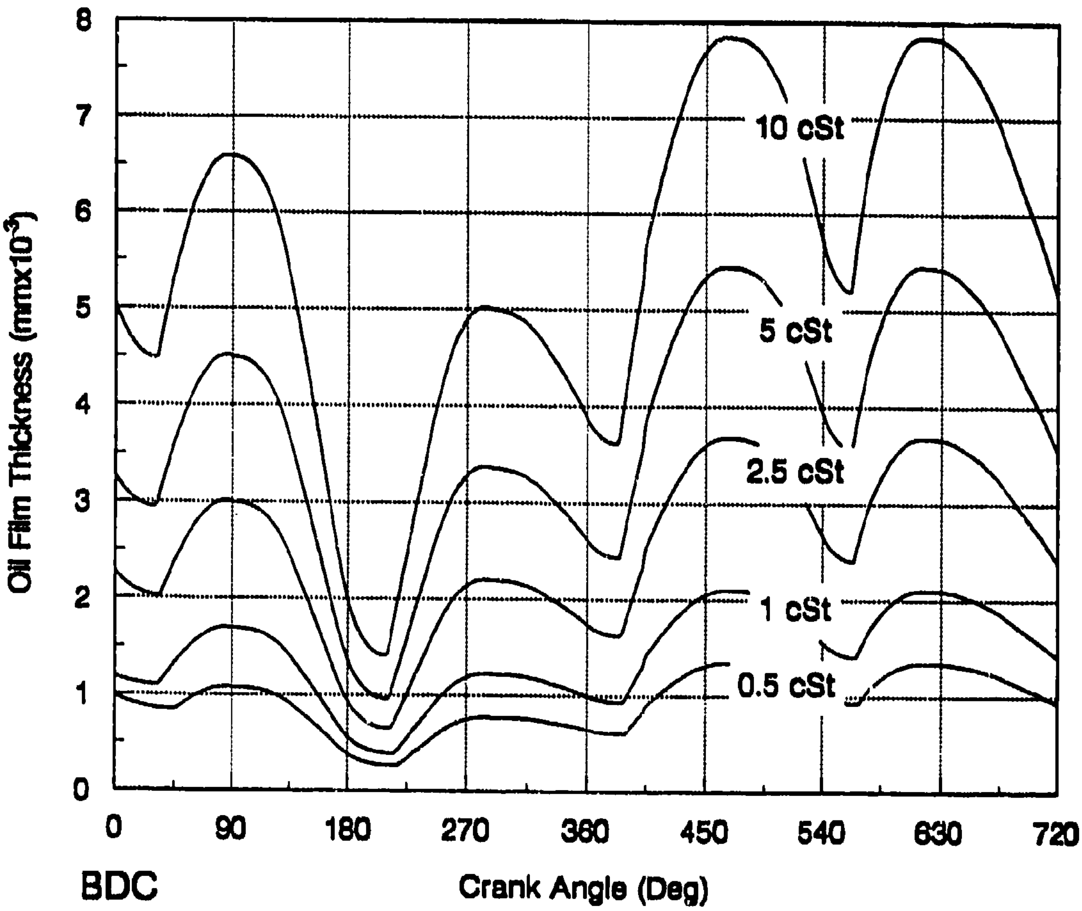


Figure 26. Theoretical oil film thickness throughout combustion cycle at 2200 rpm
(Note: 2200 rpm corresponds to maximum torque.)

The minimum film thickness is predicted to occur approximately at 35° of crank rotation after top dead center on the firing stroke, due to the dynamics of the crank mechanism combined with the increasing combustion pressure. This position corresponds to approximately 14 mm from the top ring reversal point and a sliding speed of over 10 m/s. Minimum film thickness is predicted to increase almost linearly with viscosity and is almost an order of magnitude greater at 10 cSt than at 0.5 cSt, as shown in Fig. 27. The minimum film thickness also decreases with decreasing speed, as the hydrodynamic lift component is reduced and more time is available to allow the oil to be squeezed from the contact. The decrement in speed from 2600 to 2200 rpm produces a disproportionately severe reduction in film thickness, as the mean combustion pressure is marginally greater under maximum torque conditions. Combustion pressure decreases rapidly at speeds below maximum torque. However, the reduction in combustion pressure is not sufficient to counteract the decrease in hydrodynamic lift produced at low speeds.

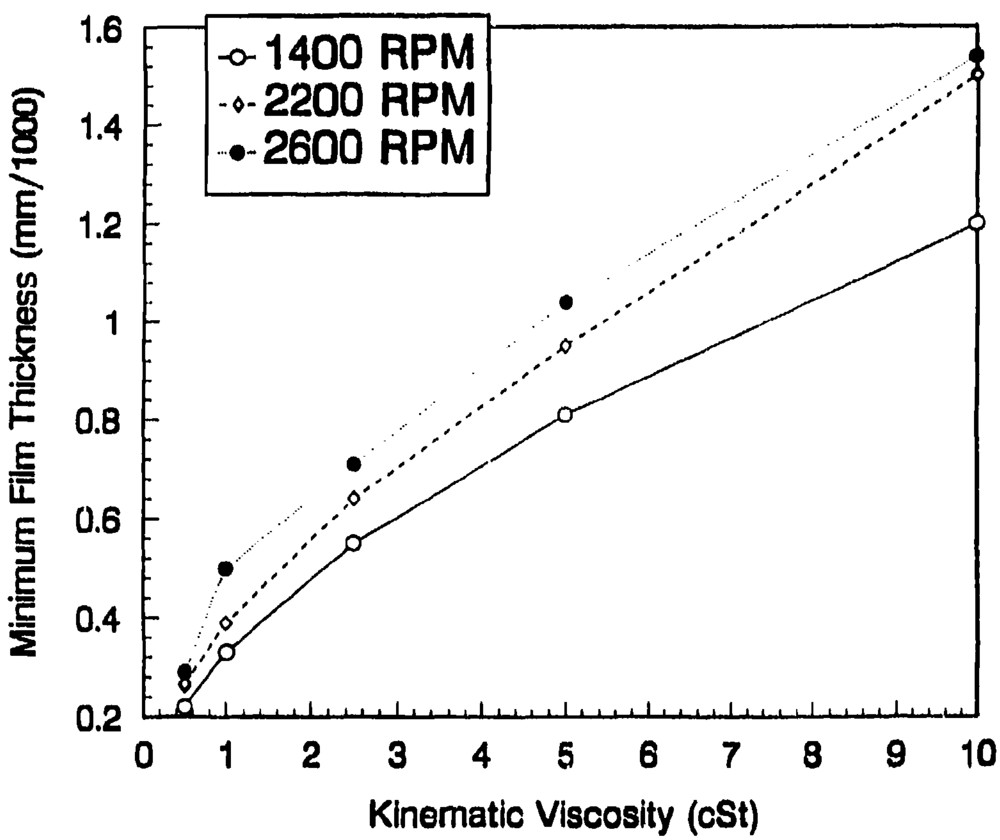


Figure 27. Theoretical minimum oil film thickness in SCE-903 engine at full-load conditions

At a critical film thickness, asperity interaction between the opposing surfaces begins. Based on the surface roughness measurement, one can obtain a λ value as described in Equation 1 below. The parameter λ is the ratio of the film thickness (h) to the composite surface roughness.

$$\lambda = \frac{h}{\sqrt{R_1^2 + R_2^2}} \qquad \text{(Eq. 1)}$$

The denominator is the composite surface roughness calculated from the Root Mean Squared (RMS) surface roughness of both surfaces, R_1 and R_2. For surfaces with a Gaussian height distribution, no asperity interactions are expected if λ is greater than approximately 2.5. At λ less than 1, severe asperity interaction is expected. The range $1 < \lambda < 2.5$ is a transition region. The RMS surface roughness of the worn liner and piston ring is approximately 0.371×10^{-3} and 0.18×10^{-3} mm, respectively. According to this theory, a minimum film thickness (h) of between 0.41×10^{-3} and 0.9×10^{-3} mm is required to prevent intermetallic contact between the opposing surfaces. However, the measured profile of the cylinder liner has a negative skewness of approximately –5 and a high kurtosis between 20 and 50. (Gaussian random surfaces have a skewness of 0 and a kurtosis of 3.) This result indicates that relatively deep grooves are present and much of the original plateau honed surface topography remains. The surface profile of the piston ring also has a slight negative height distribution, with a skewness of approximately 1.2 and a kurtosis of approximately 8. The probability of asperity interaction between such surfaces is less than for a random Gaussian height distribution.

For an RMS surface roughness of 0.4×10^{-3} mm, a minimum oil viscosity of approximately 1.5 cSt is required to prevent asperity contact at 1400 rpm (see Fig. 27). The average cylinder liner temperature in the uncooled SCE-903 engine was measured using surface thermocouples and was found to be approximately 260°C. Since the oil viscosity at this temperature is also approximately 1.5 cSt, it should provide at least a partial hydrodynamic film at 1400 rpm. Moreover, it is recognized that extrapolation of the oil viscosity to this temperature is not fully accurate due to a number of effects including degradation and shear thinning.(28)

The engine test series described in Appendix H were performed at 2600 rpm. This engine speed is predicted to provide additional film strength and reduces the probability of wear when compared with low-speed operation. Clearly, any further increases in temperature are predicted to produce more severe wear, especially if combined with decreased engine speeds. These effects, combined with the potentially decreased wear resistance of some oils, make the ring zone one of the more critical areas in low-heat rejection engines.

B. Bench Wear Test Equipment

Bench wear tests were performed using the Cameron-Plint test apparatus, which is intended primarily for the rapid assessment of the performance of lubricants and lubricant/wear material combinations. The apparatus, shown in Fig. 28, provides a reciprocating contact similar to that found in many engine components. The sliding speed, amplitude, applied load, and temperature may be varied over a wide range. In addition, test specimens may be easily machined from a range of materials. The friction coefficient and electrical contact resistance are measured during

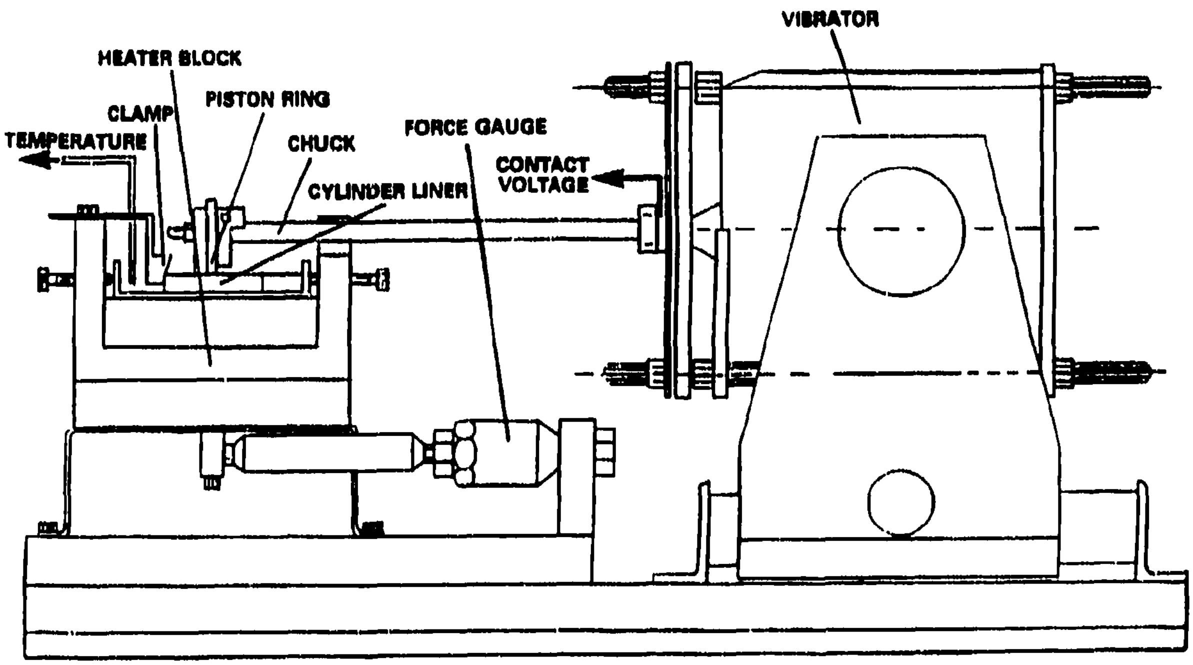


Figure 28. Schematic diagram of the Cameron-Plint test apparatus

each test, and the results are plotted using an X-t plotter. A Lunn-Furey circuit was used to measure the contact resistance formed between the sliding specimens, and the result provides an indirect measure of the strength of the lubricating film between the surfaces. This film may be due to either molecular surface layers formed during boundary lubrication or relatively thick hydrodynamic and elastohydrodynamic (EHD) fluid films.

Two specimen configurations and metallurgies were used in the present study. Initially, the contact configuration was designed to reflect the metallurgies present at the interface between the piston ring and cylinder liner. Test flats were machined from the cylinder liner of the VTA-903T engine that was used in the previously described single-cylinder engine tests (primarily an unhardened pearlitic grey cast iron). The opposing (reciprocating) specimen was formed from a segment of the chrome-plated piston ring from the same engine. A relatively small contact area of approximately 1 mm^2 was formed by the barrel face ring on the test flat. No material was removed during any of the tests from the very hard chrome-faced ring. As a result, all wear measurements were taken on the opposing liner using a Talysurf profilometer.

Initial tests were performed with the ring rigidly mounted in the reciprocating specimen holder. However, the slight curvature across the ring was not sufficient to ensure perfect alignment with the test flat, i.e., the contact area would occur at the edge of the ring. Test repeatability was poor due to the wide variation in contact geometry between succeeding tests. Subsequent test development produced a floating ring design. The sliding direction is perpendicular to that normally seen by the piston ring. However, the ring is free to align itself with the test flat in the plane perpendicular to the direction of motion. Test repeatability was improved while greatly reducing setup time.

For most tests, a second, simple-contact geometry was used. During these tests, a simple, high-pressure counterformal contact was formed, using a ball-on-flat geometry. The upper specimen consists of an AISI E-52100 steel specimen of either 12.7 mm (0.5 in.) or 6.4 mm (0.25 in.), depending on the contact load required (see TABLE 5). The lower specimen was of the same material polished to a mirror finish. This metallurgy corresponds exactly to that used

TABLE 5. Specification of AISI E-52100 Test Specimens

Material	AISI E-52100 Steel
Ball Size	0.25 and 0.5 in.
Hardness, R_c	64 to 66
Surface Roughness, CLA	0.034 μm
Thermal Conductivity	36 W/M°C
Specific Heat Capacity	405 J/kg°C
Thermal Diffusivity	1.15×10^{-5}
Density	7810 kg/m^3
Chemical Composition, wt%	
C	0.95–1.1
Si	0.10–0.35
Mn	0.4–0.7
Cr	1.2–1.6

in the conventional four-ball wear test. The simple ball-on-flat geometry has the additional benefit of producing a well-defined scar on the ball that may be accurately measured using optical microscopy. The volume of material corresponding to a given wear scar diameter may be derived using a standard mathematical relationship.(29) Unless otherwise stated, the tests were performed under fully flooded lubrication conditions.

Elastic deformation of the substrate material close to the counterformal contact will artificially increase the apparent wear scar diameter on the ball, and this effect may be accurately predicted for unworn specimens using the Hertz equations. Significant specimen deformation is present in the highly loaded four-ball wear test (<2000 N). However, in the present relatively lightly loaded test series, the true wear volume is between one and two orders of magnitude greater than the deviation caused by elastic deformation. As a result, this effect may be ignored during the present study. During initial tests, additional measurements of the scar formed on the opposing test flat were also taken using surface profilometry for comparison with the measurements from the ball.

C. Bench Wear Test Results

1. Initial Tests With Lightly Loaded Ring Zone Materials

This wear test series was performed to specifically represent both the metallurgy and contact loading at the piston ring/cylinder liner interface. The test conditions chosen are provided in TABLE 6. The tests were performed at 160°C, which is well below the 260°C cylinder liner temperature measured during the single-cylinder engine test series. As a result, it is hoped that the results will more accurately reflect the basic wear resistance of the oils and metallurgy, rather than high-temperature performance. These conditions produce boundary contact with some hydrodynamic lift. A more complete analysis of the effects of fluid film lift will be provided in subsequent sections.

TABLE 6. Conditions Used to Derive Test Results in Fig. 29

Parameter	Value	Unit
Load	20	N
Temperature	160	°C
Duration	480	min
Speed	17	Hz
Amplitude	15	mm
Lub. Supply	Flooded	
Materials	Chrome Ring/CI Liner	

The results obtained from these lightly loaded tests are provided in Fig. 29. The test temperature of 160°C is not sufficient to promote excessive degradation of the oils during the 480-minute test. As a result, the superior high-temperature performance of the polyolester-based oils was not evident. The wear observed with Oil D was especially severe and was slightly more than the base stock from which it is derived. The level of wear observed for Oil E (both base stock and formulated oils) was less than for Oil D, possibly due to its higher viscosity (10 cSt for Oil D versus 14 cSt for Oil E at 100°C). As expected, each of the fully formulated oils (Oil A, Oil B, and Oil C) produced relatively little wear.

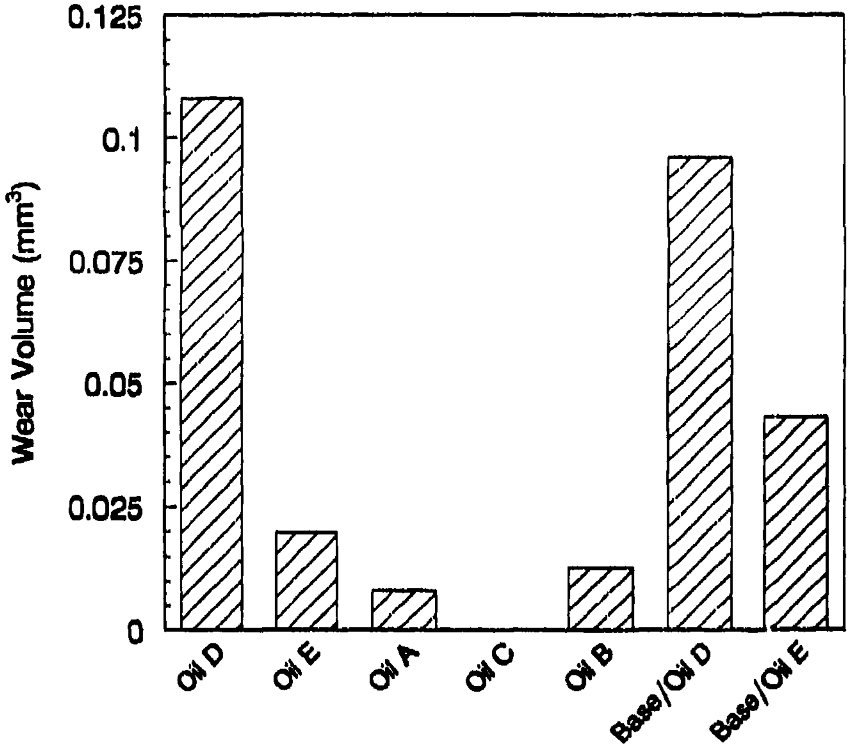


Figure 29. Wear tests with ring zone materials at 160°C

2. Comparison of Oils D and E to Their Base Stocks

The wide variation noted in the previous section between the wear resistance of Oils D and E was unexpected. Oils D and E are similar oils with the same high-stability, low deposit-forming additive package, and are largely di-pentaerythritol hexapentanoate and di-pentaerythritol hexananoate, respectively.(12) To determine the cause of the variation observed, supplementary tests were performed to determine the wear protection provided by the base stocks in each instance, with the results shown in Figs. 30 and 31.

The tests were performed in a fully flooded contact at the conditions provided in TABLE 7. As expected, both base stocks provide very similar wear protection over the complete load range. However, the additized Oil D produces **more** wear at low loads than the base stock from which it is derived. At higher loads, the Oil D base stock becomes less effective and a crossover occurs. In contrast, Oil E produces appreciably less wear than its base stock over the complete load range studied. Neither base stock produces a measurable contact resistance at applied loads

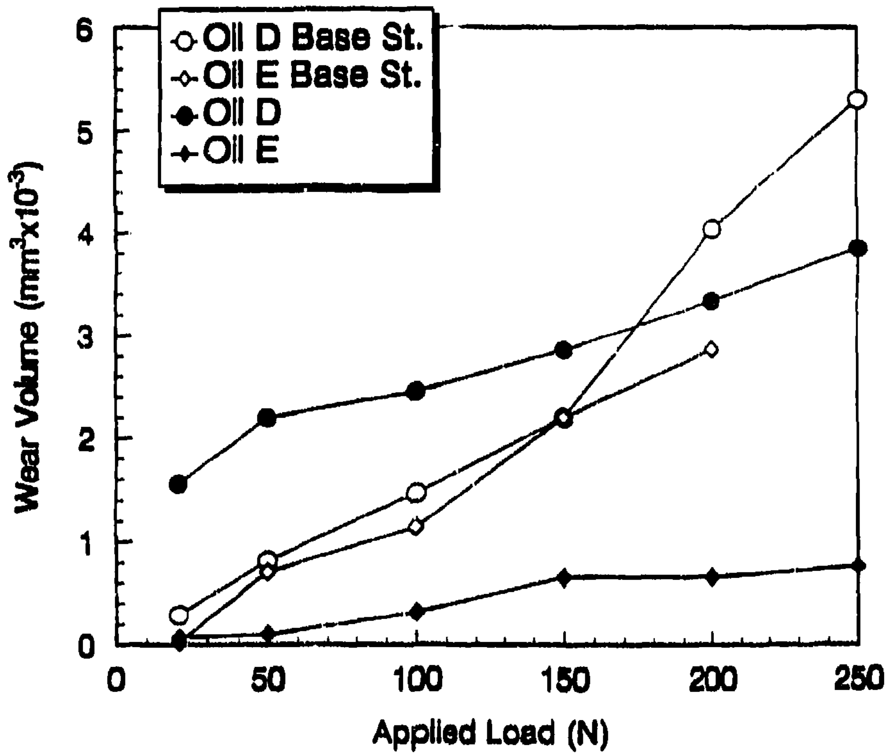


Figure 30. Wear volume for Oils D and E compared to their base stocks

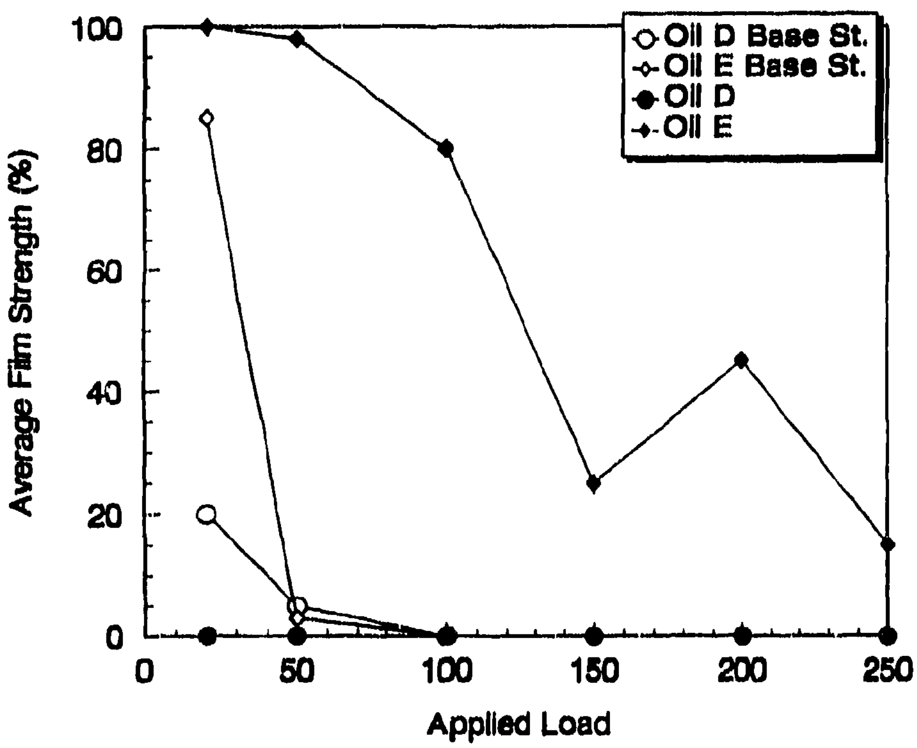


Figure 31. Average film strength for Oils D and E compared to their base stocks

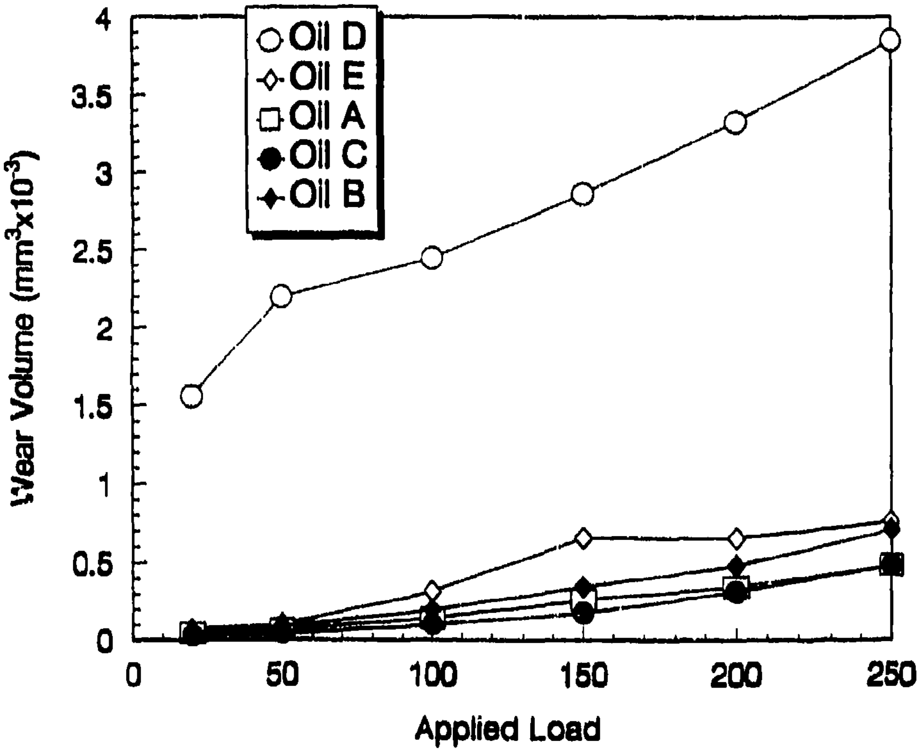
TABLE 7. Conditions Used to Derive Test Results in Fig. 32

Parameter	Value	Unit
Load	20-250	N
Temperature	160	°C
Duration	20	min
Speed	30	Hz
Amplitude	4.75	mm
Lub. Supply	Flooded	
Materials	52100 ball and polished flat	

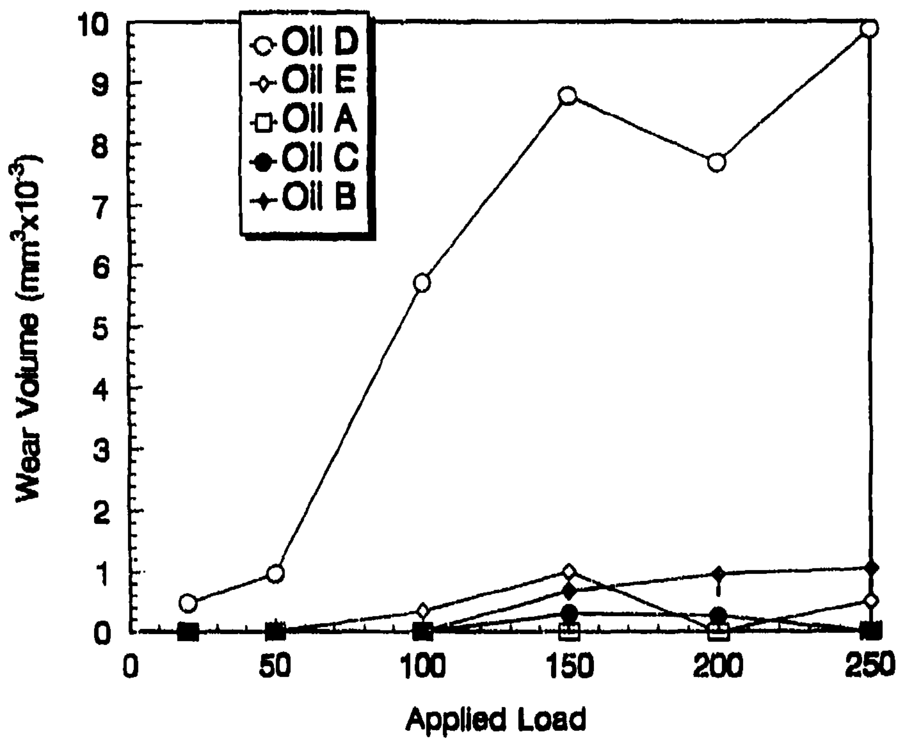
in excess of 50 N. In contrast, however, a strong contact film is observed for Oil E, while no film is observed for Oil D at any load. Clearly, the additive package in Oil E is producing a boundary lubricant film, independent of its viscosity. Similarly, Oil E produces marginally lower friction in this test than either Oil D or either base stock. As a result, it appears that the additive package (which does not contain antiwear additives) has a synergistic effect with Oil E and an antagonistic effect with Oil D. However, further analysis is needed in this area.

3. Comparison of Oils Under High-Load Conditions

As previously stated, present state-of-the-art high-temperature lubricants are formulated primarily for detergency, dispersancy, and thermal oxidative stability. Such oils provide decreased protection under highly loaded contact conditions in which surface active chemical compounds are required. A bench test series was performed to evaluate the wear protection provided over a wide range of contact loads. Once again, a test temperature of 160°C was used to reflect the crankcase oil temperature expected to exist during the AIPS test series. The tests were performed with standard metallurgy AISI E-52100 steel, at the conditions detailed in TABLE 7. The wear volumes for each oil are shown in Figs. 32a and 32b as measured for the test ball and flat, respectively.



a. Test Ball



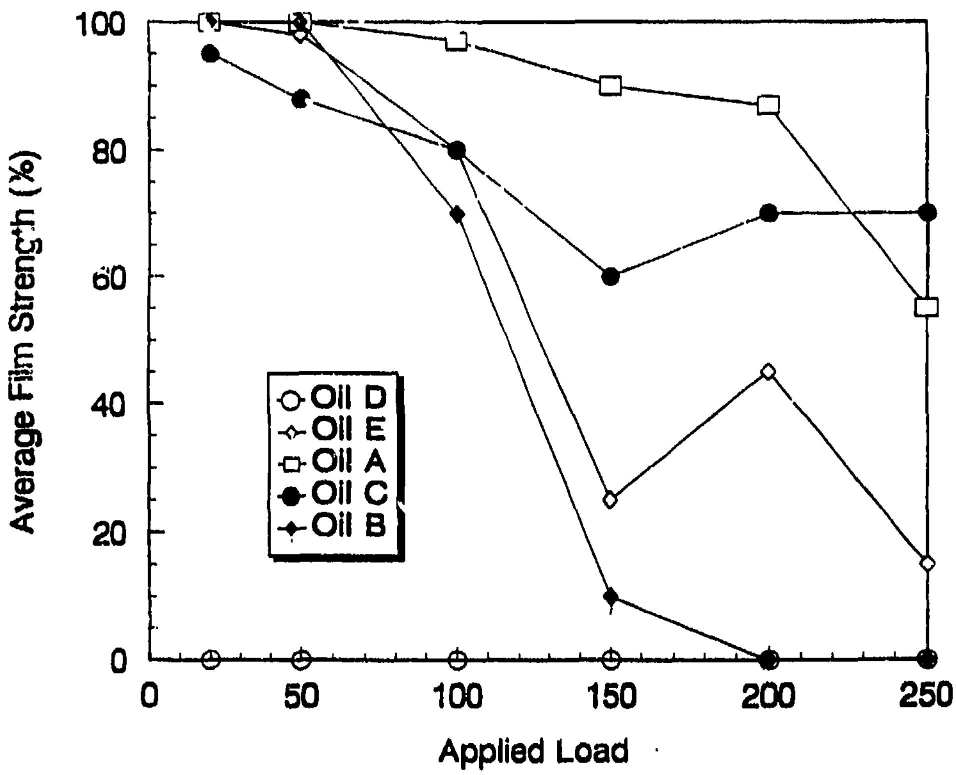
b. Test Flat

Figure 32. Wear volume with AISI E-52100 steel as a function of applied load

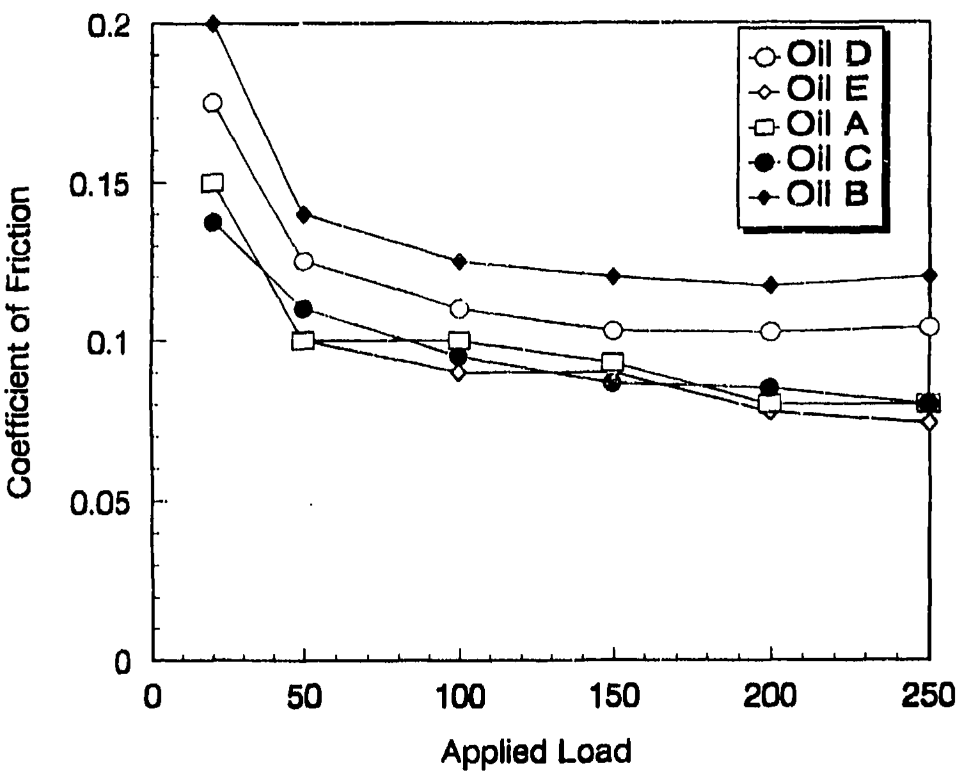
Each of the oils except Oil D produced relatively low wear, which increases linearly with applied load. Severe wear was observed with Oil D over the complete load range. In general, these results with AISI E-52100 steel closely reflect those for the ring/liner material obtained in the previous section. As a result, the more convenient 52100 material is used in most subsequent tests. Similar trends were apparent from measurements on both the test ball and the opposing flat. However, greater test variability was present in the wear measurements from the test flat than the ball. The optical technique used to measure the wear scar diameter on the test ball considers the complete scar and is largely unaffected by local irregularities. In contrast, the surface profile taken using the Talysurf reflects only a strip 5 micrometers wide and so has greater potential for random variation. In subsequent tests with this geometry, the wear measurement was taken only on the ball.

The contact resistance formed throughout the duration of each test is plotted in Fig. 33a. The measured resistance often varied during each test and produced a random trace due to intermittent asperity contacts. The tabulated result is the average measured. Most of the oils produced a strong contact resistance at low loads, due to either boundary lubrication or formation of a relatively thick EHD or hydrodynamic film. The measured film strength decreased as increasing contact pressure destroyed the film and produced intermetallic contact. Once again, however, Oil D produced very different results to the remaining oils and formed no contact resistance, even at the lowest applied load studied. This result would indicate that the contact resistance for the remaining oils that have similar viscosity to Oil D (Oil C and Oil A) is due to the formation of a boundary rather than a hydrodynamic film. Moreover, Oils E and B, which are more viscous than the remaining oils, produce a weaker surface film. However, it should be noted that the pressure/viscosity relationship--which affects the elastohydrodynamic (EHD) film strength--for each of the oils is unknown.

The measured friction coefficient is typically greater than 0.1, which is appreciably greater than expected for hydrodynamic lubrication. Moreover, the average coefficient of friction produced by each of the oils increases with decreasing contact pressure, as shown in Fig. 33b. This increase may be **partly** due to the force measurement transducer on the Cameron-Plint apparatus



a. Contact Resistance Between Opposing Specimens



b. Coefficient of Friction

Figure 33. Tests with AISI E-52100 steel as a function of applied load

acting as an accelerometer, thereby producing a bias error in the results. Some correlation was observed between friction and the contact resistance between the surfaces. Oils that produced a weak contact film such as Oils D and A produced a higher coefficient of friction than the remaining oils, while Oil A, which produced a strong film over the complete load range, has a correspondingly low coefficient of friction. No contact film was observed with Oil D at any applied load, even though its viscosity is similar to both Oils C and A, both of which produced a strong contact film over the complete load range. Again, these results indicate poor boundary lubrication characteristics for Oil D, independent of viscosity.

The ranking achieved between the wear characteristics for each of the oils appears to directly contradict analysis performed on used oils removed from the full-scale tests, as detailed in TABLE 4. The physical and chemical characteristics of Oil D remained largely unchanged during the 200-hour engine test, while the remaining oils failed to complete the test. As a result, the effects of increasing temperature and lubricant degradation need to be considered by the test procedure.

4. Wear Tests With Used Engine Oils

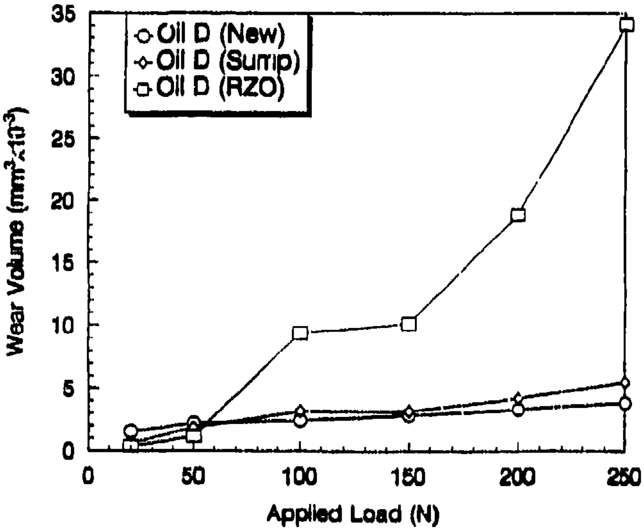
The intrinsic lubricating qualities of an oil during its life cycle within the engine are likely to be affected by a range of parameters, including additive concentration (as the oil evaporates), additive depletion, vaporization, and polymerization of the base stock. Extrinsic factors such as build up of carbon and wear debris will also be dominant variables. The limited oil volume present at the critical top ring reversal point experiences additional rapid degradation, which may further reduce its effectiveness compared with the bulk lubricant. As detailed in Section IV, limited volumes of Oils C, B, and D removed from the engine (both sump and ring zone) were available for testing.(30-32) Bench wear tests were performed with the last sample removed from the engine at, or immediately before, the end of the test (the engine test duration and oil condition in each instance are provided in TABLE 4). The purpose of these tests is to define the effects of oil degradation on wear.

These bench tests were performed at the conditions used in the previous section and detailed in TABLE 6. The results obtained from bench wear tests are shown in Figs. 34, 35, and 36 for Oils D, C, and B, respectively. The wear protection provided by both Oils D and C removed from the sump at the conclusion of each test was similar to that provided by the new oils. Similarly, little variation is seen between the boundary film strength and friction coefficient produced by the new and used oils in each instance. No sample of the Oil B crankcase oil at the conclusion of the engine test was available. The relatively good results obtained for the Oils C and D sump oils reflect their good conditions at test conclusion, as shown in TABLE 4.

However, more severe wear was produced by both the Oils D and C oils removed from the ring zone area. It should be noted that the level of wear produced by the Oil C oil from the ring zone is still comparable only to that produced by new Oil D. The strength of the boundary film produced by Oil C was greatly reduced, possibly due to additive depletion. In contrast, the almost nonexistent surface film produced by the Oil D oil was strengthened by the engine test. This increased surface film may be due to the slight increase in viscosity producing hydrodynamic lift or else the presence of reactive species formed during the lubricant degradation process.

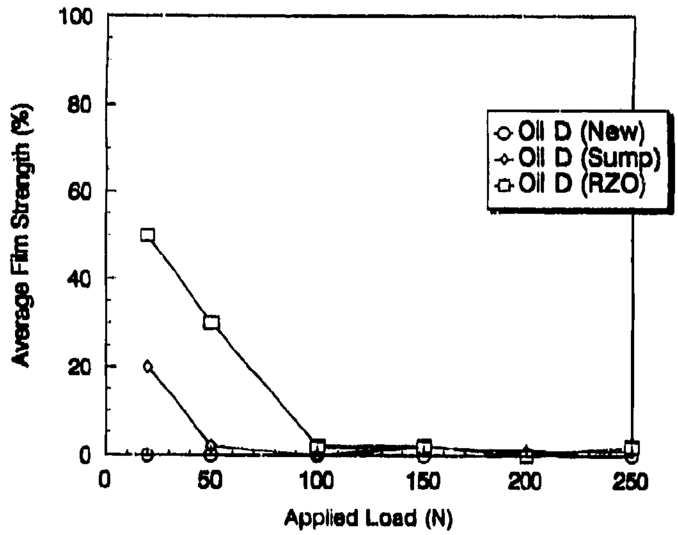
Oil B from the ring zone produced low wear and was similar to unused Oil B or Oil C, as shown in Fig. 36. Oil B is the only petroleum-based fluid tested that may partially explain the significantly different results obtained. The measured friction coefficients and the strength of the surface film measured by contact resistance was also similar to that seen with the base oil. None of Oil B removed from the sump was available for wear testing; however, the kinematic viscosity of Oil B was greatly increased, with a concomitant reduction in TFOUT time during the short 40-hour engine test. Significantly, however, the iron content in the oil at the conclusion of the engine test remained relatively low, as given in TABLE 4.

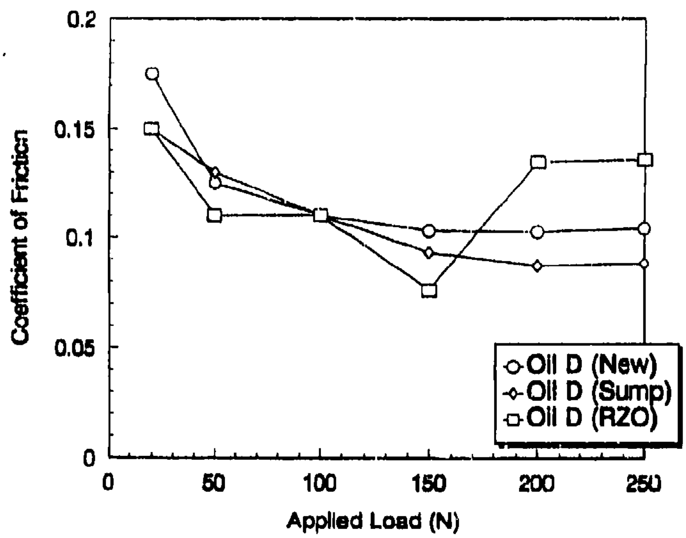
Clearly, the rapid oil degradation experienced at the high temperatures present in the ring zone area is sufficient to affect the ranking achieved between the oils.



a. Wear Volume

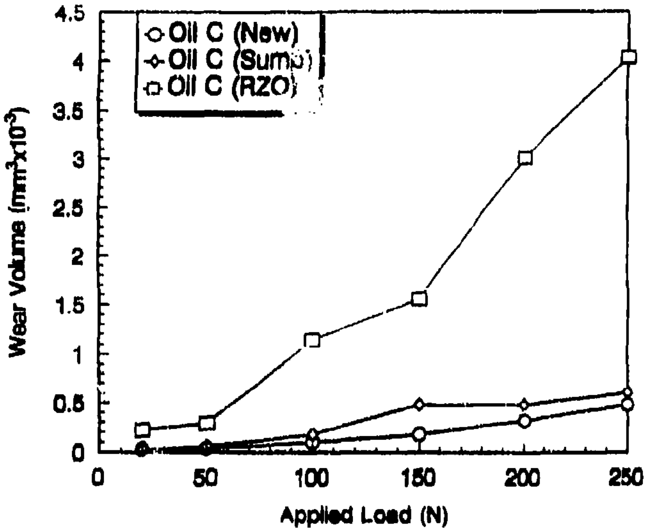
b. Boundary Film Strength



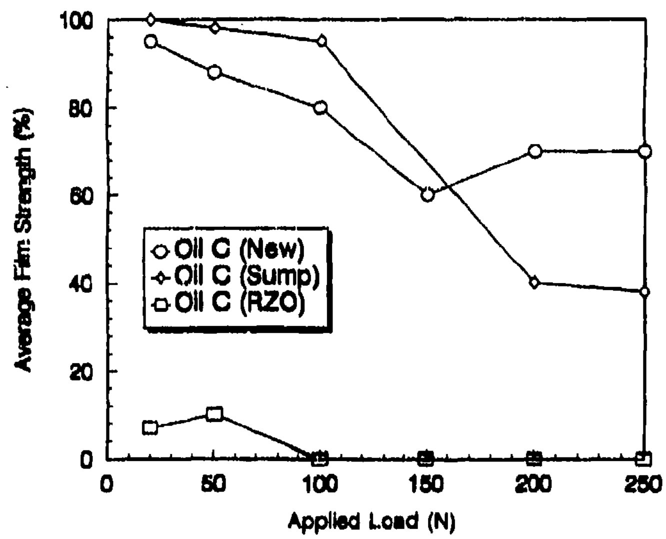


c. Average Friction Coefficient

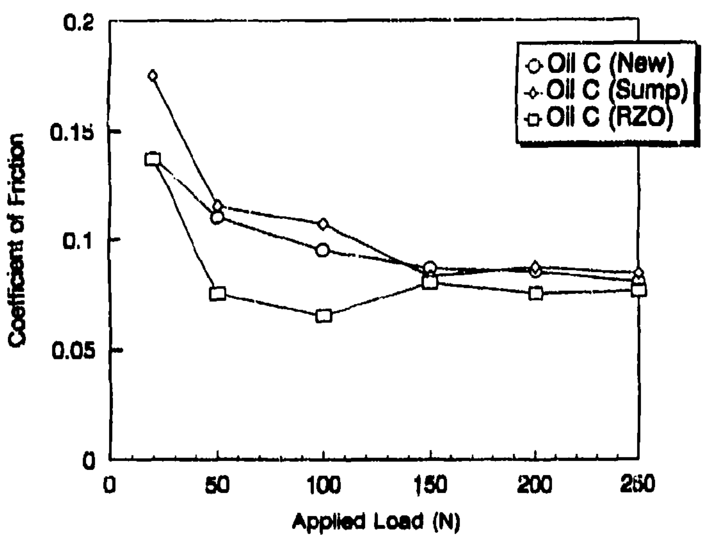
Figure 34. **<u>Comparison of new and used Oil D</u>**



a. Wear Volume

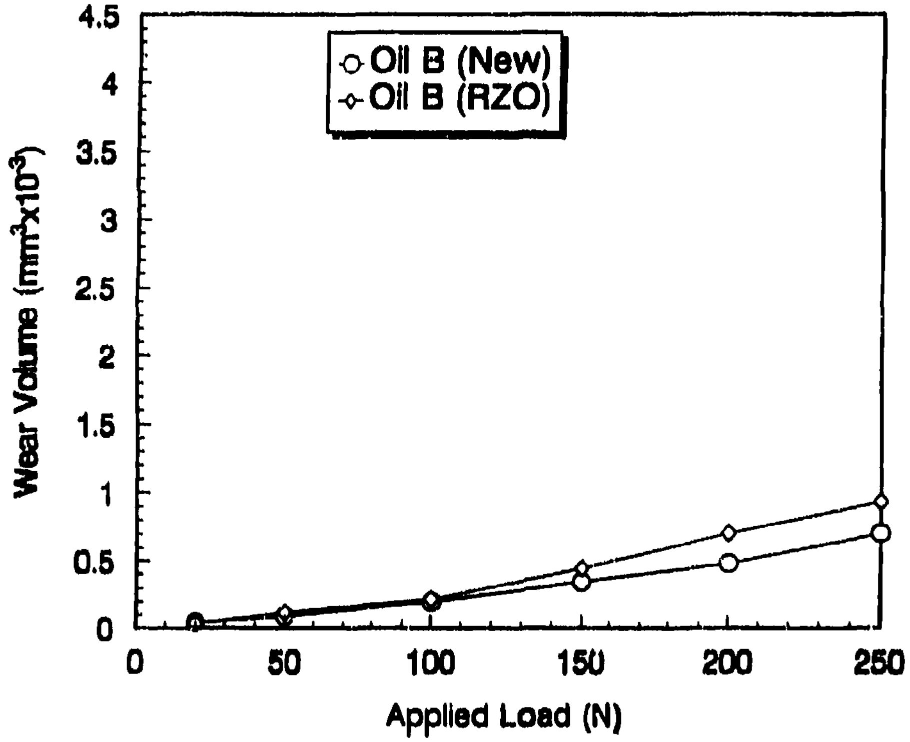


b. Boundary Film Strength

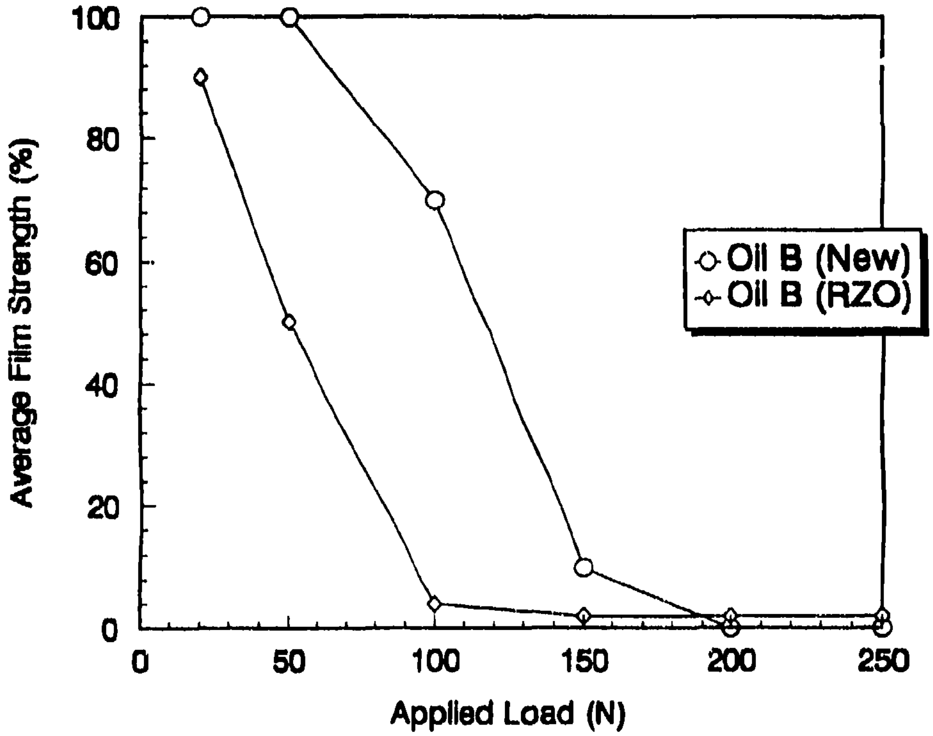


c. Average Friction Coefficient

Figure 35. __Comparison of new and used Oil C__



a. Wear Volume



b. Average Film Strength

Figure 36. <u>Comparison of new and used Oil B</u>

5. High-Temperature Tests With Lightly Loaded Ring Zone Materials

The test series described in the previous section defined the wear characteristics of new and used oils under temperature conditions approximating that in the crankcase. Lubricant degradation in the ring zone area was shown to have a significant effect on wear resistance. Lubricant oxidation will occur under the test conditions used, given sufficient time; however, it is unlikely to affect the wear results in the present relatively short test. Furthermore, wear tests under fully flooded conditions do not accurately reflect the thin film of oil present at the top ring reversal point. To better simulate the conditions existing in practical applications, a new test procedure was developed which does not use a fully flooded contact. Instead, a flexible rubber tube was mounted to the reciprocating specimen, and fresh oil was delivered to the contact area at a rate of 25 mg/min. Wear tests were performed at temperatures between 160° and 350°C, which is expected to reflect the range of conditions present in practical low-heat rejection engine. The remaining test conditions are provided in TABLE 8.

TABLE 8. Contact Parameters Used in Initial High-Temperature Wear Tests (Fig. 39)

Parameter	Value	Unit
Speed	30	Hz
Load	100	N
Duration	20	min
Flow Rate	25	mg/min
Geometry	Ball-on-flat	
Temperature	150 to 350	°C

The test results obtained using this initial procedure are given in Fig. 37. In general, wear rate increased rapidly for each of the oils at temperatures above 310°C. As in previous tests, Oil D produced appreciably more wear than the remaining oils over the complete test range studied. However, relatively low wear was observed for Oil B, which reflects the previous results observed for samples of this oil removed from the ring zone area (Fig. 36).

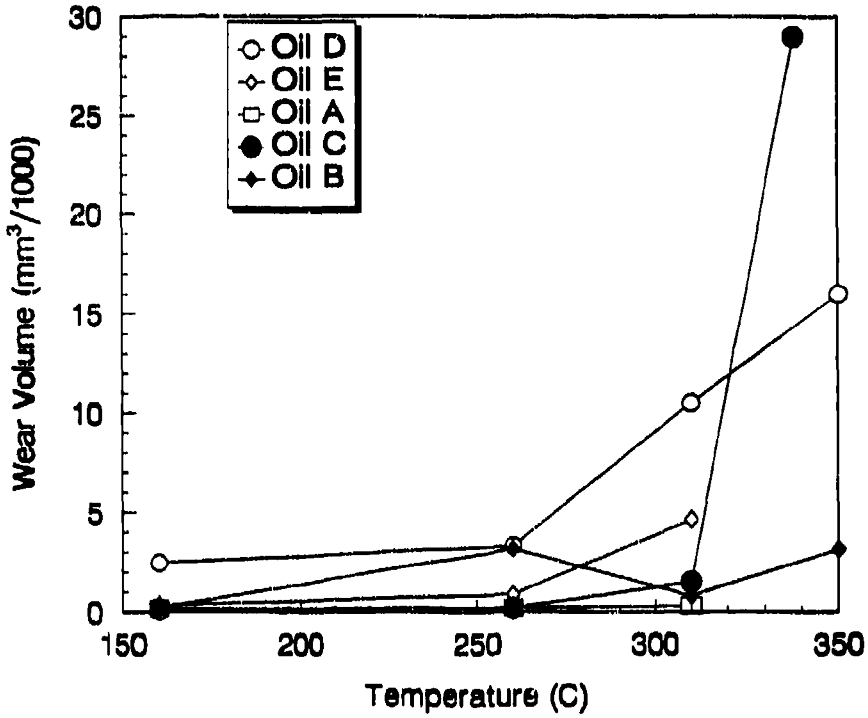


Figure 37. <u>**Effect of increasing temperature on wear rate under partially starved lubrication conditions**</u>

However, it should be noted that relatively poor repeatability was observed in the higher temperature tests. At high temperatures, a large volume of deposit was observed around the contact area. This deposit partially obstructed the flow of fresh oil from the supply tube attached to the specimen holder. To ensure more accurate and continuous oil delivery, a scraper mechanism was designed to simulate the action of the ring pack in a conventional piston assembly. Papke used a similar concept to produce a thin lubricant film in a previous study of oil oxidation/deposit, but in the absence of wear.(33) A schematic diagram of the revised contact configuration and lubricant supply system is shown in Fig. 38. An aluminum slider is now mounted in tandem with the wear materials on the reciprocating specimen holder and is lightly spring loaded against the test flat. The contact face on the slider is machined so as to provide two elongated contacts similar to the second and third piston rings on an engine. The outlet on the oil supply is located between the elongated contacts on the slider so as to provide a continuous, well-distributed, oil film on the test flat. As a result, the scraper is very similar in operation to the oil control ring in a conventional ring pack. The reciprocating motion of both the test specimen and the oil supply/slider mechanism ensures that only a thin film of oil is

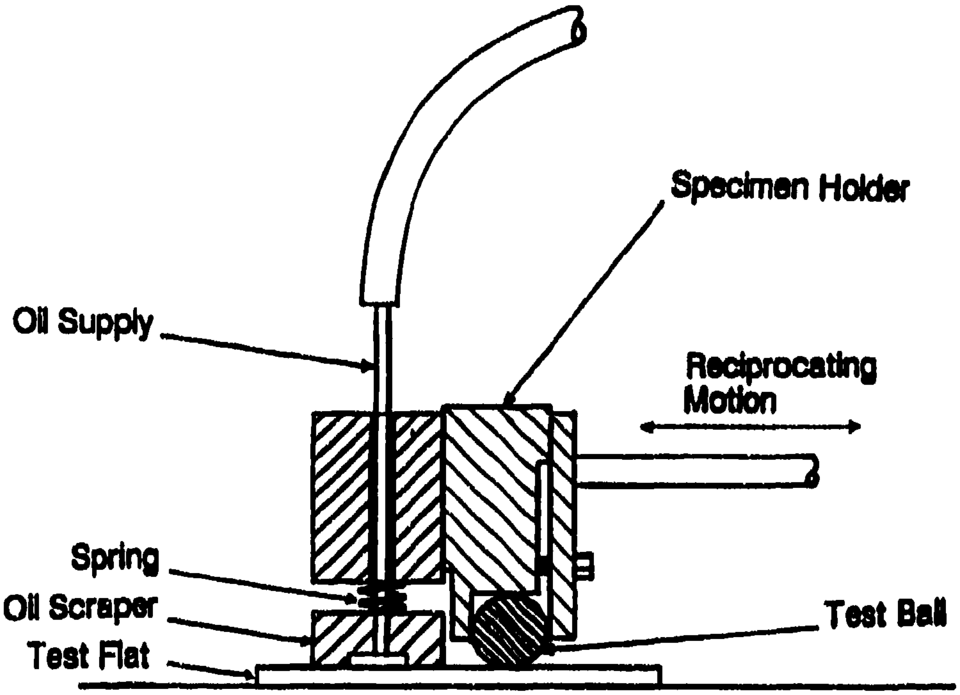


Figure 38. Schematic diagram of revised contact geometry/lubricant supply system used in high-temperature tests

provided to the wear scar. The formation of a thin film closely reflects conditions present at top ring reversal and minimizes the effects of oxygen diffusion, which is often the rate-controlling step in the oxidation reaction when even a small reservoir of fluid is present.(33)

The oil scraper mechanism was manufactured in aluminum to minimize the out-of-balance forces on the reciprocating specimen holder mechanism. Nonetheless, a relatively low oscillating frequency of 17 Hz was used to reduce strain on the test apparatus. Little or no wear occurs on the aluminum slider due to the low applied contact loading combined with the large geometrical area of the contact. The initial test results obtained with this procedure are plotted in Fig. 39 at the revised test conditions detailed in TABLE 9. Note the applied load was reduced from 100 to 30 N to more closely represent the conditions at the ring liner interface.

The high temperatures used significantly alters the relative protection provided by each of the oils. The increased oxidation resistance and thermal stability of both Oils D and E are now significant benefits. As a result, these oils now produce similar or less wear than Oils A and B,

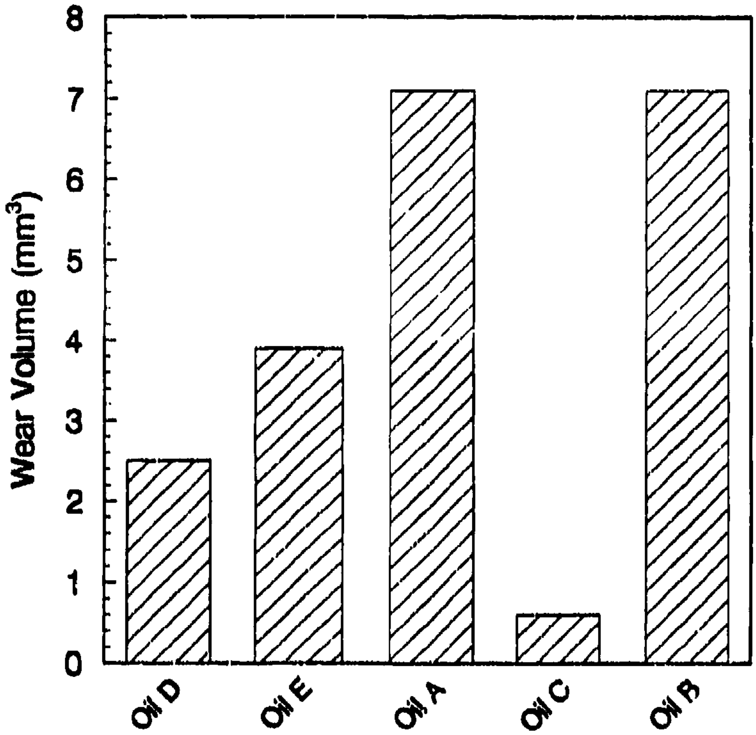


Figure 39. Wear scar volume with fresh oils at 310°C

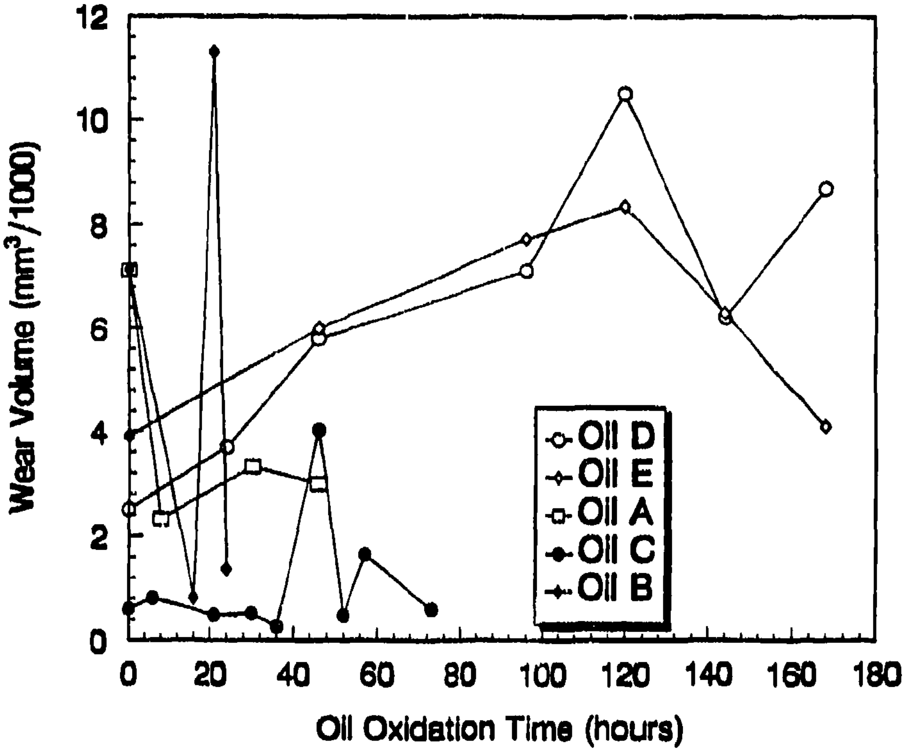
TABLE 9. Contact Parameters Used in High-Temperature Wear Tests

Parameter	Value	Unit
Speed	17	Hz
Load	30	N
Duration	20	min
Flow Rate	25	mg/min
Materials	AISI E-52100 Steel	
Geometry	Ball on flat	
Temperature	310	°C

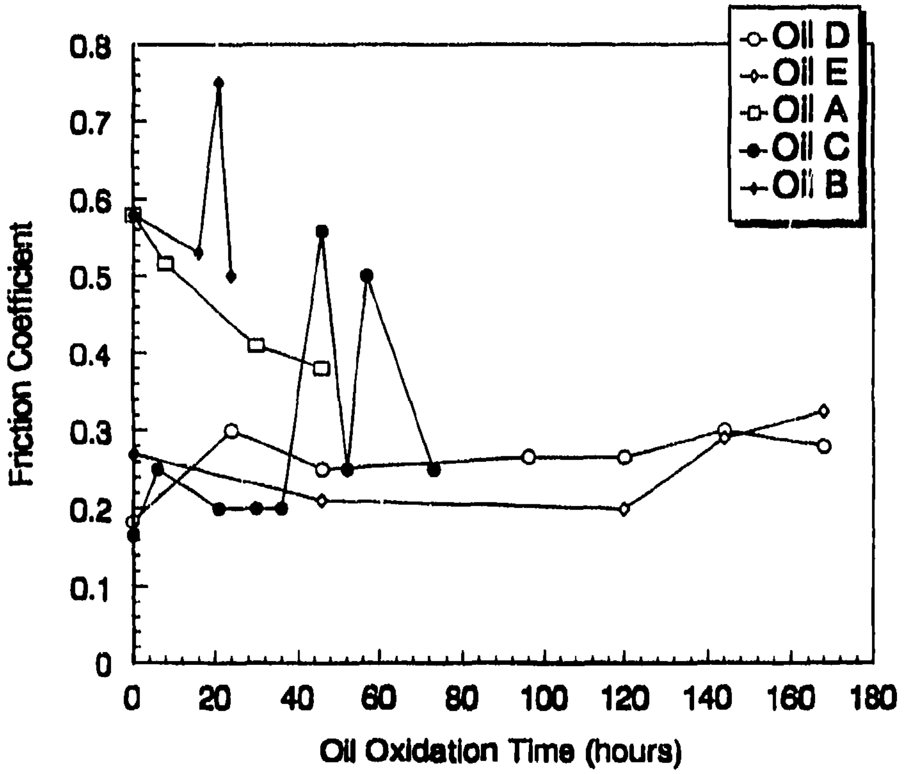
both of which are fully formulated. In addition, the differences in wear rate previously observed between Oils D and E are not present at this temperature. However, the fully formulated synthetic Oil C still produces appreciably less wear than any of the remaining lubricants. Clearly, oxidative degradation of the oil plays a significant role in wear prevention under these conditions. However, in practical applications, the crankcase oil has undergone some oxidation prior to reaching the ring liner interface. To simulate this effect, high-temperature wear tests were performed using oil samples that were oxidized according to ASTM D 4636, as detailed in Section IV. The resulting wear volume and friction coefficient are plotted in Fig. 40. The test conditions are the same as in the previous test (detailed in TABLE 9).

Increasing oxidation time increases the level of wear observed for both Oils D or E, reflecting the results observed for the ring zone oils in Fig. 34. However, the measured coefficient of friction for Oils D and E is appreciably less than that of most remaining oils. For oil oxidation times of up to 40 hours, Oil C produces relatively mild wear with a friction coefficient similar to that of Oils D and E. This relatively low wear rate was also observed in previous wear tests with the Oil C oil obtained from the ring zone area (Fig. 35). However, for oxidation times greater than 50 hours, the friction/wear rate observed with Oil C becomes erratic and increases. Visual examination of the wear scars using optical microscopy shows increased plastic deformation and scarring, probably due to a scuffing-related process. The oil oxidation time required for the onset of scuffing reflects the onset of lubricant breakdown, as shown in Fig. 41. The cause of the relatively large variation in test results observed after the onset of the scuffing-related wear mechanism is unclear. It is most likely due to the formation of high molecular weight deposits on and around the wear scar, which provides some wear protection. These deposits are also likely to influence the oil delivery system, despite the use of the scraper mechanism.

High friction and wear were observed for both the Oils A and B, even with no prior oxidation. Both wear rate and friction coefficient decreased with increasing oxidation time for Oil A and, to a lesser extent, for Oil B. This decrease may have been due to formation of viscous deposits on the test surfaces or formation of reactive degradation products in the oil. The comparatively effective wear resistance of severely oxidized Oil B was previously observed in Fig. 36a. Nonetheless, the measured friction coefficient remains unacceptably high for each of the high-temperature tests with these fluids. This result is in good agreement with the high levels of wear metals present in samples of Oil A obtained when the engine test was terminated at 75 hours (see TABLE 4). This severe wear was not predicted by the low-temperature tests in previous sections.

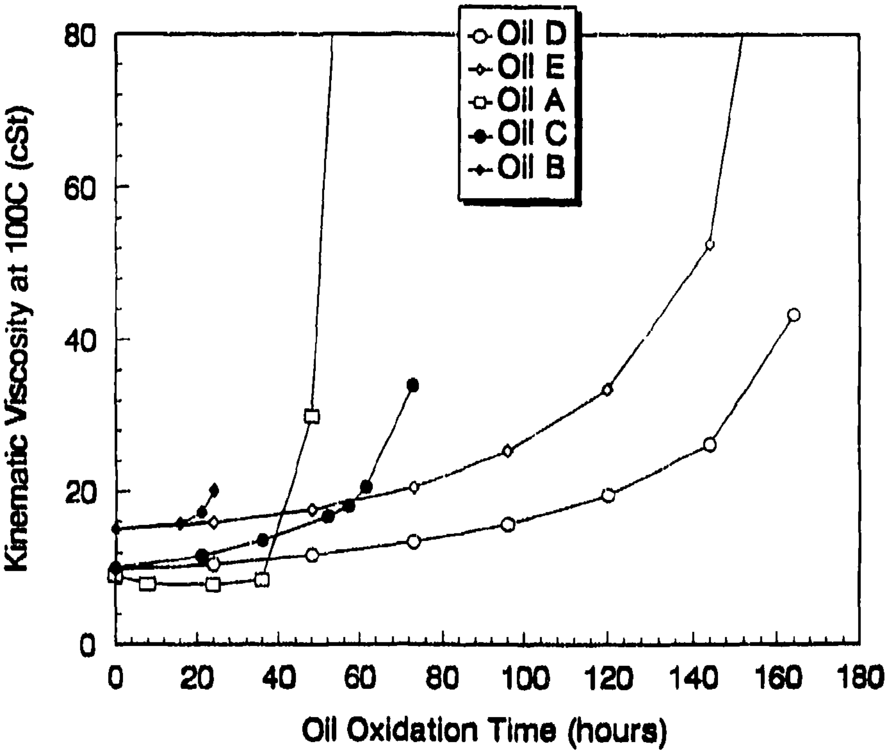


a. Wear Volume

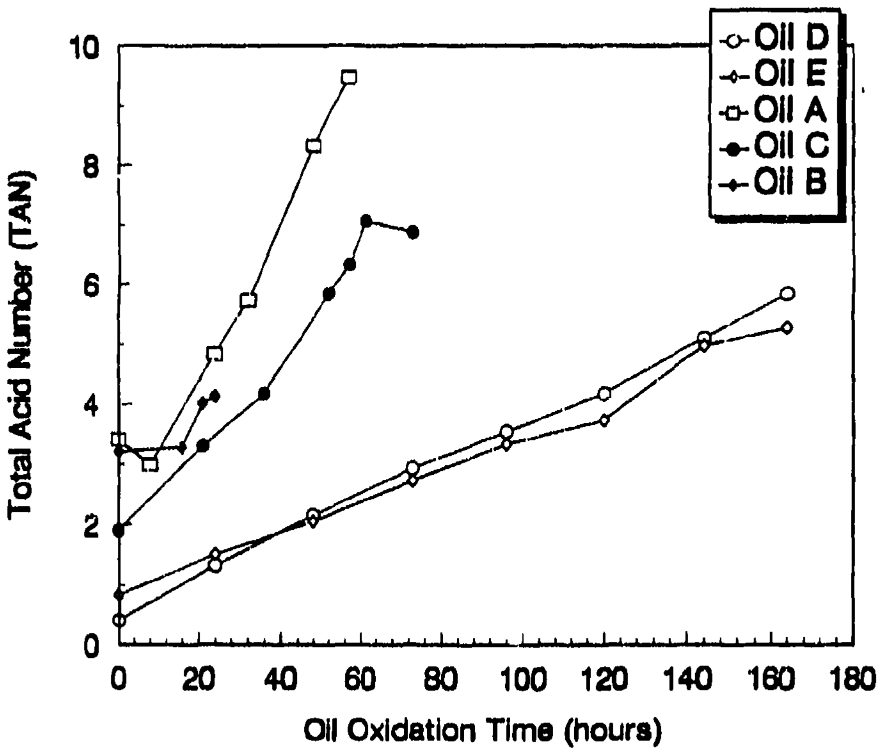


b. Friction Coefficient

Figure 40. Effect of oil oxidation on high-temperature tests with each of the oils



a. Viscosity



b. Acid Number

Figure 41. **Effect of oil oxidation according to ASTM D 4636**

As previously stated, the oil degradation within the engine is somewhat similar to that occurring in the oil oxidation bath used in the present test series. The kinematic viscosity of the used engine oils is provided in TABLE 4 as a function of engine run hours. A relatively large increase in kinematic viscosity was observed for some of the oils. In particular, the viscosity of Oils A and B had increased to a value similar to or exceeding that considered to be the breakpoint in the artificial oxidation tests, while the TFOUT time was considerably reduced. The regular addition of makeup oil to the engine is probably a primary factor preventing complete failure of these oils. Clearly, according to the high-temperature bench test results, these oils will provide poor high-temperature wear protection, even though they still provide apparently satisfactory protection at lower temperatures.

6. Artificial Oil Oxidation

Oxidation resistance and deposit control are primary factors in the characterization of oils for use in high-temperature applications. The Thin Film Oxygen Uptake Test (TFOUT) as defined in ASTM D 4742-88 is a good indicator of the time required for the onset of severe lubricant oxidation and shows correlation with sequence IIID engine test results.(24) However, only 1.5 grams of oil are available for subsequent wear testing with each oil. An accelerated laboratory procedure to artificially oxidize the oil was developed. This technique produced larger sample volumes suitable for subsequent wear testing as well as providing a measure of the oxidative stability of each oil. The test procedure was based around ASTM D 4636, which uses 200 mL of test oil in a heated glass reservoir and allows periodic sample withdrawal and evaluation. Dry air is continuously bubbled through the oil to accelerate the oxidation process, and a sample temperature of 210°C was found to produce oxidation in a reasonable time period. Metallic test coupons are also immersed in the oil and provide catalytic reactive surfaces similar to those found in real systems.

The kinematic viscosity (at 100°C) and acid number for each of the oils are presented in Fig. 41, and largely reflect the TFOUT results presented in TABLE 3. As expected, Oils D and E provide superior oxidation resistance to the remaining oils and demonstrate a relatively gradual viscosity increase. The viscosity of the petroleum oil (Oil B) increased very rapidly compared with the remaining oils, which are all synthetic based. The residue from both Oils B and A at the conclusion of the test was sufficiently oxidized to form a solid at room temperature.

Acid number also increased steadily for each of the synthetic oils, with the least increase seen for Oils D and E, as shown in Fig. 41. No clear breakpoint in acid number was observed for any of the oils, except petroleum Oil B. The more rapid increase in acidity for both Oils A and B is reflected in a relatively large mass loss rate from the metallic specimens submersed in the oil during the oxidation process, as shown in Fig. 42. In particular, petroleum-based Oil B corroded each of the aluminum, copper, and iron specimens. Both Oils D and E produced only slight mass loss from the copper specimens but had no measurable effect on the aluminum or iron specimens.

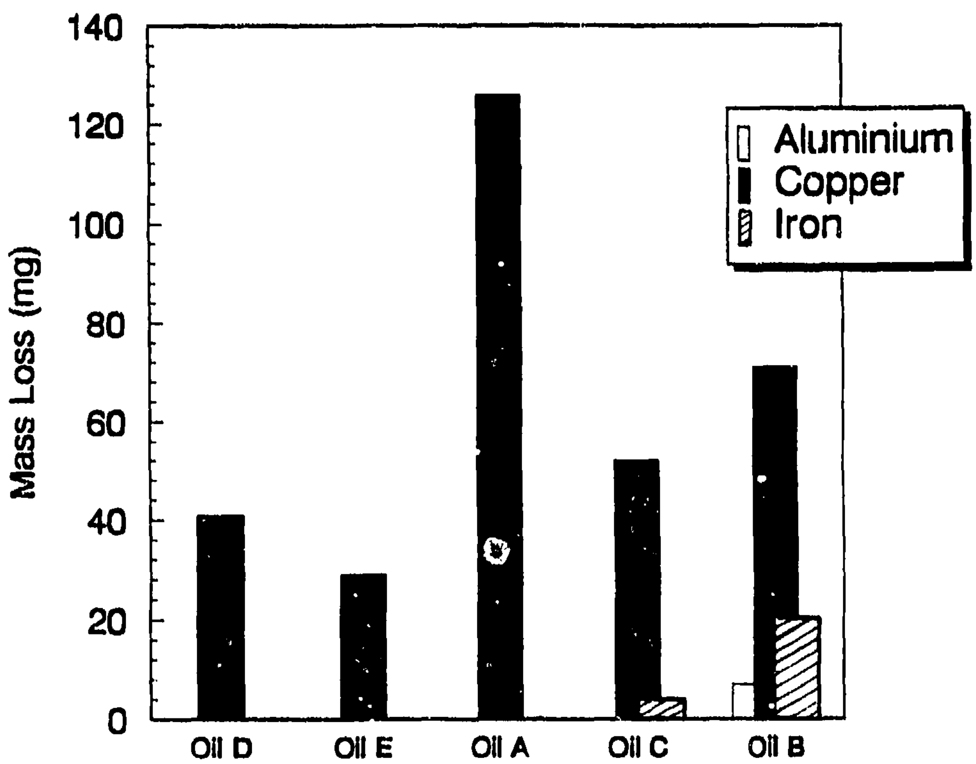


Figure 42. Mass loss from metal coupons during oil oxidation

D. Microlubrication Wear Test

1. Need for the Test

Effective modeling of the lubrication process is a prohibitively difficult task. As previously stated, lubricant polymerization, additive depletion, oxidation resistance, lubricant vaporization, wear resistance, particulate contamination, and many other effects combine to define lubricant effectiveness in a given application. The high-temperature bench wear tests in the previous section demonstrated the importance of oxidation in the wear process. However, these tests require preoxidation of a relatively large volume of oil over an extended time period. In addition, the relatively large volume of oil required precludes detailed testing of oils removed from the ring zone area.

Most alternative characterization techniques attempt to isolate specific aspects of the oil, independent of the remaining attributes: wear tests do not normally account for the ongoing oxidation process present in practical applications; moreover, oxidation tests do not consider the effects of lubricant polymerization and the wear debris produced during the wear process. Gates and Hsu developed an Oxidation-Wear-Coupled Test that combines the effects of lubricant oxidation and wear in a single test.(34) The resulting procedure was shown to correlate well with ASTM Engine Sequence IIID Test reference oil engine wear data.

The microsample wear test combined the thin-film oxidation test with a simultaneous wear test to monitor the wear behavior of the lubricant during oxidation. Typically, several microliters of lubricant are carefully added to the contact of a conventional four-ball wear test. The oil is held in position by surface tension during the test and is heated by the frictional energy dissipated from the contact. The presence of nascent metal surfaces, readily available oxygen, and a limited lubricant volume ensures that the oil is quickly degraded. The wear mechanism present is continuously monitored via the friction force output. At a critical point, additive depletion, lubricant oxidation, and buildup of wear debris cause incipient failure of the boundary film. The contact temperature rises, promoting rapid lubricant degradation and relatively sudden failure. Klaus, et al. (35) produced a detailed study of both the deposits and lubrication mechanisms involved using gel-permeation chromatography and scanning electron microscopy. The results of the study indicate that a barrier of grease-like material is formed around the contact area. This buildup of polymer and deposit around the contact junction acts as a dam to prevent lubricant access and also traps remaining unused oil in a viscous mixture. This mixture will be composed of the original lubricant and the high molecular weight products, which are formed by the oxidation of the lubricant.

2. Initial Test Development

The oxidation reaction for a variety of organic esters, mineral oils, and synthetic hydrocarbons is of the Arrhenius type.(36–38) The equation has the following form:

$$K = me^{-E/RT} \qquad \text{(Eq. 2)}$$

where: K = Reaction rate constant

T = Temperature

m = Coefficient

E = Activation energy

R = Gas constant.

Clearly, the lubricant temperature in the contact is critical to the oxidation process. Over the past 30 years, a range of models have been developed to predict these temperatures for a range of contact conditions.(39-42) Many of the models and corresponding experimental study have been directed towards the standard four-ball wear test. Francis (42) calculated the interfacial temperature distribution within a sliding hertzian contact. The maximum temperature occurs towards the rear of the apparent contact area and may be defined as follows:

$$T_{\text{Contact}} = T_{\text{Bulk}} + \Delta T \qquad \text{(Eq. 3)}$$

where: $B = vR/\alpha$

R = Diameter of apparent contact

k = Thermal conductivity (36.8 W/M°C)

$$\Delta T = \frac{\left(\frac{1.852Q}{\pi R k}\right)}{\left[1.996 - 1.091B^{-0.818} - 0.537B^{-0.271} + B^{0.5}\right]} \qquad \text{(Eq. 4)}$$

ν = Sliding velocity

α = Thermal diffusivity ($k/\rho C = 1.15 \times 10^{-5}$)

ρ = Density (7810 kg/M^3)

C = Specific heat capacity (405 J/kg°C)

Q = Rate of heat generation.

This theory assumes that the gap between the surfaces is small, i.e., boundary lubrication, and that both specimens are the same temperature. Experimental measurements of the mean contact temperature indicate that Equation 4 (and also most other equations) underestimate the contact temperature.(41, 43) The contact temperature obtained using such equations is commonly multiplied by a correction factor of 1.6 to achieve more correct correlation with measured results.(34) Moreover, the equation assumes that the frictional energy is uniformly distributed over the apparent contact area. In reality, more concentrated events will occur at asperity contacts to produce a greater localized temperature. This equation models a fast-moving heat source across a flat surface. Francis indicates that this criteria is satisfied for values of B greater than approximately 10. For the contact conditions in the present study, the dimensionless coefficient B has a value of approximately 9.5.

The average temperature of the crankcase oil during the high-temperature SCE-903 engine tests is 166°C, while the temperature of the top ring reversal point was measured to be approximately 230°C. To a limited extent, the microsample of oil held around the contact area contains the bulk of the lubricant and in this respect corresponds to the sump. To simulate these conditions, the test temperature was set at 160°C. Contact conditions were then selected to produce a temperature within the conjunction approaching that in the ring zone area. Equation 4 predicts a mean surface temperature increase of 64°C for conditions of 40 N applied load and a sliding speed of 0.442 m/s.

An initial test series was performed with a chrome ring specimen sliding on a honed section of the cast iron cylinder liner. These initial tests were performed using 4 μL of Oil A carefully applied to the contact junction using a 5-μL syringe. The test conditions were set to correspond with the required contact parameters as calculated in the previous section and detailed in TABLE 10. The time period required for the onset of scuffing was the measured parameter.

TABLE 10. Test Conditions Used in Microlubrication Wear Tests

Parameter	Value	Unit
Load	40	N
Temperature	160	°C
Duration	To Scuffing Onset	
Speed	40	Hz
Amplitude	4.7	mm
Materials	Chrome Ring/CI Liner	

The results from this initial set of investigations are provided in TABLE 11. The time required for the onset of lubricant failure was erratic, and repeatability was poor. Visual examination of the test flat around the wear scar indicated that considerable spreading of the oil had taken place, and little of the high molecular weight deposit reported by previous workers using the four-ball apparatus was present. A number of different surface topographies were evaluated to reduce spread of the lubricant away from the contact. Overall, a polished finish provided the optimum test repeatability and also produced the maximum test duration, which indicates that more of the oil remained at the contact. In addition, a slight beveled edge was machined at the top and bottom of the piston ring specimen. The slightly rounded corners trapped additional lubricant close to the contact area and, combined with the revised surface topography, produced a significant increase in test accuracy, as shown in TABLE 11. In this subsequent test procedure, a large volume of viscous residue was deposited around the contact area.

TABLE 11. Repeatability of Oxidative/Wear Coupled Tests in Original (Honed Liner/Standard Ring) and Final (Polished Liner/Beveled Ring) Configuration

	Time to Lubricant Failure, minutes	
Test No.	Honed Liner Standard Ring	Polished Liner Beveled Ring
1	20	40
2	17	49
3	15	37
4	12	35
5	31	--

3. Comparison of Oils Using the Microlubrication Wear Test Procedure

Microlubrication wear tests were performed with each of the five test oils at the conditions outlined in TABLE 10. The resulting test duration required for the onset of scuffing with various lubricant volumes is plotted in Fig. 43.

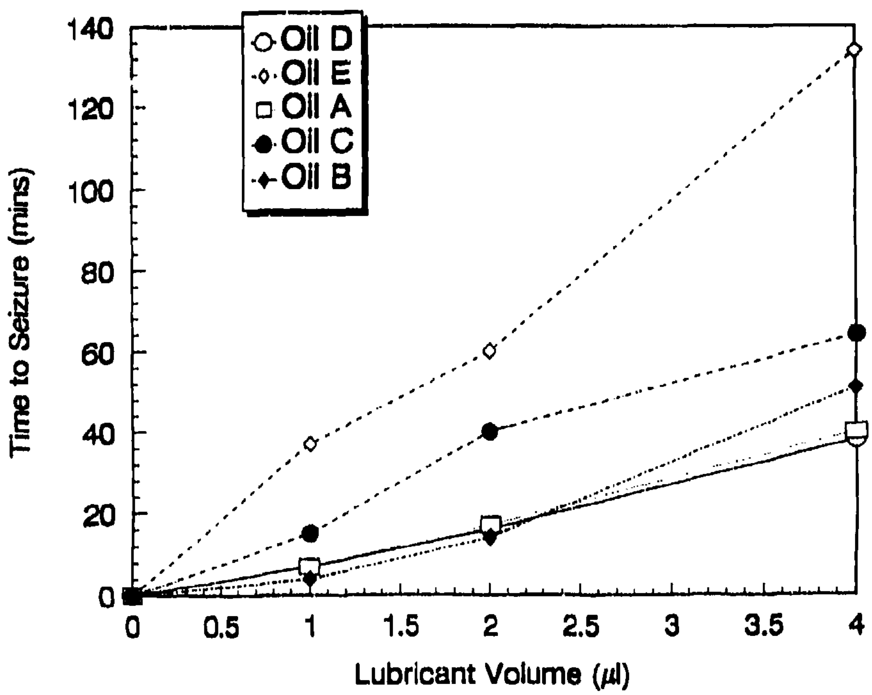


Figure 43. Test duration required for scuffing onset at conditions detailed in TABLE 9

As expected, the life of each oil is directly proportional to the initial volume supplied. This result confirms the test duration required for the onset of scuffing is indeed influenced by deterioration in the oil. Additional tests performed with Oil B (results of which are not plotted) indicate that the time required for the onset of seizure does not increase appreciably for an initial lubricant supply volume of greater than approximately 8 μL. Visual examination indicates that an oil volume of greater than 8 μL merely disperses across the test specimens.

A significant variation in the amount of time required for the onset of scuffing was observed between each of the oils. The oils may be approximately ranked according to their oxidation resistance as defined in TFOUT tests (see TABLE 3), and also with the high-temperature friction measurements (Fig. 22b): Oil E is by far the most effective oil, followed by Oil C. Significantly, however, Oil D has a TFOUT time exceeding 300 minutes and is supposedly very similar to Oil E but still produces a consistently short lubricant life. This anomaly may be due to minor variations in the chemical composition of Oil D combined with its lower viscosity (9.8 cSt versus 15 cSt). However, it is unlikely that high viscosity is the sole reason for the good performance of Oil E, as Oil B also has a kinematic viscosity of 15 cSt, but failed in a time period similar to that for Oil D. Clearly, the microlubrication wear test is sensitive to the oxidative stability of the oil, in addition to its wear resistance and possibly viscosity.

Although Oils D and E are derived from similar base stocks and contain the same additive package, fundamental differences do exist between them, and several possible explanations exist for the wide variation in lubricant life observed. Previous workers noted that Oil E only produced one fourth of the viscosity change upon oxidation.(12) The more rapid increase in viscosity will prevent oil flow around the contact area and, indeed, Oil E typically lasted for approximately four times as long as Oil D. In addition, a wide variation in the measured wear rate was observed between the oils under fully flooded conditions. The measured wear volume on a 0.5-in. AISI 52100 steel ball sliding on a polished 52100 steel flat is shown in Fig. 44 for both microlubrication and fully flooded conditions. Each data point represents a single wear test, as the procedure cannot be resumed once the 2-μL oil reservoir is disturbed during measurement of the wear scar. The measured wear rate with Oil D is appreciably greater than that seen with

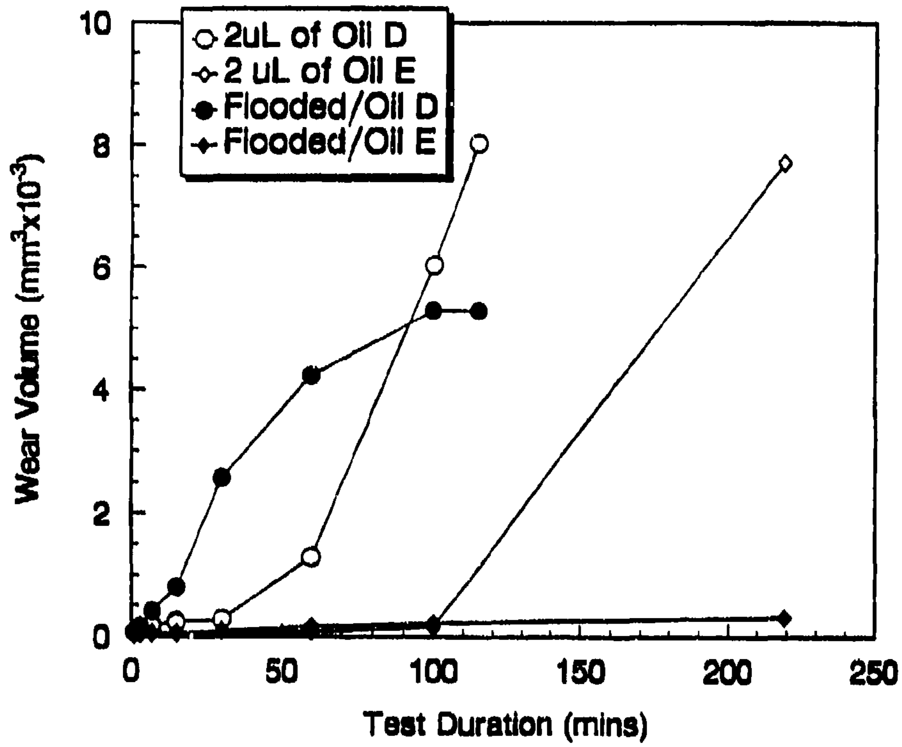


Figure 44. Comparison between wear results obtained under fully flooded and microlubrication conditions

Oil E under both lubrication conditions. For short test times, the wear rate is decreased under microlubrication. However, the wear rates increase rapidly after extended test durations in the partially lubricated tests, possibly due to an accumulation of wear particles in the restricted lubricant reservoir. Such particles are removed from the contact area during bulk lubrication. The more rapid accumulation of wear debris with Oil D would assist in formation of a viscous barrier of deposit, which, previously, was normally attributed to lubricant degradation products.(35) Scuffing and lubricant starvation towards the end of the test as the oil became more viscous may also have been a contributing factor to the increased wear observed.

4. Effect of Operating Conditions on Time Required for Scuffing

Additional microlubrication wear tests were performed with Oils D and E to define the effects of different parameters on the measured oil life and also to study the unexplained variation between these two oils.

Microlubrication wear tests were performed with 2 μL of oil as a function of temperature, with the results shown in Fig. 45. The remaining test conditions are defined in TABLE 10. As expected, lubricant life decreases rapidly with increasing temperature, and failure is almost instantaneous at 260°C. Some viscosity effects were observed, and at 50°C, a strong hydrodynamic film was formed after approximately 3 hours of testing. The relatively large wear scar formed after this extended test period allowed formation of a thick film, resulting in a low-friction coefficient of 0.018 and a large electrical contact resistance. However, at higher temperatures, no electrical resistance was measured, and friction remained similarly high (approximately 0.14) for each oil. Moreover, a temperature difference of approximately 40°C is required to account for the variation in life observed between the two oils, while a difference of only 12°C is required to account for the variation in viscosity. (The viscosity temperature relationship for Oils D and E is shown in Fig. 9).

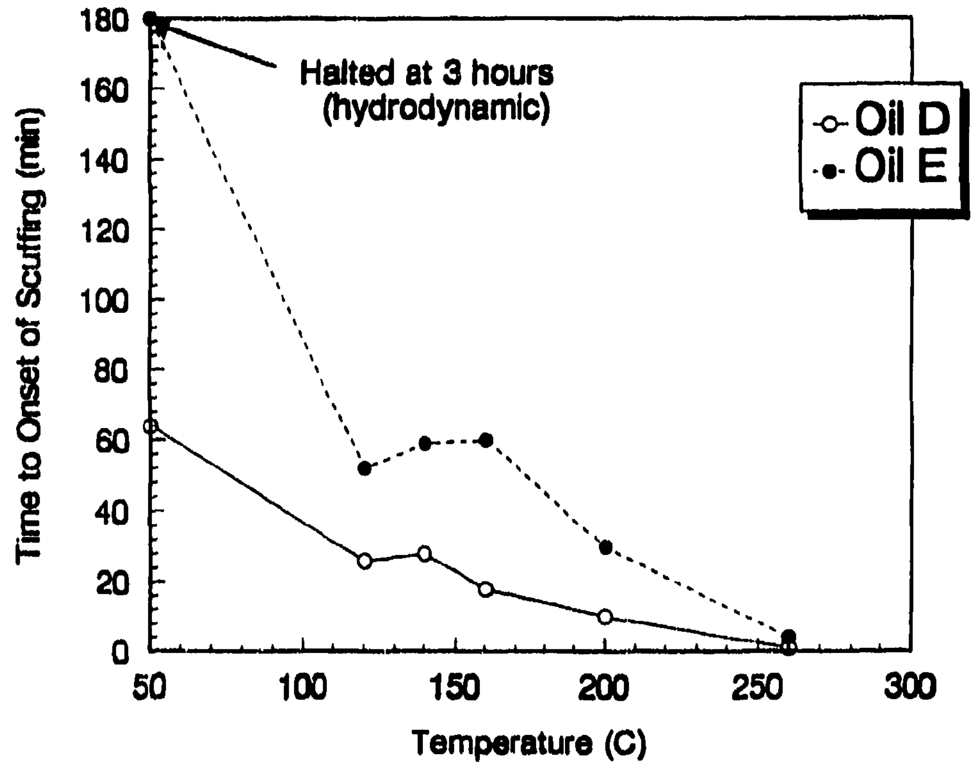


Figure 45. **Effect of increasing temperature on time to onset of scuffing at a load of 40 N and a reciprocating speed of 40 Hz**

A second test series was performed at a sliding speed of 30 Hz to define the effects of applied load on the time required for the onset of seizure, with the results shown in Fig. 46. The time required for the onset of scuffing decreases with increasing load. Instantaneous scuffing occurs at an applied load of approximately 190 N for both oils. This value solely represents the ultimate load-carrying capacity of the oils; consequently, a relatively large volume of fresh and unused oil remains at the end of the test. At lower loads, prior to instantaneous failure, Oil E remains appreciably more effective than Oil D over the complete load range studied. No measurable contact resistance was observed for either oil, and it is highly unlikely that hydrodynamic effects exist over the load range studied.

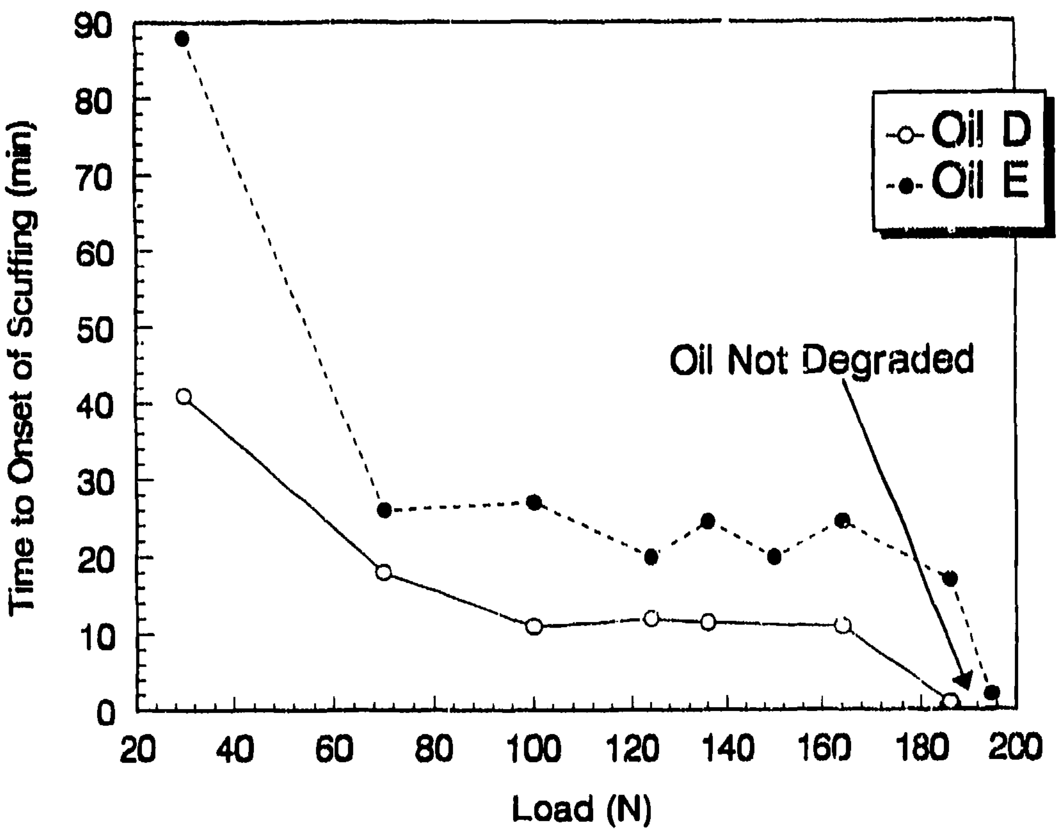


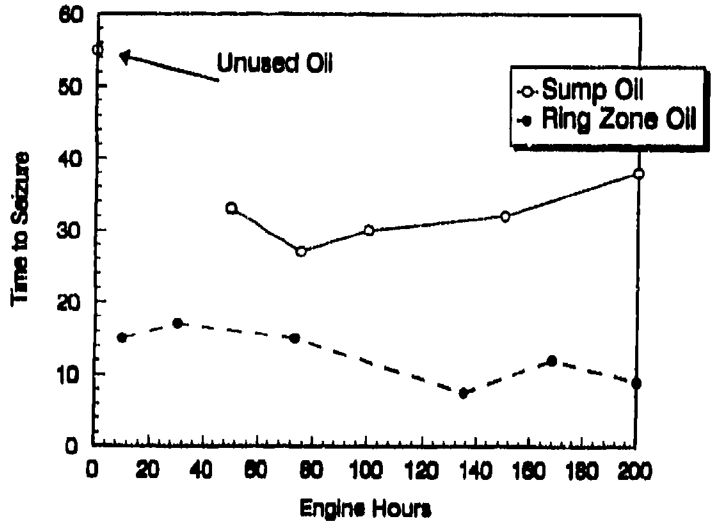
Figure 46. <u>Effect of increasing load on time to onset of scuffing at 175°C and a reciprocating speed of 30 Hz</u>

5. Effect of Oil Preoxidation on Microlubrication Test

The previous tests have demonstrated that the microlubrication technique is sensitive to the effects of temperature, applied load, and probably wear rate. It is believed that lubricant oxidation and oxidation resistance are also critical parameters in the test time to failure. Crankcase oils undergo continuous oxidation and additive depletion during practical engine operation. To determine the effect of such oil degradation on the microlubrication wear procedure, tests were performed with samples of used crankcase oils from both the sump and ring zone area of the high-temperature SCE-903 tests. Microlubrication wear tests were then performed at the test conditions in TABLE 10, with the results shown in Fig. 47.

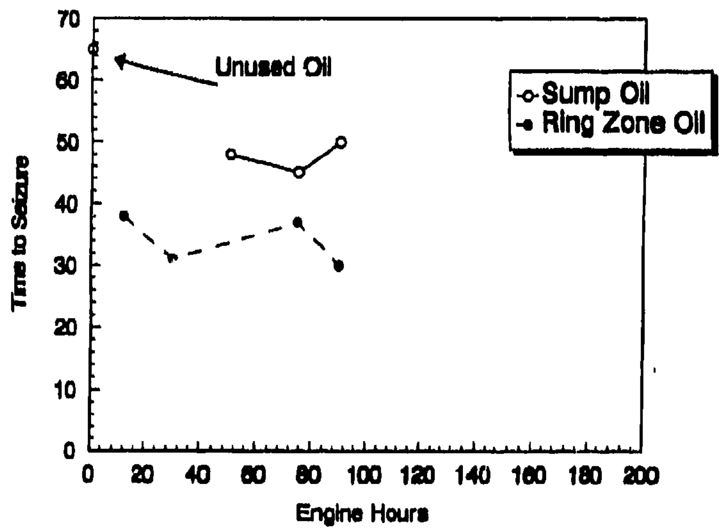
The test times required for the onset of scuffing for both Oils D and E were greatly reduced for oils removed from the ring zone and slightly less so for oils removed from the sump. This decrease is repeatable, but was not predicted by the physical and chemical properties of the used oils provided in TABLE 4. Previous fully flooded wear tests showed very little difference between new and used Oils D and C removed from the sump, but considerable degradation for these oils when removed from the ring zone. The quality of the used Oil D remains consistent to within experimental error over the 200-hour test period, which is in agreement with the physical and chemical properties of the used oil (TABLE 4). In the SCE-903 test, Oil D appears to reach a steady state in which the makeup oil is sufficient to maintain equilibrium.

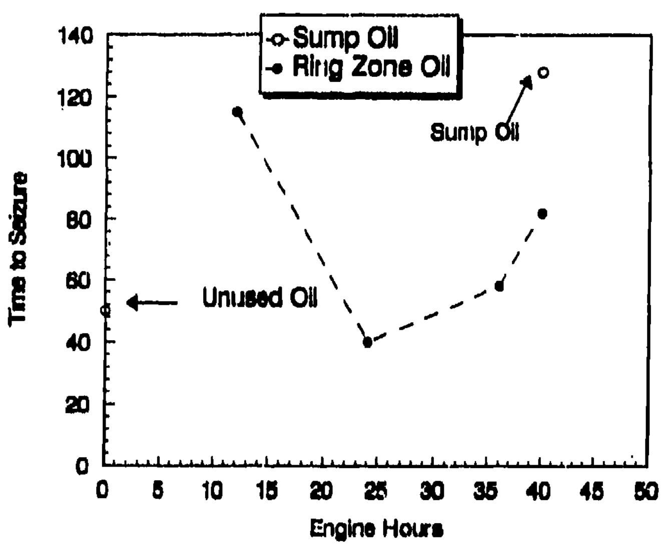
In contrast to the previous oils, the time required for seizure for used samples of the petroleum-based Oil B remains similar to new oil. The anomalous (unexpectedly good) characteristics of Oil B ring zone oil was previously noted in fully flooded wear tests, shown in Fig. 18. The SCE-903 test with this oil was halted at 40 hours due to rapid degradation, and the high viscosity of the used oil (45 cSt at 100°C) may partially explain the unexpectedly good bench wear test results.



a. Oil D

b. Oil C





c. Oil B

Figure 47. <u>Effects of engine run time on microlubrication wear test results</u>

V. DISCUSSION

The present study developed a number of wear test methodologies that attempt to simulate conditions experienced by lubricants in future low heat rejection engines. No single bench test will totally reflect the lubrication requirements of an engine or even a single component within the engine.

In four-stroke engines, the cam follower contact is among the most highly loaded areas. No measurable cam wear was observed in previous high-speed, high-temperature single-cylinder engine tests with each of the oils. However, during low-speed operation, high hertzian stresses combined with an intermittent velocity profile reduce elastohydrodynamic lift and often result in increased boundary lubrication.(44) The inclusion of antiwear additives such as ZDTP is commonly necessary to prevent wear in this area. However, the operating temperature at the camshaft is relatively low and commonly reflects the sump temperature. By comparison, the contact conditions at the top ring reversal point are very different from those of the cam/follower: relatively low loads combined with high temperatures. The inclusion of metal-based antiwear additives will typically increase lubricating oil related deposit under these conditions. As a result, the test parameters used in the present study were designed to cover a broad range of contact conditions, with particular reference to the effects of oxidation.

Oils D and E fluids, which contain no ZDTP, produce increased wear under almost all bench wear test conditions at typical sump temperatures; however, this wear is contradictory to wear metals measurement of the used engine oils provided in TABLE 4. It is also qualitatively contrary to the level of degradation measured in the used oils from the SCE-903 single-cylinder engine tests.

Previous workers have suggested that oxidation of an oil will result in a decrease in the antiwear effectiveness of the lubricant.(34, 45) Typically, the oxidation reaction rate doubles for each 10°C increase in temperature and in McGeehan's work and resulting engine piston groove deposits were found to double every 30°C.(46) As a result, high-temperature tests were performed to highlight the benefits provided by the thermally stable polyolester oils. Even at high temperatures, the wear rate observed with Oils D and E was still similar or greater than that produced by the remaining fluids. However, friction remained low with the polyolester oils with little scuffing. To a limited extent, the friction results correlate with the results of engine tests performed at BFLRF. The engine test results indicated that Oil D showed lower levels of wear metals than the remaining oils.

Oils D and E are derived from similar base stocks and contain the same additive package.(12) As expected, wear tests with the base stocks for both Oil D and Oil E produced very similar results. However, the formulated oils appear widely different, with Oil D producing more wear than its base stock. The cause of this apparent antagonism is unclear and requires further study. Bench wear tests performed with Oils D and E in a previous study (12) appear contrary to the present work, with Oil D producing almost an order of magnitude less than Oil E and the other oils tested. However, in the previous study, Oil D produced an exceedingly low friction coefficient of 0.035, compared to approximately 0.13 for the remaining oils. This result, combined with the low contact pressure of 13.8 N/mm^2, would indicate that the contact was supported on a hydrodynamic film. The reason for the lack of a hydrodynamic film with the more viscous Oil E is unclear. However, it is likely to be due to the extreme difficulty in accurately aligning an area contact for wear testing.

Relatively good correlation was observed between the oil degradation in the single-cylinder engine tests and the effects of artificial degradation in the laboratory. However, the purpose of the present study is to simulate the wear conditions present within a full-scale engine. Engine tests performed by Sutor, et al. (12) did show reduced wear with Oil E, although it was assumed that this reduction was due to the high viscosity of Oil E, when compared with Oil D. Oil E was found to produce only one-fourth of the viscosity change of Oil D during thin film microoxidation experiments, possibly reducing the true viscosity difference between the oils. However, the decreased wear resistance of Oils D and E was not evident in the high-temperature single-cylinder SCE-903 engine tests performed at BFLRF. Modeling of the hydrodynamic film between the piston ring and cylinder liner predicts only slight metal to metal contact at the conditions used in the BFLRF engine test series. As a result, no wear was evident with any of the lubricants, although extended testing with a less durable engine or more severe conditions may produce a different result. Accurate wear measurements from full-scale engine tests with each of the oils are required to provide the necessary data for correlation with the bench-scale test results. Engine wear measurements are available in Appendices A through G for each lubricant, with a table containing summarized component dimensional changes shown in Appendix H.

VI. TRANSMISSION BENCH TEST

It is an Army requirement that a newly developed HTL must be multifunctional, meaning that it will be compatible with powershift transmissions. The feasibility of this concept was initially determined by evaluating Oil D in the Allison Hydraulic Transmission Fluid, Type C-4 Graphite Clutch Friction Test. TABLE 12 shows the friction characteristics for Oil D in this test, and Fig. 48 shows the plots of slip-time and midpoint torque with test cycles. Oil D passed the C-4 requirements for graphite clutch friction. Additional powershift transmission bench tests of MIL-L-2104 are recommended to confirm the multifunctionality of Oil D and other candidate HTLs.

TABLE 12. Oil D Friction Characteristics, C-4 Graphite Clutch

	Limits		Results			Pass	Fail
	Max	Max Change	1,500 N	5,500 N	% Change		
Slip Time, Maximum	0.68	N/A*	0.590	0.590	0.000	X	
0.2 Second Dynamic Coefficient	N/A	N/A	0.126	0.120	–4.762		
Midpoint Friction Coefficient, Min	0.102	N/A	0.125	0.120	–4.000	X	
Static Friction Coefficient	N/A	N/A	0.153	0.148	–3.268		
Low-Speed Peak Friction Coefficient	N/A	N/A	0.169	0.159	–5.917		
0.25 Second Low-Speed Coefficient	N/A	N/A	0.156	0.150	–3.846		

* N/A = Not Applicable.

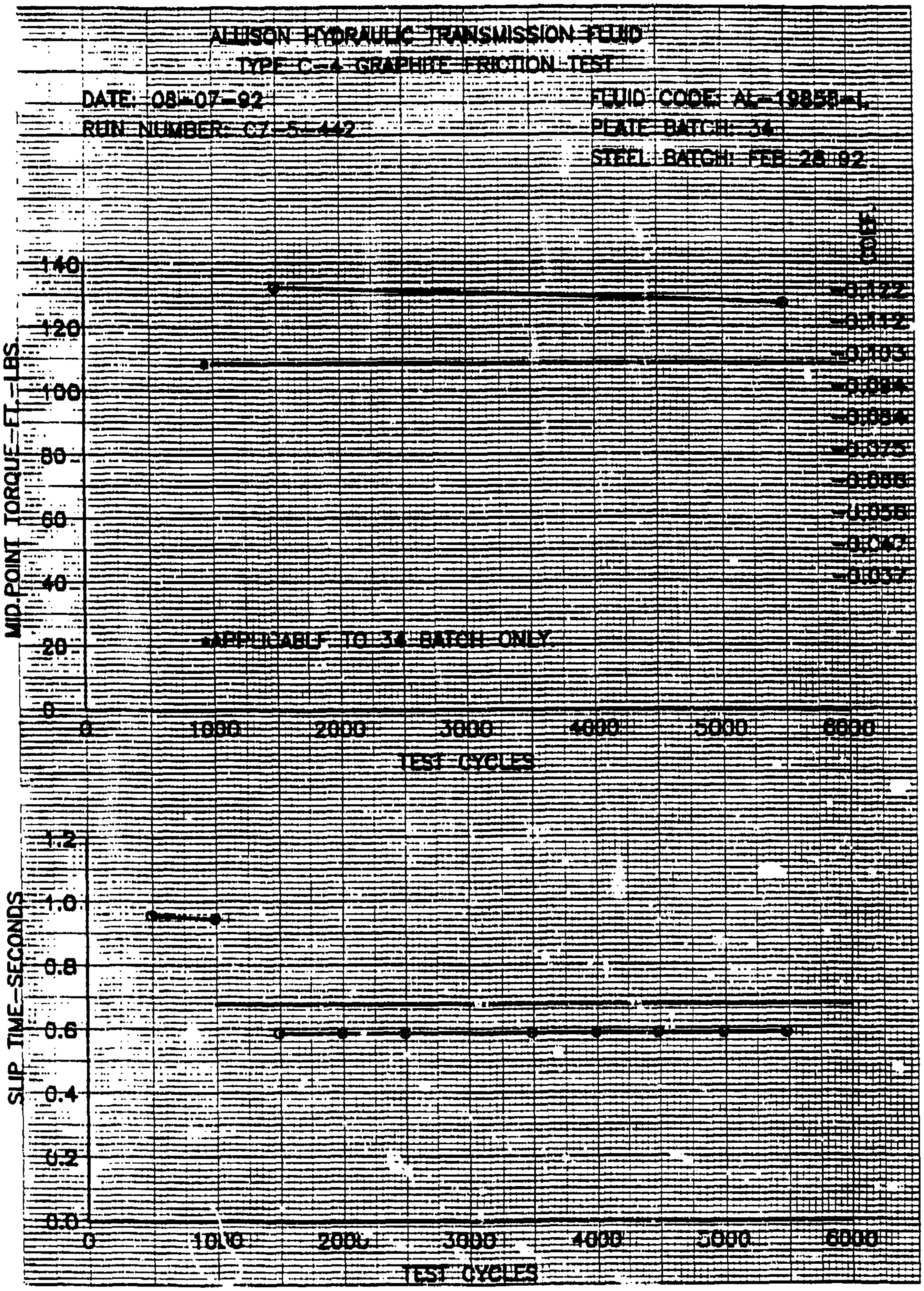


Figure 48. Allison hydraulic transmission fluid — Type C-4 graphite friction test

VII. CONCLUSIONS

As a result of this study, the following conclusions have been reached:

1. A single-cylinder diesel engine (SCE-903) was successfully modified to operate at increased cylinder liner temperatures and to serve as an evaluation tool for HTLs.

2. Oil D, one of the six lubricants evaluated, completed 200 test hours at an average cylinder wall temperature of 247°C (477°F) and an oil sump temperature of 166°C (331°F) with only minor oil degradation. However, improved piston cleanliness is needed.

3. A range of wear tests have been developed to highlight different lubricant characteristics, with particular emphasis on high-temperature operation and oxidation.

4. Both dipentaerythritol ester-based oils (D, E) have dramatically improved oxidation characteristics compared to regular synthetic and petroleum-based oils.

5. Oil D produced significantly more wear than all the remaining oils in most bench tests. This result is contrary to some previous studies with this oil.

6. Oils D and E appear to have dissimilar wear characteristics, distinct from their different viscosities: Oil D produced more wear in bench-scale testing than Oil E.

7. The dipentaerythritol ester-base stocks for Oils D and E have similar wear characteristics; however, the formulated Oil D produced more wear in bench-scale testing than its base stock.

8. As expected, each of the synthetic oils demonstrated significantly improved oxidation characteristics when compared with the single petroleum-based oil.

9. A significant difference was observed between the ranking of the oils in low-temperature laboratory wear tests when compared to high-temperature tests that produce rapid lubricant degradation.

10. In a bench wear test, both Oils D and E produced as much wear as the remaining oils at high temperatures; however, friction remained lower and significantly more preoxidation of the oil was required to produce scuffing.

11. A microsample lubrication wear test that can differentiate between the oils and is sensitive to preoxidation of the oil, applied load, temperature, and wear rate was developed.

12. Oil degradation in the crankcase and especially in the ring zone was found to have a significant effect on the wear resistance of the synthetic-based oils studied. The wear resistance of the petroleum-based oil appeared less sensitive to degradation in the engine, possibly because of the relatively large viscosity increase for this oil.

13. Mathematical modeling of the hydrodynamic film between the piston ring and cylinder liner predicts that little interasperity contact will occur at the test conditions used in previous engine tests. As a result, relatively mild cylinder liner wear was observed.

14. Oil D passed the Allison C-4 Graphite Clutch Friction test.

VIII. RECOMMENDATIONS

The following recommendations are offered for future work:

- Improved HTLs with better engine deposition protection are needed.
- Improved HTLs that have been successfully screened in the SCE-903 should be evaluated in a multicylinder low-heat rejection engine.
- Improved HTLs should be evaluated under both steady-state and cyclic operating conditions.

- Improved HTLs should be fully compatible with the two-cycle diesel and four-cycle diesel requirements of the current MIL-L-2104 oil specification.
- An accelerated bench-scale methodology, such as surface layer activation, should be developed to define the high-load wear characteristics of HTLs.
- Develop laboratory wear tests to simulate more highly loaded contact conditions present in the valve train and unit injection system. These tests could include the combined effects of sliding and rolling.
- Validate laboratory wear tests using results obtained by surface layer activation.
- Develop laboratory wear test to simulate corrosive wear observed on journal bearings in full-scale engine tests.
- Select most critical/accurate laboratory wear test to define minimum lubricity requirement of the low heat rejection engine. This test would be available for screening of potential high temperature lubricants.
- Improved candidate HTLs should be evaluated against the powershift transmission bench test requirements of MIL-L-2104 to ensure that oil multifunctionality is achieved.

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XI. LIST OF ABBREVIATIONS AND ACRONYMS

API	-	American Petroleum Institute
ASTM	-	American Society for Testing and Materials
Belvoir RDE Center	-	U.S. Army Belvoir Research, Development and Engineering Center
BFLRF	-	Belvoir Fuels and Lubricants Research Facility (SwRI)
BSFC	-	Brake Specific Fuel Consumption
BSOC	-	Brake Specific Oil Consumption
CI	-	Compression Ignition
CLR-D	-	Coordinating Lubricant Research-Diesel
CWT	-	Cylinder Wall Temperature
DIR	-	Differential Infrared
EHD	-	Elastohydrodynamic
EOT	-	End-of-Test
FTM	-	Federal Test Method
FTMS	-	Federal Test Method Standard
GCBPD	-	Gas Chromatography Boiling Point Distribution
GPC	-	Gel Permeation Chromatographic
GPC/SEC	-	Gel Permeation/Size Exclusion
HPLC	-	High Pressure Liquid Chromatography
HTL	-	High-Temperature Lubricants
ICP	-	Inductively Coupled Plasma Emission Spectrometry
IR	-	Infrared
KOH	-	Potassium Hydroxide
LHR	-	Low-Heat Rejection
MW	-	Molecular Weight
OD	-	Outer Diameter
ox-cor	-	Oxidation-Corrosion
PAO	-	Polyalphaolefin
RMS	-	Root Mean Squared
RZO	-	Ring Zone Oil
SAE	-	Society of Automotive Engineers
TAN	-	Total Acid Number
TBN	-	Total Base Number
TCP	-	Tricresylphosphate
TEO	-	Turbine Engine Oil
TFOUT	-	Thin Film Oxygen Uptake Test
TRR	-	Top Ring Reversal
VI	-	Viscosity Index
VII	-	Viscosity Index Improvers
VM	-	Engine Manufacturer
WDK	-	Total Piston Deposit Rating
WTD	-	Weighted Total Deposits
XRF	-	X-Ray Fluorescence
ZDTP	-	Zinc Dithiophosphate

APPENDIX A

SCE-903 High-Temperature Lubricant Evaluation
Test No. AIPS-1

SCE-903 HIGH-TEMPERATURE LUBRICANT EVALUATION

Test Lubricant: AL-8924-L
Test Fuel: AL-17696-F
Test No: AIPS-1
Date: 15 May 1990

Conducted For

U.S. Army Belvoir Research, Development and Engineering Center
Logistics Equipment Directorate
Fort Belvoir, Virginia 22060-5606

By

Belvoir Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78228-0510

TEST SUMMARY

The SCE-903 is a vee-configured two-cylinder engine, with one cylinder active and the second cylinder for balance. The SCE-903 is being used to screen candidate high-temperature lubricants for future low-heat rejection diesel engines. The target operating conditions are 340°F oil sump and 318°F oil gallery temperatures at 2600 rpm and a full-load air/fuel ratio of 28 to 1. The cylinder block is uncooled and the cylinder head temperature is 250°F during engine operation.

The AIPS-1 test candidate was a commercially available 5W-30 synthetic diesel engine oil. The lubricant evaluation lasted 75 hours, after which time the engine was disassembled for parts rating and inspection. The evaluation was halted due to significant leakage from the rear crankshaft seal. The ratings revealed slight front-to-back cylinder liner scuffing, slight piston skirt scuffing, and very mild ring face distress. All three rings were free with moderate groove and land deposits. The connecting rod piston pin bushing revealed distress due to the high-temperature operation, and the connecting rod and main bearings revealed exposed copper. The end-of-test lubricant inspection revealed substantial oil degradation, with both large viscosity and Total Acid Number increases. Used oil wear metal contents by ICP were 100 ppm of iron and 82 ppm of copper, relatively high considering the duration of the test.

SCE-903
OPERATING CONDITIONS SUMMARY

Date: 05/15/90 **Test No.: AIPS-1**

Lubricant: AL-8924-L **Fuel: AL-17696-F**

Test Hours: 75

	Mean	Standard Deviation
Engine Speed, rpm	2597	2.1
Torque, lb-ft	113	1.6
Observed Power, Bhp	56	0.8
Air/Fuel Ratio	28.2	0.4
Fuel Rate, lb/hr	20.9	0.3
BSFC, lb/Bhp-hr	0.373	0.006
BMEP, psi	150.37	2.1
Oil Consumption Rate, lb/hr	0.377	
BSOC, lb/Bhp-hr	0.0067	
Temperatures, °F		
Oil Sump	330	5.7
Oil After Cooler	315	4.2
Coolant Into Head	242	3.6
Coolant Out of Head	248	2.7
Exhaust	1106	8.1
Inlet Air	220	13.1
Fuel Inlet	107	3.5
Cylinder Liner, All Positions	527	17.8
Thrust Top	637	17.8
Upper Mid	480	24.9
Lower Mid	553	10.6
Bottom	518	33.7
Antithrust		
Top	487	13.5
Upper Mid	466	19.1
Lower Mid	540	11.4
Bottom	536	11.7
Pressures, psig		
Manifold	15.7	0.2
Oil Gallery	14.1	0.9
Exhaust Back	14.9	0.3

OIL PROPERTIES

Test No.: AIPS-1
Lubricant: New Oil (AL-8924-L)

Lubricant Analysis	AL-8924-L
K. Vis, 40°C, cSt	56
K. Vis, 100°C, cSt	10
Viscosity Index	167
HTHS Vis at 150°C, cP, D 4624	3.13
Flash Point, °C	224
Pour Point, °C	-39
Sulfated Ash, wt%	1.1
TAN	3.56
TBN, D 664	5.69
N, wt%, D 4629	0.14
TFOUT, minutes, D 4742	183
Elements, XRF, wt%	
S	0.33
Ca	0.25
Ba	NIL
Zn	0.13
P	0.13
Element, ICP, ppm	
Ca	2500
HPDSC, minutes, at	
180°C	80
190°C	43
200°C	22
210°C	13

OIL PROPERTIES

Test No.: **AIPS-1**
Lubricant: **AL-8924-L**

Properties	Test Hours 0	50	75
K. Vis, 40°C, cSt	56	172.3	218.7
K. Vis, 100°C, cSt	10	22.4	26.2
Viscosity Index	167	156	153
HTHS Vis at 150°C, cP, D 4624	3.1	ND*	6.5
Flash Point, °C	224	ND	268
TAN	3.6	6.1	7.6
TBN, D 664	5.7	3.7	2.8
Sulfated Ash, wt%	1.1	2.0	2.3
TFOUT, minutes, D 4742	183	60	50
TGA Soot, wt%	NIL	0.4	1.1
Coag Insols, wt%			
Pentane B	ND	ND	0.09
Toluene B	ND	ND	0.09
HPDSC at 180°C, minutes	80	7	6
Elements, ICP, ppm			
Fe	NIL	78	100
Cu	NIL	56	82
Pb	NIL	21	50
Cr	NIL	3	3
Al	NIL	11	9
Si	ND	291	305
Sn	ND	<15	<15
Ca	2500	5587	6094

* ND = Not Determined.

SCE-903
OIL CONSUMPTION AND WEAR METALS BY XRF

Lubricant: AL-8924-L

Test Time, hours	Total Oil Consumed		K. Vis, 100°C, cSt	Wear Metals, ppm	
	lb	kg		Fe	Cu
0.0	0.00	0.00	9.58	<10	<10
4.5	4.28	1.94	ND*	ND	ND
8.5	6.26	2.84	13.89	<10	<10
12.5	8.82	4.00	15.49	<10	<10
16.5	10.53	4.77	16.42	<10	<10
17.5	11.15	5.05	ND	ND	ND
21.0	12.40	5.62	17.20	38	22
25.0	13.61	6.17	17.32	30	27
30.0	14.72	6.67	18.95	34	31
33.0	15.79	7.15	19.89	52	27
38.0	17.39	7.88	21.78	55	34
43.0	19.26	8.73	22.69	64	36
47.0	20.81	9.43	22.50	52	31
50.0	22.23	10.07	22.40	58	33
54.5	23.02	10.43	22.76	61	48
58.5	24.81	11.24	24.46	67	50
65.0	27.40	12.41	26.07	65	52
69.0	28.27	12.81	23.76	66	48
75.0	28.27	12.81	27.48	71	60

	lb/hr	kg/hr
Average Oil Consumption Rate	0.377	0.171

* ND = Not Determined.

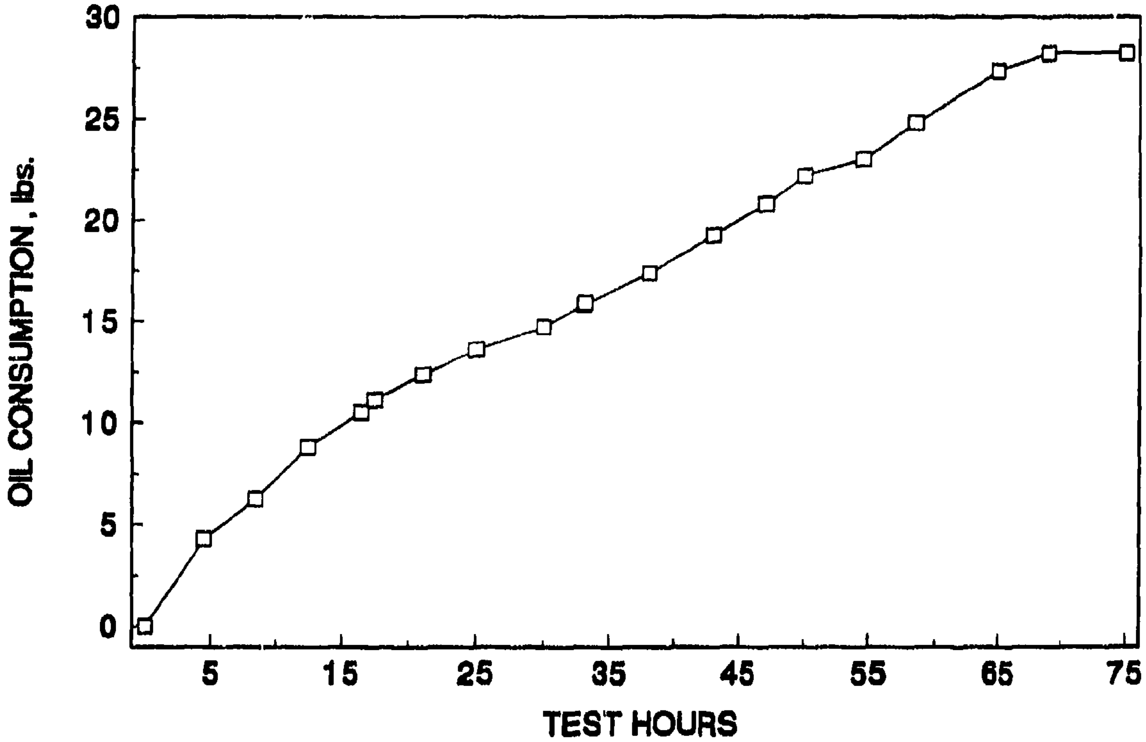


Figure A-1. AIPS-1, AL-8924, oil consumption

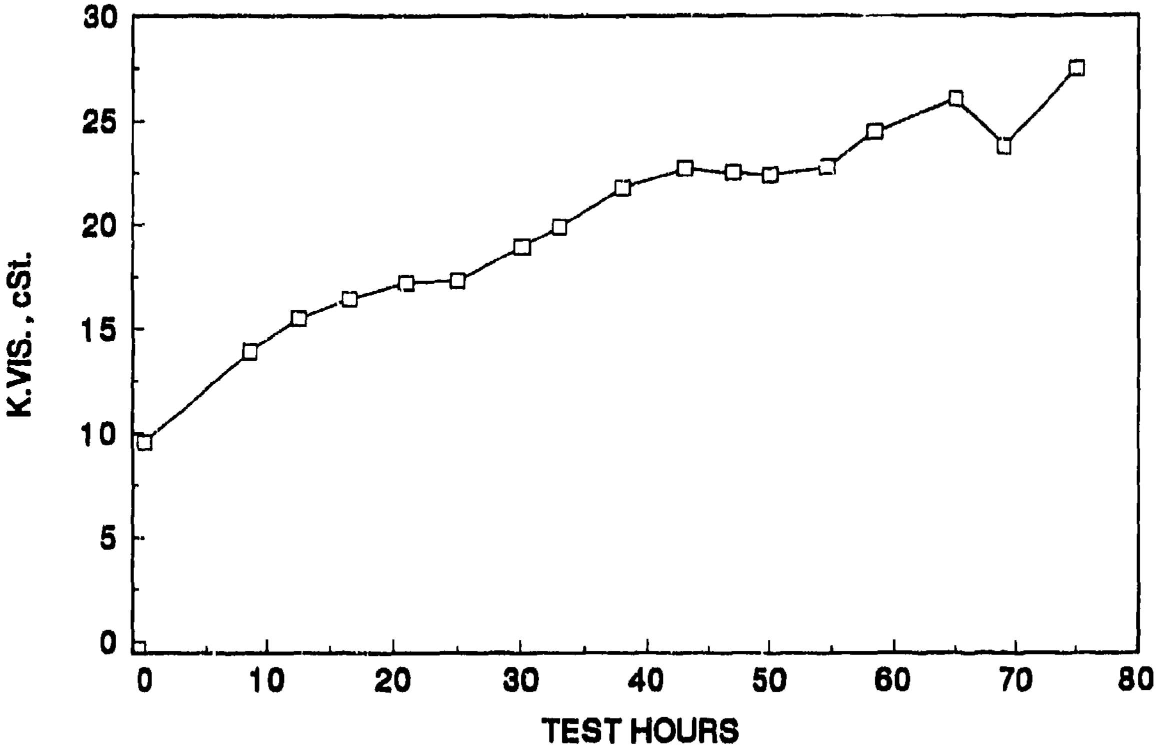


Figure A-2. AIPS-1, AL-8924, K. vis., 100°C

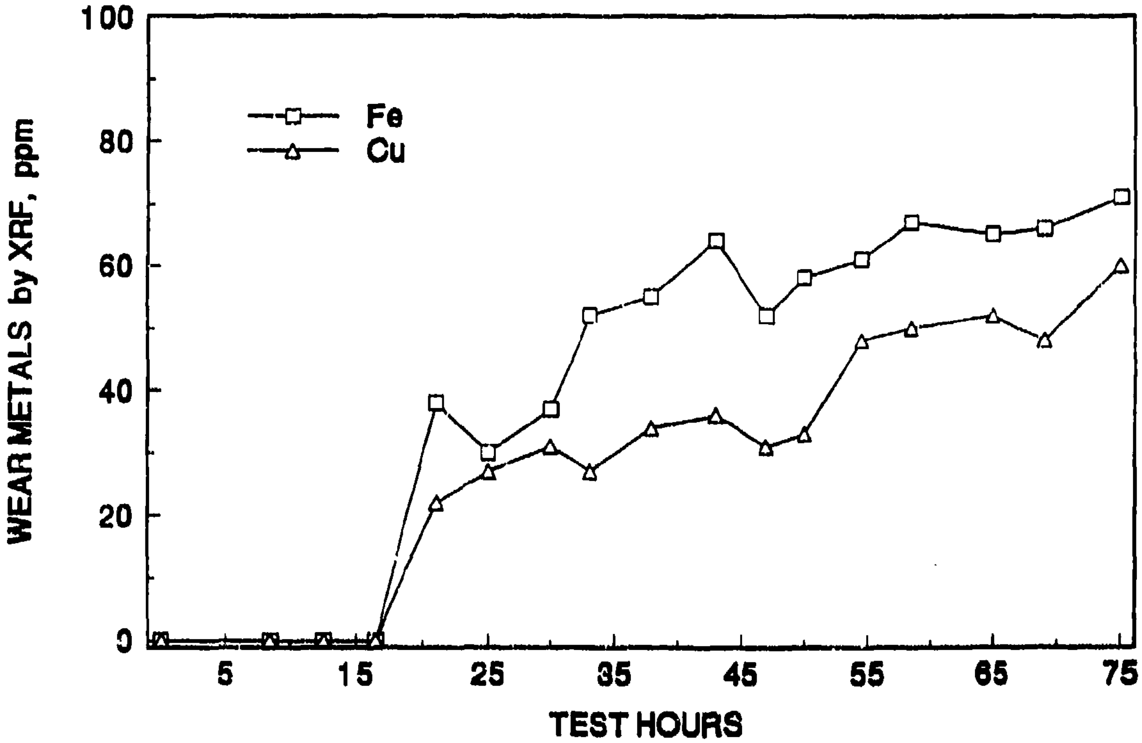


Figure A-3. AIPS-1, AL-8924, wear metals

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS*

Test No.: AIPS-1
Lubricant: AL-8924-L
Test Hours: 75

	Before**		After		Change		Specified Limits	
	T-AT	F-B	T-AT	F-B	T-AT	F-B		
CYLINDER LINER***								
Inside Diameter								
Top	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5.4995 - 5.5010	Worn Limit: 5.505
Middle	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5.4995 - 5.5010	Worn Limit: 5.505
Bottom	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5.4995 - 5.5010	Worn Limit: 5.505
Taper	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0015 Max	
Out-of-Round								
Top	0.0000		0.0000		0.0000		0.0020 Max	
Middle	0.0000		0.0000		0.0000		0.0020 Max	
Bottom	0.0000		0.0000		0.0000		0.0020 Max	
PISTON DIAMETER								
At Skirt	0.0000		5.4892		5.4892		5.4890 - 5.4900	
PISTON PIN-BORE								
Bore	0.0000		1.7500		1.7500		1.7485 - 1.7489	Worn Limit: 1.7500
Pin	0.0000		1.7486		1.7486		1.7488 - 1.7490	Worn Limit: 1.7478
Clearance	0.0000		0.0014		0.0014		-0.0005 - 0.0001	Worn Limit: 0.0022
PISTON-CYLINDER LINER CLEARANCE								
Minimum	-5.4892		-5.4892		0.0000		0.0095 - 0.0120	Worn Limit: 0.0170
Maximum	-5.4892		-5.4892		0.0000		0.0095 - 0.0120	Worn Limit: 0.0170
PISTON RINGS								
Eng Gap								
Ring No. 1	0.0000		0.0000		0.0000		0.0170 - 0.0270	
Ring No. 2	0.0000		0.0000		0.0000		0.0200 - 0.0300	
Ring No. 3	0.0000		0.0000		0.0000		0.0100 - 0.0250	
Ring Proudness								
Ring No. 1								
Measurement Point								
1	0.0000		0.0035		0.0035			
2	0.0000		0.0038		0.0038			
3	0.0000		-0.0030		-0.0030			
4	0.0000		0.0005		0.0005			
Ring No. 2								
Measurement Point								
1	0.0000		0.0010		0.0010			
2	0.0000		0.0018		0.0018			
3	0.0000		-0.0011		-0.0011			
4	0.0000		0.0028		0.0028			

* Measurements are in inches. Change = After - Before.
** Before test measurements were not determined.
*** T-AT = Thrust-Antithrust.
F-B = Front-Back.

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS* (CONT'D)

Test No.: AIPS-1
Lubricant: AL-8924-L
Test Hours: 75

	Before**		After		Change		Specified Limits	
	A	B	A	B	A	B		
BEARINGS***								
Main Bearing Journals								
1	0.0000	0.0000	3.7487	3.7485	3.7487	3.7485	3.7490 - 3.7500	Worn Limit: 3.7470 Max
2	0.0000	0.0000	3.7489	3.7491	3.7489	3.7491	3.7490 - 3.7500	Worn Limit: 3.7470 Max
Connecting Rod Bearing Journals								
1	0.0000	0.0000	3.1244	3.1244	3.1244	3.1244	3.1240 - 3.1250	Worn Limit: 3.1220
	F	BA	F	BA	F	BA		
Main Bearing Shells								
1	0.0000	0.0000	3.7559	3.7559	3.7559	3.7559		
2	0.0000	0.0000	3.7560	3.7552	3.7560	3.7552		
Connecting Rod Bearing Shells								
1	0.0000	0.0000	3.1287	3.1287	3.1287	3.1287		
	Min	Max	Min	Max	Min	Max		
Main Bearing Journal-Shell Clearances								
1	0.0000	0.0000	0.0072	0.0074	0.0072	0.0074	0.0015 - 0.0050	Worn Limit: 0.007
2	0.0000	0.0000	0.0061	0.0071	0.0061	0.0071	0.0015 - 0.0050	Worn Limit: 0.007
	Min	Max	Min	Max	Min	Max		
Connecting Rod Journal-Shell Clearances								
1	0.0000	0.0000	0.0043	0.0043	0.0043	0.0043	0.0015 - 0.0045	Worn Limit: 0.007
Main Bearing† Weights, grams								
1 Upper	0.0000		0.0000		0.0000			
1 Lower	0.0000		0.0000		0.0000			
2 Upper	0.0000		0.0000		0.0000			
2 Lower	0.0000		0.0000		0.0000			
Connecting Rod Bearing† Weight, grams								
1 Upper	0.0000		0.0000		0.0000			
1 Lower	0.0000		0.0000		0.0000			
	T	AT	T	AT	T	AT		
VALVES††								
Stem to Guide Clearance (Average)								
Intake	0.0000	0.0000	0.0029	0.0026	0.0029	0.0026	0.0015 - 0.0032	
Exhaust	0.0000	0.0000	0.0029	0.0027	0.0029	0.0027	0.0015 - 0.0032	
Recession								
Intake	0.0000	0.0000	0.0225	0.0159	0.0225	0.0159	-0.0050 - -0.0250	
Exhaust	0.0000	0.0000	0.0692	0.0680	0.0692	0.0680	-0.0520 - -0.0720	

* Measurements are in inches. Change = After - Before.
** Before test measurements were not determined.
*** A = Micrometer anvil parallel to weights; B = Micrometer anvil perpendicular to weights; F = Front; BA = Back.
† Bearing weights not determined.
†† T = Thrust; AT = Antithrust.

SCE-903
POST-TEST RATINGS OF ENGINE DEPOSITS AND CONDITIONS

Test No.: AIPS-1
Lubricant: AL-8924-L
Test Hours: 75

PISTON	
Skirt Rating	Polished areas normal, with few fine to coarse vertical line cuttings.
Top Groove Fill, %	69
Second Groove Fill, %	38
WDK Weighted Total Deposits	559.12
RINGS	
Ring Freedom	
No. 1	Free
No. 2	Free
No. 3	Free
Ring Distress Demerits	No. 1 = 1.00; No. 2 = 0.50; No. 3 = 0.00
LINER	
Scuffing, %	10.5
Bore Polish, %	2.5
Distress	0
VALVES	
Head	
Intake	100% Light Carbon
Exhaust	100% Light Carbon
Tulip	
Intake	T* - 0.5% Carbon; AT - 1.0% Carbon
Exhaust	T - 1.0% Carbon; AT - 1.0% Carbon
Face	
Intake	T - Good Condition; AT - Trace Carbon Embedment
Exhaust	T and AT - Light Amount of Carbon Embedment
Stem	
Intake	T and AT - Clean
Exhaust	T - 5% No. 9 Lacquer; AT - 15% No. 9 Lacquer

	Top	Bottom
BEARING DISTRESS,		
% Exposed Cu		
Front Main	3	1, 1 heavy scratch
Rear Main	0	0
Connecting Rod		
Active	1	0
Slipper	ND**	ND
ROD BUSHING, % Wear Band		
Active	25 burned, heavy pitting	50 burned, heavy pitting
Slipper	ND	ND

* T = Thrust; AT = Antithrust.
** ND = Not Determined.

SINGLE CYLINDER ENGINE TESTS

TEST IDENTIFICATION

TEST TYPE	LABORATORY	OIL CODE			TEST FUEL
1K	BF'RF	AL-8924			HOWELL HYDROCARBONS BATCH
STAND #	RUN #	ENG #			
1	01	SC-903			
DATE STARTED	DATE COMPLETED	DATE RATED	RATER	TEST HOURS	
/ /	05/15/90	05/31/90	AB	75	

RATINGS SUMMARY

		GROOVES						LANDS						UPPER SKIRT		UNDRCRWN		PIN BORES			
	DEP FACTOR	NO. 1		NO. 2		NO. 3		NO. 1		NO. 2		NO. 3						FRONT		REAR	
		A %	DEM	A %	DEM	A %	DEM	A %	DEM	A %	DEM	A %	DEM	A %	DEM	A %	DEM	A %	DEM	A %	DEM
CARBON	HC-1.0	50	50.00	23	23.00			69	69.00	16	16.00										
	HC-0.5	25	12.50	19	9.50																
	LC-.25	25	6.25	23	5.75			30	7.50	17	4.25	3	0.75								
	TOTAL	100	68.750	65	38.250			99	76.500	33	20.250	3	0.750								
LACQUER	8-9			15	1.350					11	0.990					10	0.800				
	7-7.9			6	0.650					10	0.770										
	6-6.9															85	5.610	20	1.320		
	5-5.9			2	0.100					4	0.200										
	4-4.9					15	0.600							9	0.360						
	3-3.9													9	0.306			5	0.160		
	2-2.9			12	0.348	35	0.910			15	0.375	87	2.262	6	0.132	5	0.105	25	0.525	15	0.375
	1-1.9					25	0.350														
	0-0.9					15	0.075	1	0.005	7	0.035	10	0.050					25	0.150	35	0.175
	TOTAL			35	2.248	100	1.935	1	0.005	67	2.370	97	2.312	24	0.798	100	6.515	100	2.155	100	0.550

	GROOVES			LANDS			UPPER SKIRT	UNDRCRWN	PIN BORES	
	1	2	3	1	2	3			FRONT	REAR
RATING	68.750	40.498	1.935	76.505	22.620	3.062	0.798	6.515	2.155	0.550
WDK LOCATE FCT	1.5	1.5	25	1	1	25	50	20	0	0
IND WDK RATING	103.125	60.747	48.375	76.505	22.620	76.550	39.900	130.300	0.000	0.000
WD1 LOCATE FCT	1	1	35	1	1	20	70	20	100	100
IND WD1 RATING	68.750	40.498	67.725	76.505	22.620	61.260	55.860	130.300	215.500	55.000

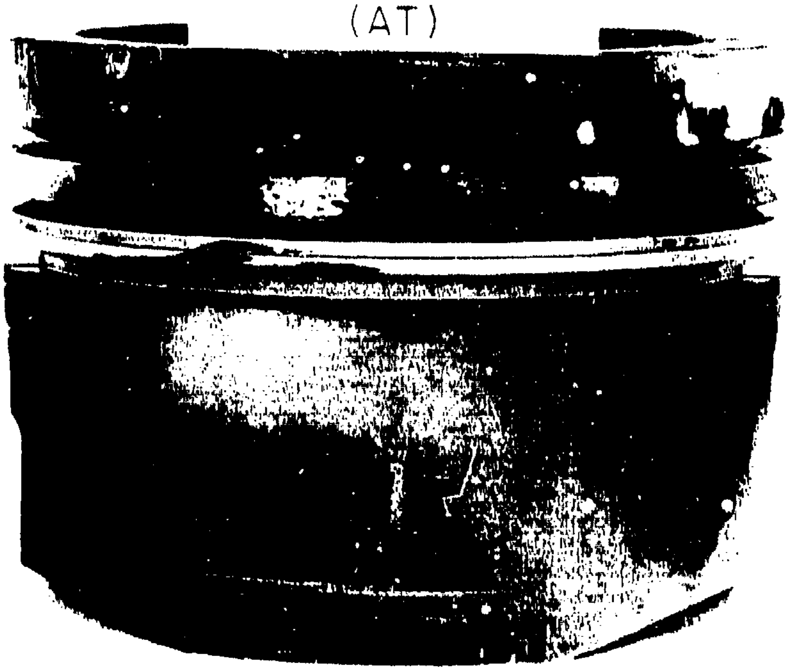
WDK WTD	558.12	WD1 WTD	794.00	WTD	223.39		
TGF	69	SECOND GROOVE FILL	38			CROWNLAND POLISHED CARBON	69

RING CONDITION Normal

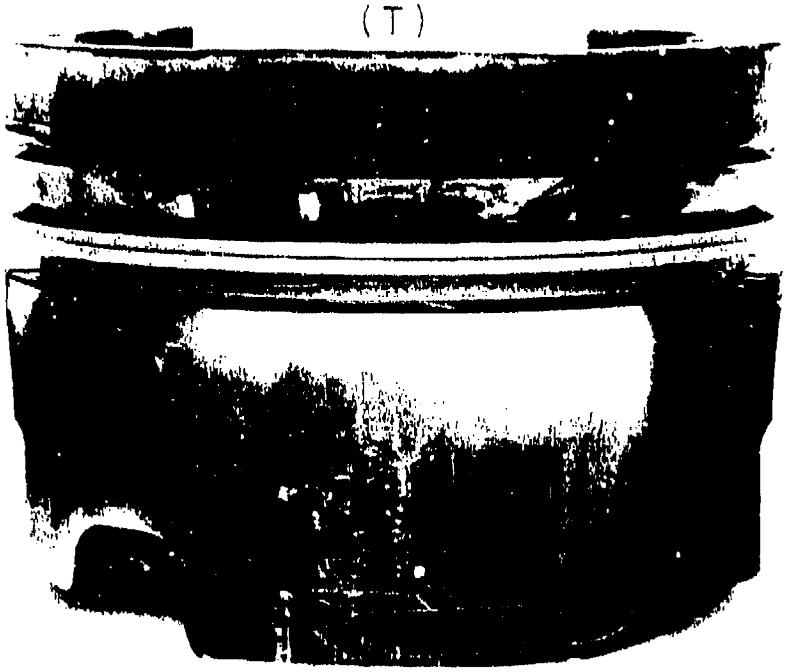
PISTON CONDITION 2nd land 15% scuffing.3rd land 10% scuffing.

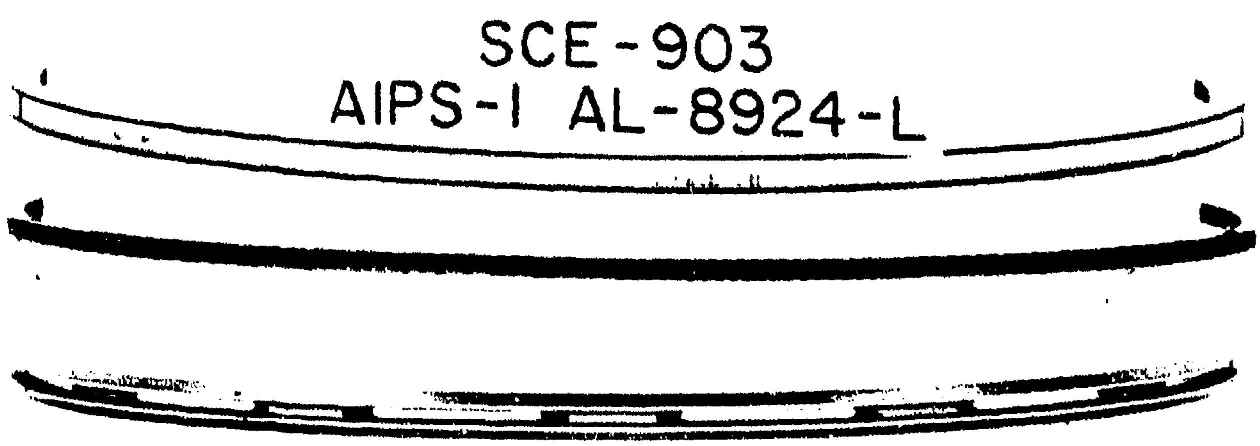
LINER CONDITION 11% scuffing.

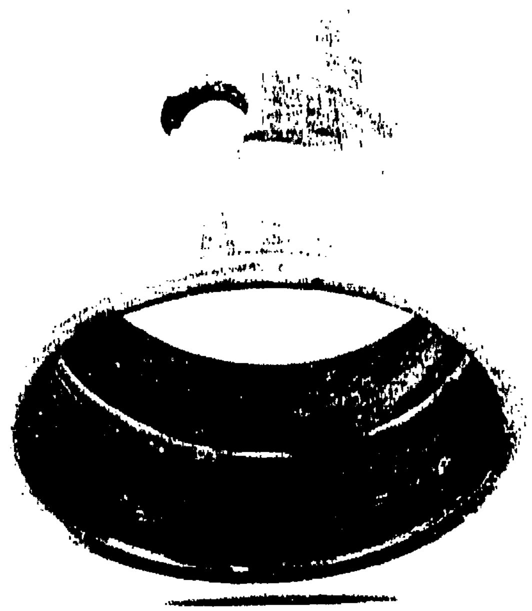
SCE-903
AIPS-I AL-8924-L
(AT)



SCE-903
AIPS-I AL-8924-L
(T)



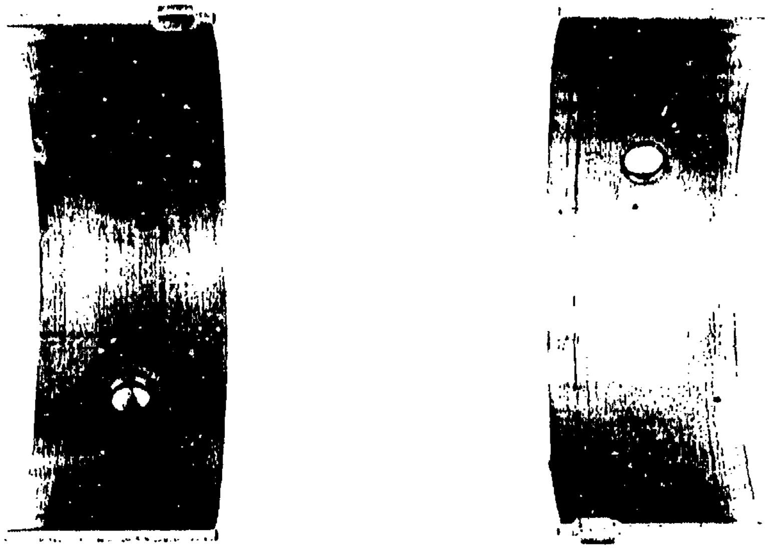

SCE-903
AIPS-I AL-8924-L



SCE-903
AIPS-I AL-8924-L
TOP ROD BUSHING

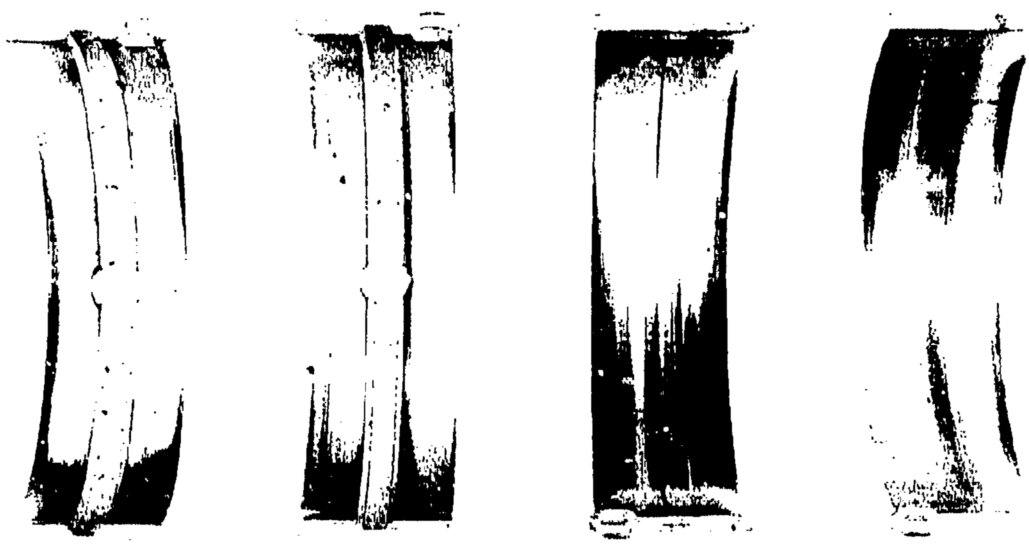
SCE-903
AIPS-I AL-8924-L
BOTTOM ROD BUSHING

TOP BOTTOM

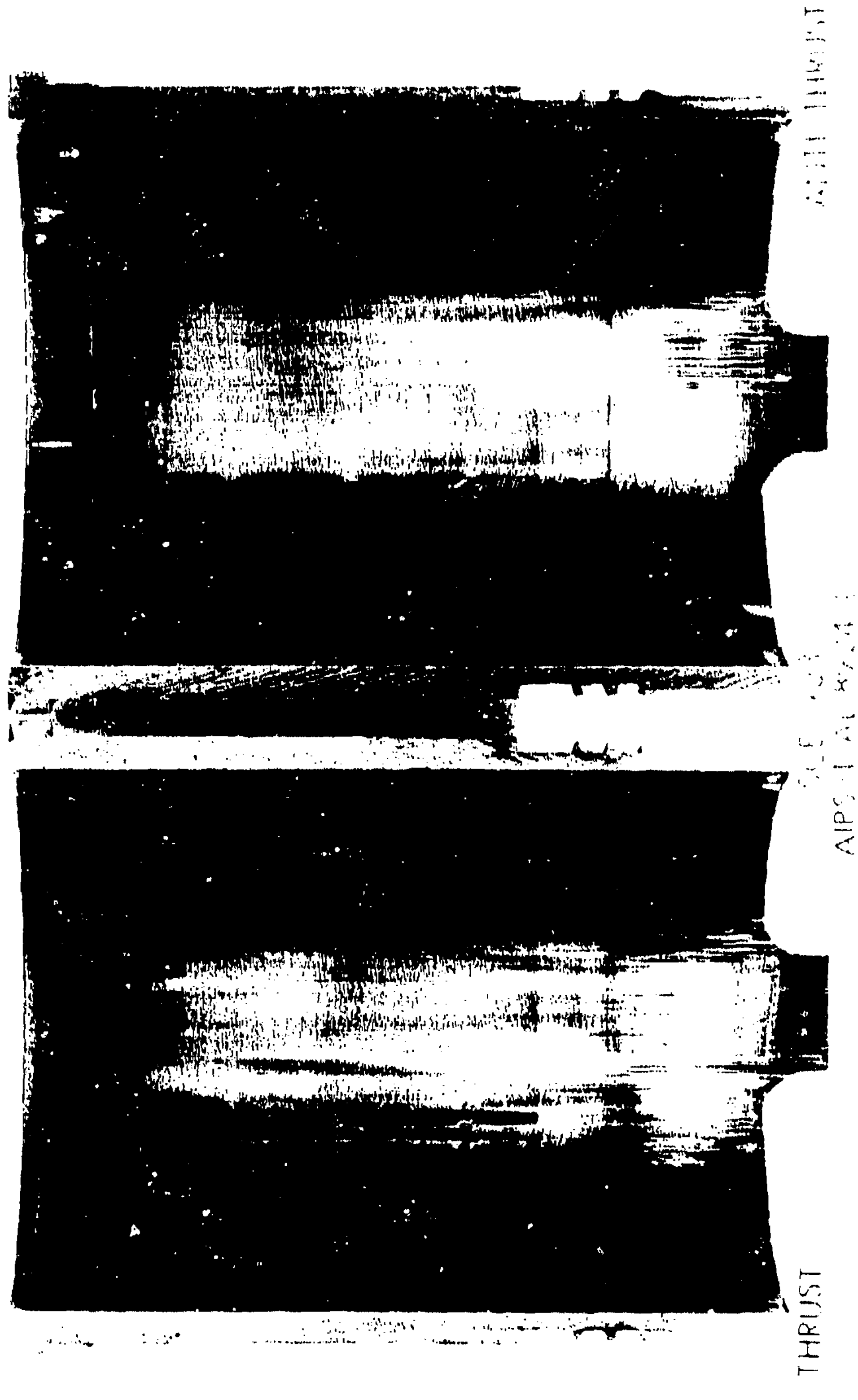


SCE-903
AIPS-I AL-8924-L
ROD BEARINGS

TOP FRONT TOP REAR BOTTOM FRONT BOTTOM REAR



SCE-903
AIPS-I AL-8924-L
MAIN BEARINGS


THRUST

APPENDIX B

SCE-903 High-Temperature Lubricant Evaluation
Test No. AIPS-2

SCE-903 HIGH-TEMPERATURE LUBRICANT EVALUATION

Test Lubricant: AL-19372-L
Test Fuel: AL-17696-F
Test No.: AIPS-2
Date: 05 October 1990

Conducted For

U.S. Army Belvoir Research, Development and Engineering Center
Logistics Equipment Directorate
Fort Belvoir, Virginia 22060-5606

By

Belvoir Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78228-0510

TEST SUMMARY

The SCE-903 is a vee-configured two-cylinder engine, with one cylinder active and the second cylinder for balance. The SCE-903 is being used to screen candidate high-temperature lubricants for future low-heat rejection diesel engines. The target operating conditions are 340°F oil sump and 318°F oil gallery temperatures at 2600 rpm and a full-load air/fuel ratio of 28 to 1. The cylinder block is uncooled and the cylinder head temperature is 250°F during engine operation.

The AIPS-2 test candidate was a commercially available 15W-40 mineral-based diesel engine oil. The lubricant evaluation lasted 40 hours, after which time the engine was disassembled for parts rating and inspection. The test was halted due to viscosity increase, leakage from the rear crankshaft seal, and blowby increase. The blowby increase was caused by the alignment of the three ring gaps of the power cylinder. The ratings revealed no cylinder liner scuffing or bore polish, and no ring face distress. All three rings were free with moderate groove and land deposits. The connecting rod piston pin bushing appeared to be free of distress. There was no bearing distress evident, likely due to the shortness of the test and the viscosity increase of the lubricant. The end-of-test lubricant inspection revealed substantial oil degradation, with a 200-percent viscosity increase and a Total Acid Number increase. Used oil wear metal contents by ICP were 26 ppm of iron and 41 ppm of copper.

SCE-903
OPERATING CONDITIONS SUMMARY

Date: 10/05/90 | **Test No.: AIPS-2**

Lubricant: AL-19372-L | **Fuel: AL-17696-F**

Test Hours: 40

	Mean	Standard Deviation
Engine Speed, rpm	2598	1.531
Torque, lb-ft	116.51	1.69
Observed Power, Bhp	57.63	0.850
Air/Fuel Ratio	28.79	0.883
Fuel Rate, lb/hr	20.48	0.512
BSFC, lb/Bhp-hr	0.356	0.009
BMEP, psi	156.13	2.118
Oil Consumption Rate, lb/hr	0.405	
BSOC, lb/Bhp-hr	0.007	
Temperatures, °F		
Oil Sump	332	8.092
Oil After Cooler	314	5.950
Coolant Into Head	242	2.023
Coolant Out of Head	248	2.112
Exhaust	1089	12.710
Inlet Air	218	3.966
Fuel Inlet	114	2.793
Cylinder Liner, All Positions	472	24.630
Thrust Top	488	6.911
Upper Mid	462	8.717
Lower Mid	436	8.003
Antithrust		
Top	500	9.250
Pressures, psig		
Manifold	15.6	0.152
Oil Gallery	19.9	2.659
Exhaust Back	14.6	0.173

OIL PROPERTIES

Test No.: AIPS-2
Lubricant: AL-19372-L

Lubricant Analysis	AL-19372-L
K. Vis, 40°C, cSt	97.9
K. Vis, 100°C, cSt	14.59
Viscosity Index	155
App Vis, at -15°C, D 2602	>15000
App Vis, at -20°C, D 4684	113652
HTHS Vis at 150°C, cP, D 4624	3.86
Flash Point, °C	221
Pour Point, °C	-19
Sulfated Ash, wt%	0.91
TAN	3.19
TBN, D 664	6.33
Gravity, °API	21.7
Carbon Residue Ramsbottom, wt%	3.59
N, wt%, D 4629	0.098
TFOUT, minutes, D 4742	200
IR Trace No.	20
Elements, XRF, wt%	
S	1.10
Ca	0.18
Ba	ND
Zn	0.15
P	0.12
Elements, ICP 8A, ppm	
Ba	<1
B	8
Mg	4
Mn	<1
Mo	1
Ni	<1
P	1029
Zn	1431
HPDSC, minutes, at	
180°C	57
190°C	34
200°C	20
210°C	10

OIL PROPERTIES

Test No.: AIPS-2
Lubricant: AL-19372-L

Properties	Test Hours 0	Test Hours 40
K. Vis, 40°C, cSt	97.9	525.4
K. Vis, 100°C, cSt	14.6	45.8
Viscosity Index	155	140
HTHS Vis at 150°C, cP, D 4624	3.9	10.1
Flash Point, °C	221	255
TAN	3.2	8
TBN, D 664	6.3	3.4
Sulfated Ash, wt%	0.91	1.89
TFOUT, minutes, D 4742	200	86
TGA Soot, wt%	NIL	1.6
Coag Insols, wt%		
Pentane B	NIL	0.13
Toluene B	NIL	0.08
HPDSC at 180°C, minutes	57	12
Elements, ICP, ppm		
Fe	NIL	26
Cu	NIL	41
Pb	NIL	14
Cr	NIL	1
Al	NIL	8
Si	ND*	85
Sn	ND	2
Ca	1914	4458

* ND = Not Determined.

SCE-903
OIL CONSUMPTION AND WEAR METALS BY XRF

Lubricant: AL-19372-L

Test Time, hours	Total Oil Consumed		K. Vis, 100°C, cSt	Wear Metals, ppm	
	lb	kg		Fe	Cu
0	0.00	0.00	17.81	<10	<10
6	2.31	1.05	21.82	<10	<10
12	5.26	2.38	27.44	<10	<10
18	8.02	3.63	31.58	11	18
24	10.10	4.58	35.28	18	14
30	12.07	5.47	40.24	17	23
36	13.76	6.23	46.91	15	20
40	16.19	7.34	46.83	17	27
	lb/hr	kg/hr			
Average Oil Consumption Rate	0.405	0.183			

* ND = Not Determined.

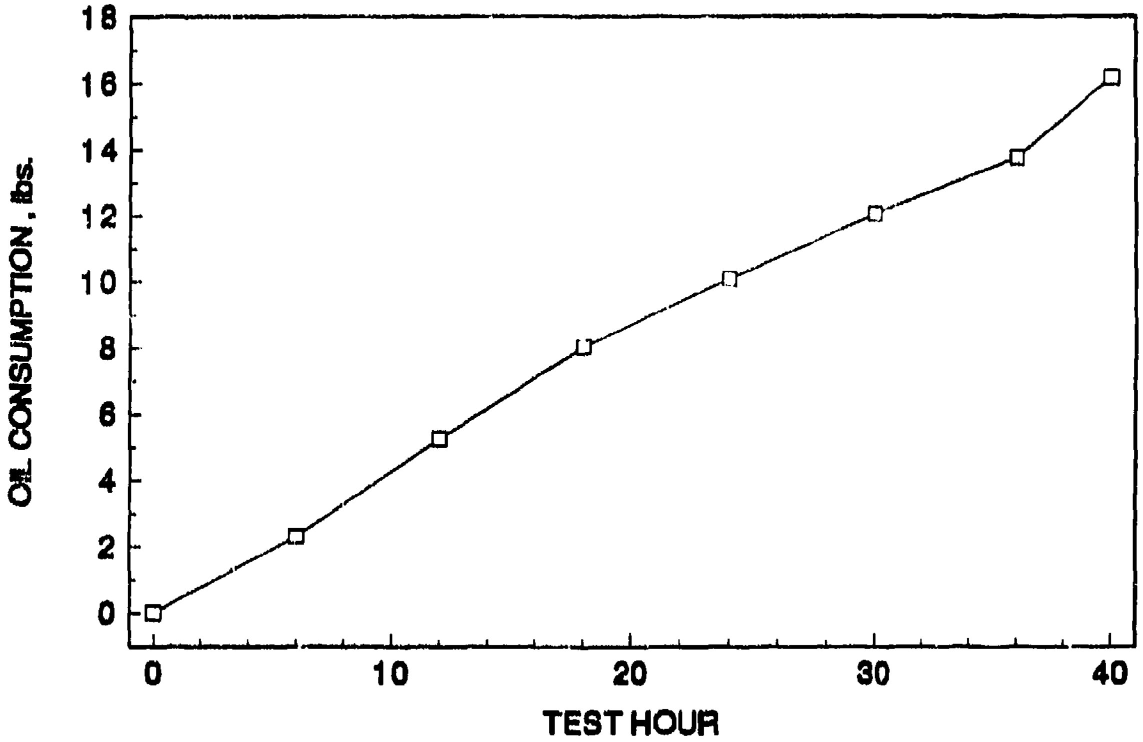


Figure B-1. AIPS-2, AL-19372, oil consumption

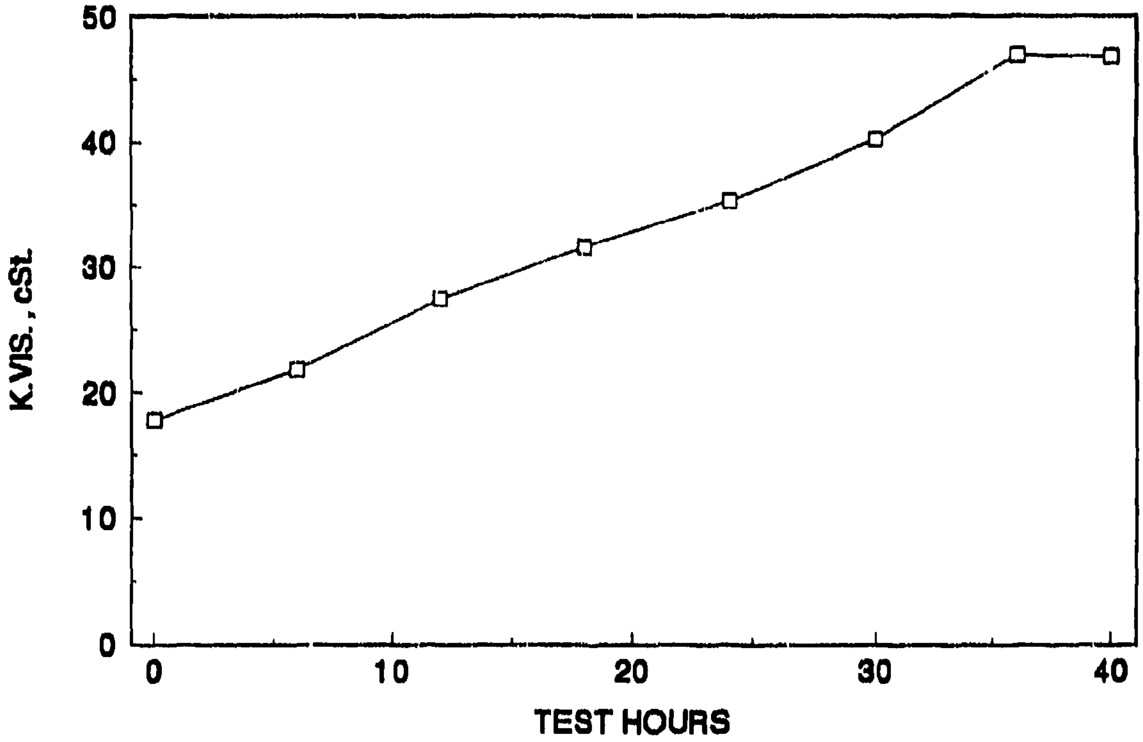


Figure B-2. AIPS-2, AL-19372, K. vis., 100°C

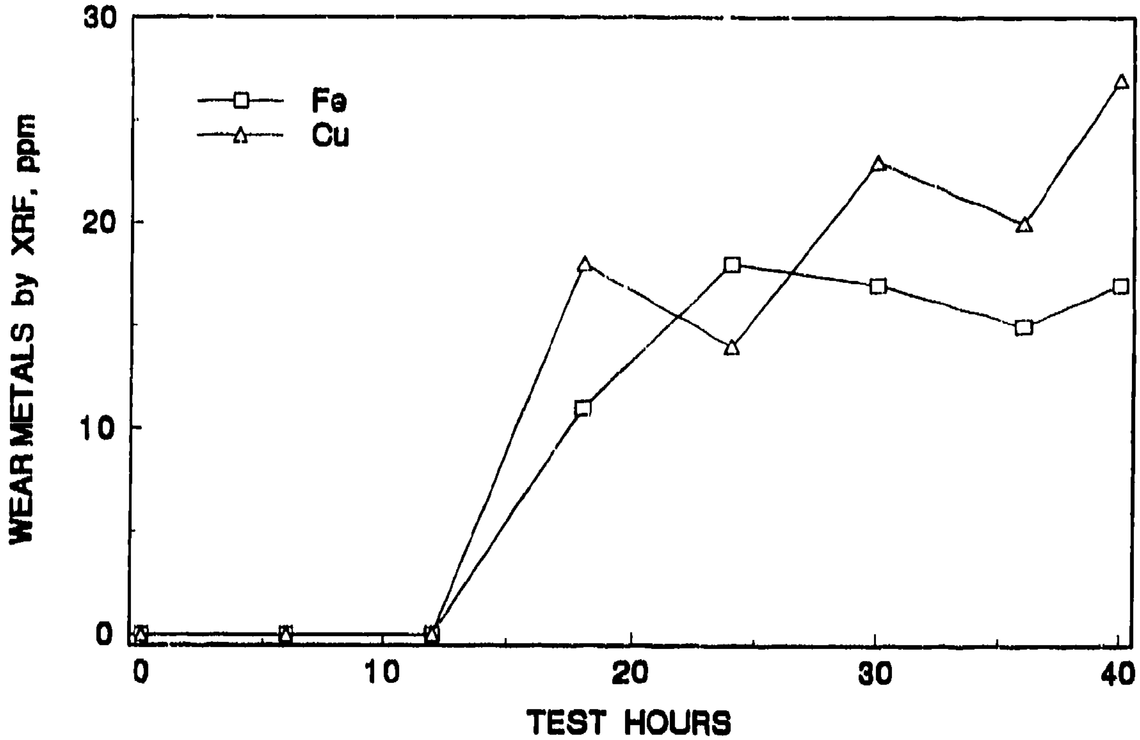


Figure B-3. AIPS-2, AL-19372, wear metals

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS*

Test No.: AIPS-2
Lubricant: AL-19372-L
Test Hours: 40

	Before T-AT	Before F-B	After T-AT	After F-B	Change T-AT	Change F-B	Specified Limits	
CYLINDER LINER**								
Inside Diameter								
Top	5.5010	5.5012	5.4999	5.5003	-0.0011	-0.0009	5.4995 - 5.5010	Worn Limit: 5.505
Middle	5.4995	5.5006	5.4995	5.5003	0.0000	-0.0003	5.4995 - 5.5010	Worn Limit: 5.505
Bottom	5.4997	5.5012	5.4998	5.5007	0.0001	-0.0005	5.4995 - 5.5010	Worn Limit: 5.505
Taper	0.0013	0.0000	0.0001	0.0004	-0.0012	0.0004	0.0015 Max	
Out-of-Round								
Top	0.0002		0.0004		0.0002		0.0020 Max	
Middle	0.0011		0.0008		-0.0003		0.0020 Max	
Bottom	0.0015		0.0009		-0.0006		0.0020 Max	
PISTON DIAMETER								
At Skirt	5.4892		5.4898		0.0006		5.4890 - 5.4900	
PISTON PIN-BORE								
Bore	1.7500		1.7510		0.0010		1.7485 - 1.7489	Worn Limit: 1.7500
Pin	1.7486		1.7485		-0.0001		1.7488 - 1.7490	Worn Limit: 1.7478
Clearance	0.0014		0.0025		0.0011		-0.0005 - 0.0001	Worn Limit: 0.0022
PISTON-CYLINDER LINER CLEARANCE								
Minimum	0.0103		0.0097		-0.0006		0.0095 - 0.0120	Worn Limit: 0.0170
Maximum	0.0120		0.0109		-0.0011		0.0095 - 0.0120	Worn Limit: 0.0170
PISTON RINGS								
End Gap								
Ring No. 1	0.0230		0.0250		0.0020		0.0170 - 0.0270	
Ring No. 2	0.0230		0.0270		0.0040		0.0200 - 0.0250	
Ring No. 3	0.0220		0.0230		0.0010		0.0100 - 0.0250	
Ring Proudness								
Ring No. 1								
Measurement Point								
1	-0.0072		0.0020		0.0092			
2	-0.0130		0.0070		0.0200			
3	-0.0130		0.0025		0.0155			
4	-0.0120		0.0050		0.0170			
Ring No. 2								
Measurement Point								
1	0.0020		0.0060		0.0040			
2	-0.0010		0.0042		0.0052			
3	-0.0015		-0.0030		-0.0015			
4	-0.0020		0.0050		0.0070			

* Measurements are in inches. Change = After - Before.
** T-AT = Thrust-Antithrust.
F-B = Front-Back.

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS* (CONT'D)

Test No.: AIPS-2
Lubricant: AL-19372-L
Test Hours: 40

	Before		After		Change		
	A	B	A	B	A	B	Specified Limits
BEARINGS**							
Main Bearing Journals							
1	3.7487	3.7485	3.7487	3.7480	0.0000	-0.0005	3.7490 - 3.7500 Worn Limit: 3.7470 Max
2	3.7489	3.7491	3.7489	3.7491	0.0000	0.0000	3.7490 - 3.7500 Worn Limit: 3.7470 Max
Connecting Rod Bearing Journals							
1	3.1244	3.1244	3.1244	3.1244	0.0000	0.0000	3.1240 - 3.1250 Worn Limit: 3.1220
	F	BA	F	BA	F	BA	
Main Bearing Shells							
1	3.7560	3.7558	3.7559	3.7558	-0.0001	0.0000	
2	3.7561	3.7554	3.7558	3.7551	-0.0003	-0.0003	
Connecting Rod Bearing Shells							
1	3.1287	3.1287	3.1289	3.1288	0.0002	0.0001	
	Min	Max	Min	Max	Min	Max	
Main Bearing Journal-Shell Clearances							
1	0.0071	0.0075	0.0071	0.0079	0.0000	0.0004	0.0015 - 0.0050 Worn Limit: 0.007
2	0.0063	0.0072	0.0060	0.0069	-0.0003	-0.0003	0.0015 - 0.0050 Worn Limit: 0.007
	Min	Max	Min	Max	Min	Max	
Connecting Rod Journal-Shell Clearances							
1	0.0043	0.0043	0.0044	0.0045	0.0001	0.0002	0.0015 - 0.0045 Worn Limit: 0.007
Main Bearing Weights, grams							
1 Upper	140.1418		140.1197		-0.0221		
1 Lower	160.0516		160.0135		-0.0381		
2 Upper	139.8132		139.8004		-0.0128		
2 Lower	159.9020		159.8925		-0.0095		
Connecting Rod Bearing Weight, grams							
1 Upper	84.7406		84.6857		-0.0549		
1 Lower	84.2684		84.2591		-0.0093		
	T	AT	T	AT	T	AT	
VALVES***							
Stem to Guide Clearance (Average)							
Intake	0.0025	0.0023	0.0028	0.0027	0.0003	0.0004	0.0015 - 0.0032
Exhaust	0.0026	0.0023	0.0029	0.025	0.0003	0.0002	0.0015 - 0.0032
Recession							
Intake	-0.0223	-0.0088	-0.0227	-0.0172	-0.0004	-0.0084	-0.0050 - -0.0250
Exhaust	-0.0692	-0.0689	-0.0704	-0.0706	-0.0012	-0.0017	-0.0520 - -0.0720

* Measurements are in inches. Change = After - Before.
** A = Micrometer anvil parallel to weights; B = Micrometer anvil perpendicular to weights; F = Front; BA = Back.
*** T = Thrust; AT = Antithrust.

SCE-903
POST-TEST RATINGS OF ENGINE DEPOSITS AND CONDITIONS

Test No.: AIPS-2
Lubricant: AL-19372-L
Test Hours: 40

PISTON		
Skirt Rating	Polished areas normal, with few fine vertical line cuttings.	
Top Groove Fill, %	53	
Second Groove Fill, %	43	
WDK Weighted Total Deposits	477	
RINGS		
Ring Freedom		
No. 1	Free	
No. 2	Free	
No. 3	Free	
Ring Distress Demerits	Rings clean, no discoloration, no apparent distress.	
LINER		
Scuffing, %	0	
Bore Polish, %	0	
Distress	0	
VALVES		
Head		
Intake	100% Light Carbon	
Exhaust	100% Light Carbon	
Tulip		
Intake	T* - 0.5% Carbon; AT - 1.0% Carbon	
Exhaust	T and AT - 1.0% Carbon	
Face		
Intake	T - Trace Carbon Embedment; AT - Clean, Good Condition	
Exhaust	T and AT - Light Amount of Carbon Embedment	
Stem		
Intake	T and AT - Clean	
Exhaust	T - 5% No. 9 Lacquer; AT - 15% No. 9 Lacquer	
	Top	Bottom
BEARING DISTRESS,		
% Exposed Cu		
Front Main	0	0
Rear Main	0	0
Connecting Rod		
Active	0	0
Slipper	0	0
ROD BUSHING, % Wear Band		
Active	25 burned, 5 heavy pitting	50 burned, 25 heavy pitting
Slipper	ND**	ND

* T = Thrust; AT = Antithrust.
** ND = Not Determined.

SINGLE CYLINDER ENGINE TESTS

TEST IDENTIFICATION

TEST TYPE	LABORATORY	OIL CODE			TEST FUEL
1K	BFLRF	AL-19372L			HOWELL HYDROCARBONS BATCH
STAND #	RUN #	ENG #			
1	02	CUMMINS			
DATE STARTED	DATE COMPLETED	DATE RATED	RATER	TEST HOURS	
/ /	07/31/90	08/09/90	AB	40	

RATINGS SUMMARY

	DEP FACTOR	GROOVES NO. 1 A %	GROOVES NO. 1 DEM	GROOVES NO. 2 A %	GROOVES NO. 2 DEM	GROOVES NO. 3 A %	GROOVES NO. 3 DEM	LANDS NO. 1 A %	LANDS NO. 1 DEM	LANDS NO. 2 A %	LANDS NO. 2 DEM	LANDS NO. 3 A %	LANDS NO. 3 DEM	UPPER SKIRT A %	UPPER SKIRT DEM	UNDRCRWN A %	UNDRCRWN DEM	PIN BORES FRONT A %	PIN BORES FRONT DEM	PIN BORES REAR A %	PIN BORES REAR DEM
CARBON	HC-1.0	42	42.00	40	40.00			45	45.00	25	25.00										
	MC-0.5	11	5.50																		
	LC-.25	47	11.75	10	2.50			50	12.50	6	1.50										
	TOTAL	100	59.250	50	42.500			95	57.500	31	26.500										
LACQUER	8-9			10	0.900					1	0.090			2	0.180	15	1.275				
	7-7.9			14	0.994	14	0.980	3	0.210	1	0.070					15	1.125				
	6-6.9																	15	0.975		
	5-5.9					2	0.504			1	0.050			8	0.466						
	4-4.9					10	0.400														
	3-3.9			9	0.270							11	0.330			70	2.100	5	0.185		
	2-2.9			17	0.340	37	0.925	2	0.046	7	0.175	12	0.300	8	0.192			20	0.500	20	0.500
	1-1.9					12	0.156			19	0.247	7	0.084	7	0.070			10	0.130		
	0-0.9					8	0.040			40	0.220	55	0.161	15	0.075			10	0.060	15	0.075
	TOTAL			50	2.504	100	3.005	5	0.256	69	0.852	10[illegible]	0.875	100	0.981	100	4.500	100	1.850	100	0.575

	GROOVES 1	GROOVES 2	GROOVES 3	LANDS 1	LANDS 2	LANDS 3	UPPER SKIRT	UNDRCRWN	PIN BORES FRONT	PIN BORES REAR
RATING	59.250	45.004	3.005	57.756	27.352	0.875	0.981	4.500	1.850	0.575
WDK LOCATE FCT	1.5	1.5	25	1	1	25	50	20	0	0
IND WDK RATING	88.875	67.506	75.125	57.756	27.352	21.875	49.050	90.000	0.000	0.000
WD1 LOCATE FCT	1	1	35	1	1	20	70	20	100	100
IND WD1 RATING	59.250	45.004	105.175	57.756	27.352	17.500	68.670	90.000	185.000	57.500

WDK WTD	477.54	WD1 WTD	713.21	UWTD	201.15		
TGF	53	SECOND GROOVE FILL	43			CROWN AND POLISHED CARBON	45

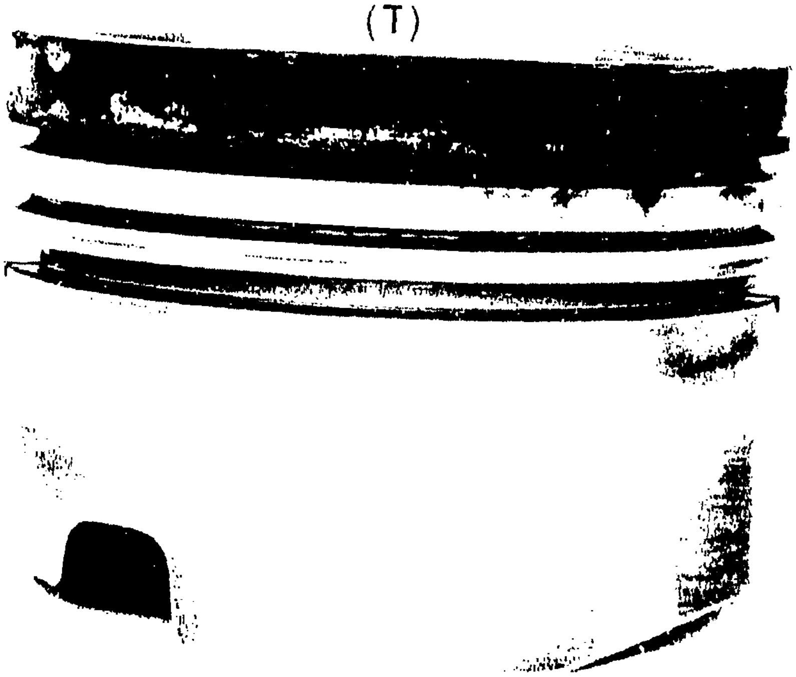
RING CONDITION Normal

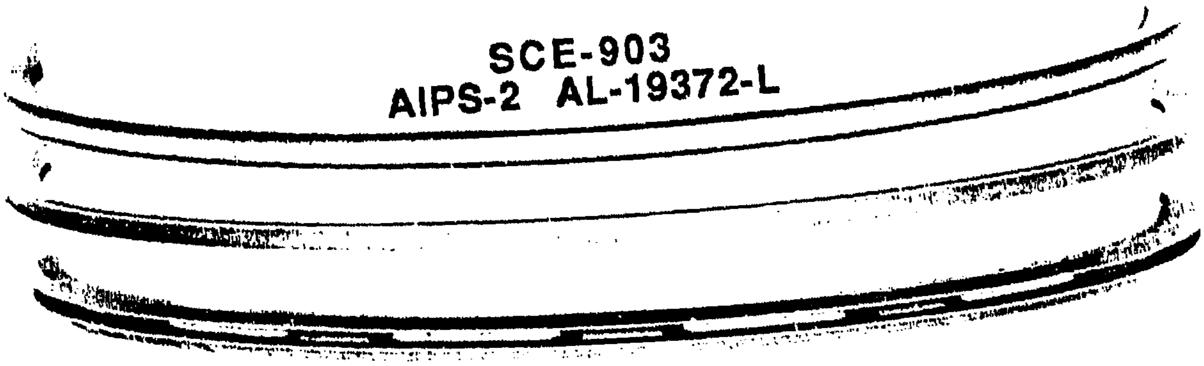
PISTON CONDITION Normal

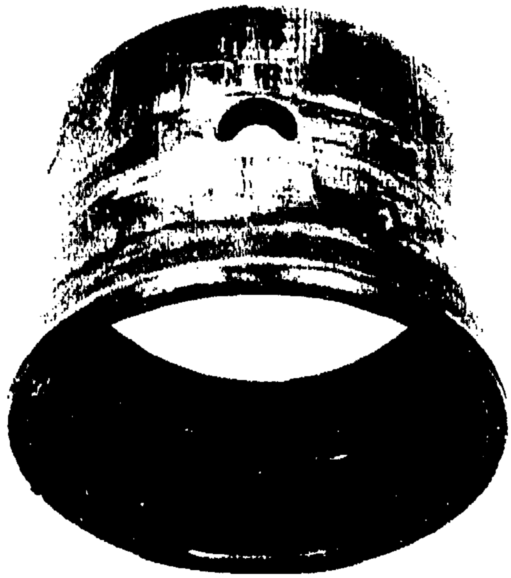
LINER CONDITION Normal

SCE-903
AIPS-2 AL-19372-L
(AT)

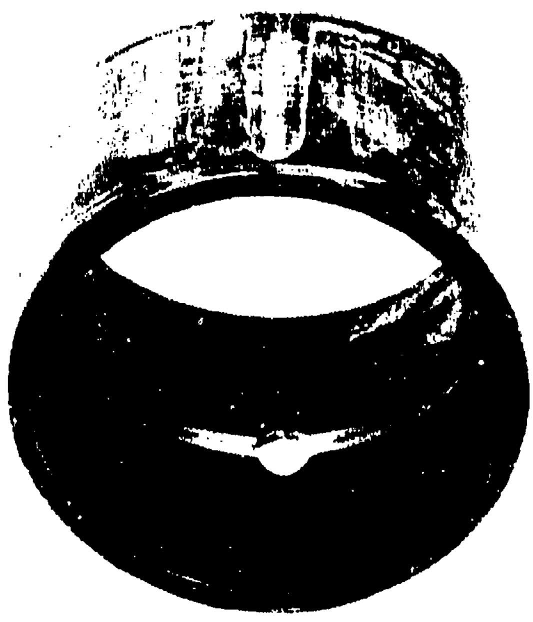
SCE-903
AIPS-2 AL-19372-L
(T)



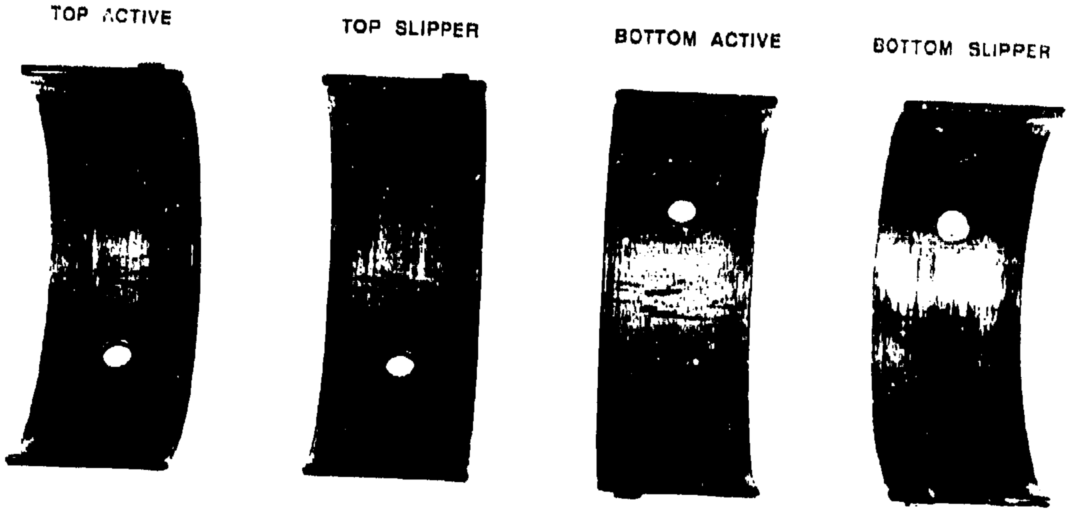

SCE-903
AIPS-2 AL-19372-L



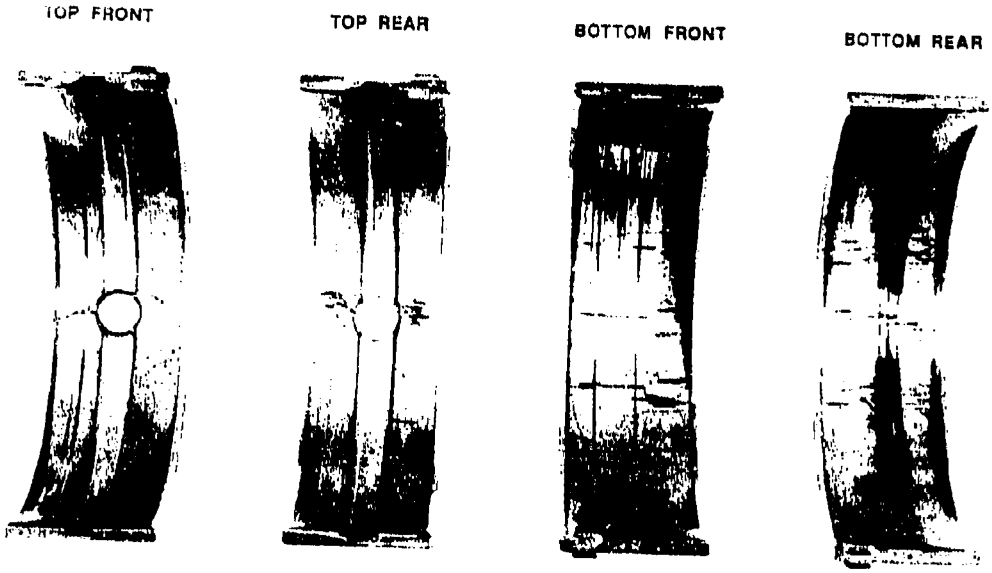
SCE-903
AIPS-2 AL-19372-L
TOP ROD BUSHING



SCE-903
AIPS-2 AL-19372-L
BOTTOM ROD BUSHING



SCE-903
AIPS-2 AL-19372-L
ROD BEARINGS



SCE-903
AIPS-2 AL-19372-L
MAIN BEARINGS

APPENDIX C

SCE-903 High-Temperature Lubricant Evaluation
Test No. AIPS-3

SCE-903 HIGH-TEMPERATURE LUBRICANT EVALUATION

Test Lubricant: AL-19371-L
Test Fuel: AL-19370-F
Test No.: AIPS-3
Date: 26 October 1990

Conducted For

U.S. Army Belvoir Research, Development and Engineering Center
Logistics Equipment Directorate
Fort Belvoir, Virginia 22060-5606

By

Belvoir Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78228-0510

TEST SUMMARY

The SCE-903 is a vee-configured two-cylinder engine, with one cylinder active and the second cylinder for balance. The SCE-903 is being used to screen candidate high-temperature lubricants for future low-heat rejection diesel engines. The target operating conditions are 340°F oil sump and 318°F oil gallery temperatures at 2600 rpm and a full-load air/fuel ratio of 28 to 1. The cylinder block is uncooled and the cylinder head temperature is 250°F during engine operation.

The AlPS-3 test candidate was a commercially available 15W-30 synthetic diesel engine oil. The lubricant evaluation lasted 90 hours, after which time the engine was disassembled for parts rating and inspection. The test was halted at 90 hours due to excessive oil loss from the rear crankshaft seal. It was determined that the course of the rear seal leakage was the seal rotating in the cast aluminum rear engine cover. This was solved by pinning the seal in place and coating the periphery of the seal with RTV. The ratings revealed no cylinder liner scuffing or bore polish, and no ring face distress. All three rings were free with moderate to heavy groove and land deposits. The connecting rod piston pin bushing, the main bearings, and connecting rod bearings appeared to be free of distress. The end-of-test lubricant inspection revealed some oil degradation, with a slight viscosity increase and a Total Acid Number increase. Used oil wear metal contents by ICP were 55 ppm of iron and 38 ppm of copper.

SCE-903
OPERATING CONDITIONS SUMMARY

Date: 10/26/90 **Test No.: AIPS-3**

Lubricant: AL-19371-L **Fuel: AL-19370-F**

Test Hours: 90

	Mean	Standard Deviation
Engine Speed, rpm	2599	3.58
Torque, lb-ft	120.93	2.42
Observed Power, Bhp	59.85	1.19
Air/Fuel Ratio	28.15	1.00
Fuel Rate, lb/hr	20.64	0.58
BSFC, lb/Bhp-hr	0.345	0.0114
BMEP, psi	161.61	3.24
Oil Consumption Rate, lb/hr	0.128	
BSOC, lb/Bhp-hr	0.0021	
Temperatures, °F		
Oil Sump	332	2.90
Oil After Cooler	317	1.70
Coolant Into Head	244	2.00
Coolant Out of Head	249	1.60
Exhaust	1086	36.10
Inlet Air	217	9.00
Fuel Inlet	112	7.16
Cylinder Liner, All Positions	456	21.40
Thrust Top	452	19.60
Upper Mid	455	6.20
Bottom	432	5.60
Antithrust		
Top	485	10.70
Pressures, psig		
Manifold	15.4	0.434
Oil Gallery	15.4	0.663
Exhaust Back	14.5	0.487

OIL PROPERTIES

Test No.: AIPS-3
Lubricant: AL-19371-L

Lubricant Analysis	AL-19346-L
K. Vis, 40°C, cSt	64.77
K. Vis, 100°C, cSt	10.08
Viscosity Index	141
HTHS Vis at 150°C, cP, D 4624	3.7
Flash Point, °C	265
Sulfated Ash, wt%	0.97
TAN	1.94
TBN, D 664	10.22
N, wt%, D 4629	0.081
TFOUT, minutes, D 4742	258
Elements, XRF, wt%	
S	0.28
Ca	0.07
Ba	NIL
Zn	0.09
P	0.08
Elements, ICP 8A, ppm	
Ba	2
B	167
Mg	1385
Mn	<1
Mo	1
Ni	1
P	1029
Zn	1203
Elements, ICP, ppm	
Ca	895
Cu	<1
HPDSC, minutes, at	
180°C	140
190°C	63
200°C	52
210°C	28

OIL PROPERTIES

Test No.: AIPS-3
Lubricant: AL-19371-L

Properties	Test Hours 0	50	75	90
K. Vis, 40°C, cSt	64.77	109.18	128.41	116.94
K. Vis, 100°C, cSt	10.08	14.62	16.38	15.48
Viscosity Index	141	138	137	139
HTHS Vis at 150°C, cP,				
D 4624	3.7	5.1	5.5	5.3
Flash Point, °C	265	277	291	282
TAN	1.9	6.3	8.3	6.8
TBN, D 664	10.2	2.4	2.5	3
Sulfated Ash, wt%	0.97	1.14	1.24	1.20
TFOUT, minutes, D 4742	258	47	36	77
TGA Soot, wt%	ND*	0.8	1.0	0.8
Coag Insols, wt%				
Pentane B	ND	0.25	0.06	0.07
Toluene B	ND	0.19	0.05	0.06
HPDSC at 180°C, minutes	142	9	7	9
Elements, ICP, ppm				
Fe	NIL	27	49	55
Cu	NIL	18	33	38
Pb	NIL	237	610	468
Cr	NIL	2	2	2
Al	NIL	7	6	6
Si	ND	63	64	55
Sn	ND	8	8	7
Ca	895	1013	1070	1066

* ND = Not Determined.

SCE-903
OIL CONSUMPTION AND VISCOSITY

Lubricant: AL-19371-L

Test Time, hours	Total Oil Consumed lb	Total Oil Consumed kg	K. Vis, 100°C, cSt
0	0.00	0.00	10.13
6	1.08	0.49	10.87
9	1.08	0.49	10.88
12	2.47	1.12	11.36
18	2.92	1.32	11.73
24	3.70	1.68	12.30
30	4.11	1.86	12.78
35	5.43	2.46	12.97
40	5.43	2.46	13.20
46	6.68	3.03	14.43
50	6.90	3.13	14.57
56	8.38	3.80	15.10
62	8.86	4.01	14.96
68	9.65	4.37	15.73
75	10.33	4.68	16.34
80	10.99	4.98	15.82
85	11.53	5.22	16.01
90	11.53	5.22	15.48

	lb/hr	kg/hr
Average Oil Consumption Rate	0.128	0.058

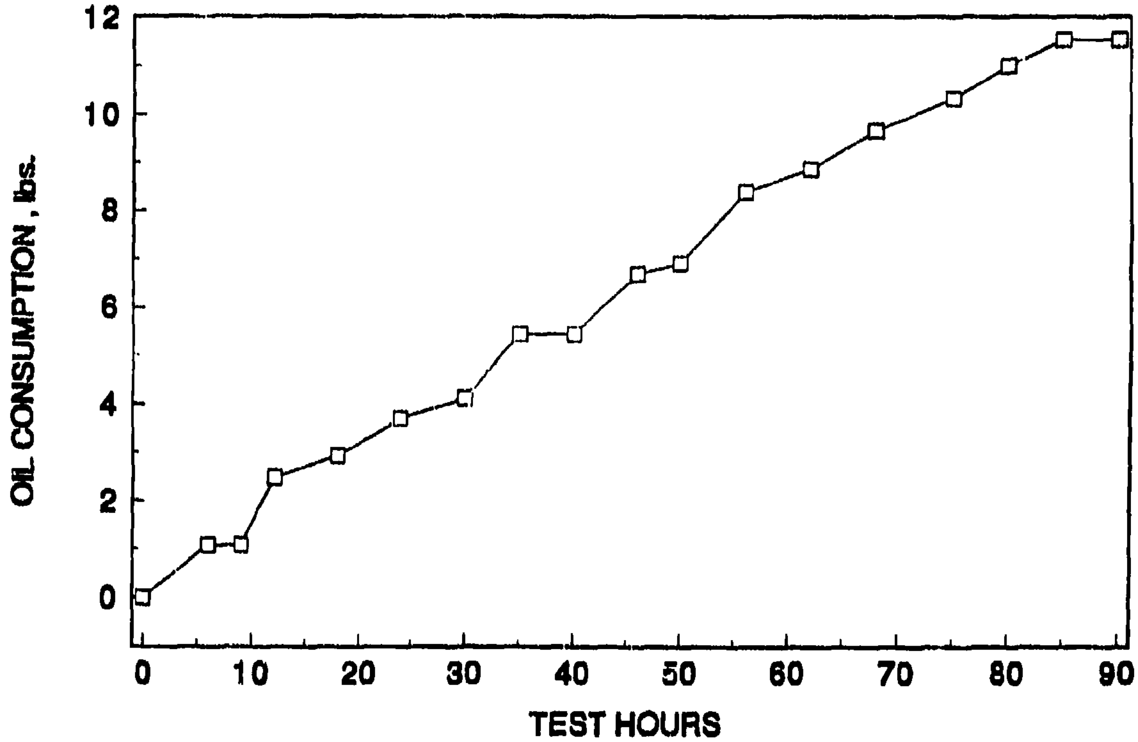


Figure C-1. AIPS-3, AL-19371, oil consumption

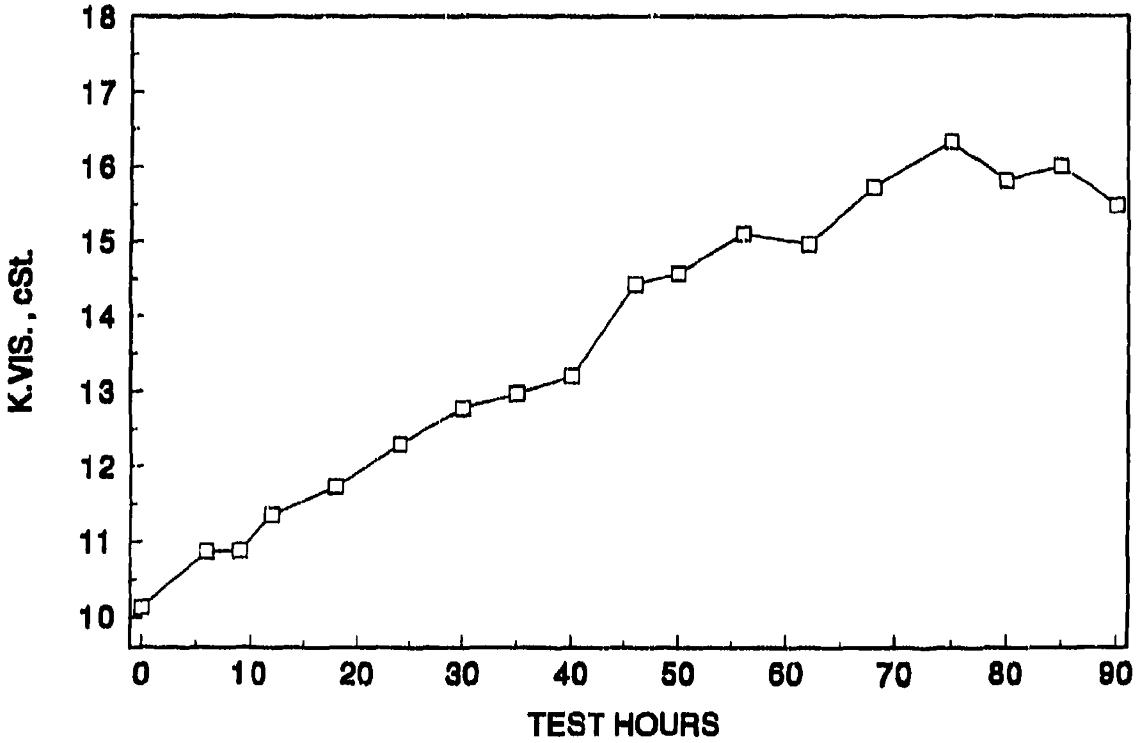


Figure C-2. AIPS-3, AL-19371, K. vis., 100°C

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS*

Test No.: AIPS-3
Lubricant: AL-19371-L
Test Hours: 90

	Before		After		Change		Specified Limits	
	T-AT	F-B	T-AT	F-B	T-AT	F-B		
CYLINDER LINER**								
Inside Diameter								
Top	5.5001	5.4997	5.5004	5.4998	0.0003	0.0001	5.4995 - 5.5010	Worn Limit: 5.505
Middle	5.5005	5.4997	5.5010	5.4997	0.0005	0.0000	5.4995 - 5.5010	Worn Limit: 5.505
Bottom	5.5002	5.4993	5.5009	5.4991	0.0007	-0.0002	5.4995 - 5.5010	Worn Limit: 5.505
Taper	0.0001	0.0004	0.0005	0.0007	0.0004	0.0003	0.0015 Max	
Out-of-Round								
Top	0.0004		0.0006		0.0002		0.0020 Max	
Middle	0.0008		0.0013		0.0005		0.0020 Max	
Bottom	0.0009		0.0018		0.0009		0.0020 Max	
PISTON DIAMETER								
At Skirt	5.4875		5.4875		0.0000		5.4890 - 5.4900	
PISTON PIN-BORE								
Bore	1.7495		1.7505		0.0010		1.7485 - 1.7489	Worn Limit: 1.7500
Pin	1.7491		1.7491		0.0000		1.7488 - 1.7490	Worn Limit: 1.7478
Clearance	0.0004		0.0014		0.0010		-0.0005 - 0.0001	Worn Limit: 0.0022
PISTON-CYLINDER LINER CLEARANCE								
Minimum	0.0118		0.0116		-0.0002		0.0095 - 0.0120	Worn Limit: 0.0170
Maximum	0.0130		0.0135		0.0005		0.0095 - 0.0120	Worn Limit: 0.0170
PISTON RINGS								
Eng Gap								
Ring No. 1	0.0230		0.0250		0.0020		0.0170 - 0.0270	
Ring No. 2	0.0250		0.0280		0.0030		0.0200 - 0.0300	
Ring No. 3	0.0180		0.0210		0.0030		0.0100 - 0.0250	
Ring Proudness								
Ring No. 1								
Measurement Point								
1	-0.0110		0.0060		0.0170			
2	-0.0120		0.0090		0.0210			
3	-0.0125		0.0010		0.0135			
4	-0.0140		0.0070		0.0210			
Ring No. 2								
Measurement Point								
1	-0.0050		-0.0030		0.0020			
2	-0.0050		-0.0030		0.0020			
3	-0.0050		-0.0050		0.0000			
4	-0.0020		-0.0010		0.0010			

* Measurements are in inches. Change = After - Before.
** T-AT = Thrust-Antithrust.
F-B = Front-Back.

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS* (CONT'D)

Test No.: AIPS-3
Lubricant: AL-19371-L
Test Hours: 90

	Before		After		Change		
	A	B	A	B	A	B	Specified Limits
BEARINGS**							
Main Bearing Journals							
1	3.7487	3.7480	3.7482	3.7480	-0.0005	0.0000	3.7490 - 3.7500 Worn Limit: 3.7470 Max
2	3.7489	3.7491	3.7489	3.7491	0.0000	0.0000	3.7490 - 3.7500 Worn Limit: 3.7470 Max
Connecting Rod Bearing Journals							
1	3.1244	3.1244	3.1241	3.1241	-0.0003	-0.0003	3.1240 - 3.1250 Worn Limit: 3.1220
	F	BA	F	BA	F	BA	
Main Bearing Shells							
1	3.7559	3.7558	3.7559	3.7557	0.0000	-0.0001	
2	3.7561	3.7554	3.7558	3.7554	-0.0003	0.0000	
Connecting Rod Bearing Shells							
1	3.1295	3.1294	3.1297	3.1293	0.0002	-0.0001	
	Min	Max	Min	Max	Min	Max	
Main Bearing Journal-Shell Clearances							
1	0.0071	0.0079	0.0075	0.0079	0.0004	0.0000	0.0015 - 0.0050 Worn Limit: 0.007
2	0.0063	0.0072	0.0063	0.0069	0.0000	-0.0003	0.0015 - 0.0050 Worn Limit: 0.007
	Min	Max	Min	Max	Min	Max	
Connecting Rod Journal-Shell Clearances							
1	0.0050	0.0051	0.0052	0.0056	0.0002	0.0005	0.0015 - 0.0045 Worn Limit: 0.007
Main Bearing Weights, grams							
1 Upper	138.1901		138.1498		-0.0403		
1 Lower	160.1621		160.0189		-0.1432		
2 Upper	140.4697		140.4419		-0.0278		
2 Lower	159.9764		159.9601		-0.0163		
Connecting Rod Bearing Weight, grams							
1 Upper	84.5595		84.3735		-0.1860		
1 Lower	83.5977		83.5835		-0.0142		
	T	AT	T	AT	T	AT	
VALVES***							
Stem to Guide Clearance (Average)							
Intake	0.0028	0.0027	0.0036	0.0030	0.0008	0.0003	0.0015 - 0.0032
Exhaust	0.0029	0.0025	0.0033	0.0031	0.0004	0.0006	0.0015 - 0.0032
Recession							
Intake	-0.0221	-0.0233	-0.0235	-0.0233	-0.0014	0.0000	-0.0050 - -0.0250
Exhaust	-0.0625	-0.0719	-0.0635	-0.0719	-0.0010	0.0000	-0.0520 - -0.0720

* Measurements are in inches. Change = After - Before.
** A = Micrometer anvil parallel to weights; B = Micrometer anvil perpendicular to weights; F = Front; BA = Back.
*** T = Thrust; AT = Antithrust.

SCE-903
POST-TEST RATINGS OF ENGINE DEPOSITS AND CONDITIONS

Test No.: AIPS-3
Lubricant: AL-19371-L
Test Hours: 90

PISTON		
Skirt Rating	Polished areas normal, with few vertical line cuttings.	
Top Groove Fill, %	99	
Second Groove Fill, %	3	
WDK Weighted Total Deposits	460	
RINGS		
Ring Freedom		
No. 1	Free	
No. 2	Free	
No. 3	Free	
Ring Distress Demerits	Some light discoloration; No apparent distress.	
LINER		
Scuffing, %	0	
Bore Polish, %	0	
Distress	0	
VALVES		
Head		
Intake	100% Light Carbon	
Exhaust	100% Light Carbon	
Tulip		
Intake	1.0% Carbon	
Exhaust	1.0% Carbon	
Face		
Intake	Clean, Good Condition	
Exhaust	Clean, Good Condition	
Stem		
Intake	T* - 5% No. 7 Lacquer; AT - Clean	
Exhaust	T - 5% No. 9 Lacquer; AT - 15% No. 9 Lacquer	

	Top	Bottom
BEARING DISTRESS, % Exposed Cu		
Front Main	0	1
Rear Main	1	0
Connecting Rod		
Active	0	0
Slipper	0	0
ROD BUSHING, % Wear Band		
Active	0	20
Slipper	ND**	ND

* T = Thrust; AT = Antithrust.
** ND = Not Determined.

SINGLE CYLINDER ENGINE TESTS

TEST IDENTIFICATION

TEST TYPE	LABORATORY	OIL CODE			TEST FUEL
1K	BFLRF	AL-19371L			HOWELL HYDROCARBONS BATCH
STAND #	RUN #	ENG #			
1	03	SCE-903			
DATE STARTED	DATE COMPLETED	DATE RATED	RATER	TEST HOURS	
/ /	10/17/90	10/25/90	AB	90	

RATINGS SUMMARY

	DEP FACTOR	GROOVES NO. 1 A %	GROOVES NO. 1 DEM	GROOVES NO. 2 A %	GROOVES NO. 2 DEM	GROOVES NO. 3 A %	GROOVES NO. 3 DEM	LANDS NO. 1 A %	LANDS NO. 1 DEM	LANDS NO. 2 A %	LANDS NO. 2 DEM	LANDS NO. 3 A %	LANDS NO. 3 DEM	UPPER SKIRT A %	UPPER SKIRT DEM	UNDRCRWN A %	UNDRCRWN DEM	PIN BORES FRONT A %	PIN BORES FRONT DEM	PIN BORES REAR A %	PIN BORES REAR DEM
CARBON	HC-1.0	98	98.00					70	70.00	7	7.00										
	HC-0.5	2	1.00																		
	LC-.25			28	7.00			24	6.00	21	5.25										
	TOTAL	100	99.000	28	7.000			94	76.000	28	12.250										
LACQUER	8-9			17	1.530					7	0.630										
	7-7.9			8	0.568							1	0.070								
	6-6.9									19	1.311										
	5-5.9			5	0.260					6	0.306										
	4-4.9					3	0.120							3	0.123	15	0.720				
	3-3.9			4	0.128					5	0.160	1	0.032			15	0.450				
	2-2.9			38	0.950	17	0.425			14	0.350	96	2.400	29	0.812	50	1.250	15	0.300	15	0.300
	1-1.9					54	0.594							12	0.132	15	0.150	45	0.450	45	0.450
	0-0.9					10	0.050	6	0.024	21	0.063	2	0.004	36	0.144	5	0.020				
	TOTAL			72	3.436	100	1.189	6	0.024	72	2.820	100	2.506	100	1.211	100	2.590	100	0.750	100	0.750

	GROOVES 1	GROOVES 2	GROOVES 3	LANDS 1	LANDS 2	LANDS 3	UPPER SKIRT	UNDRCRWN	PIN BORES FRONT	PIN BORES REAR
RATING	99.000	10.436	1.189	76.024	15.070	2.506	1.211	2.590	0.750	0.750
WDK LOCATE FCT	1.5	1.5	25	1	1	25	50	20	0	0
IND WDK RATING	148.500	15.654	29.725	76.024	15.070	62.650	60.550	51.800	0.000	0.000
WD1 LOCATE FCT	1	1	35	1	1	20	70	20	100	100
IND WD1 RATING	99.000	10.436	41.615	76.024	15.070	50.120	84.770	51.800	75.000	75.000

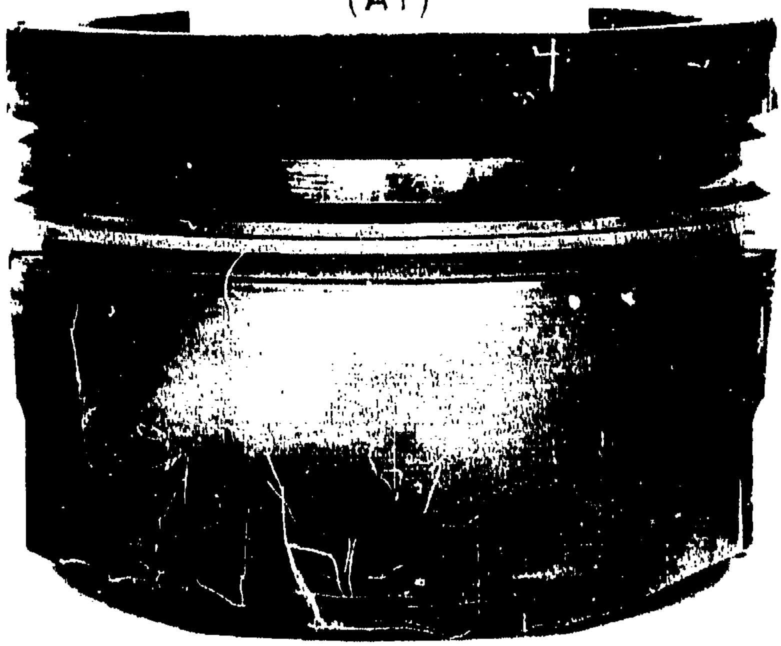
WDK WTD	459.97	WD1 WTD	578.86	UWTD	299.53
TGF	99	SECOND GROOVE FILL	3	CROWNLAND POLISHED CARBON	70

RING CONDITION Normal

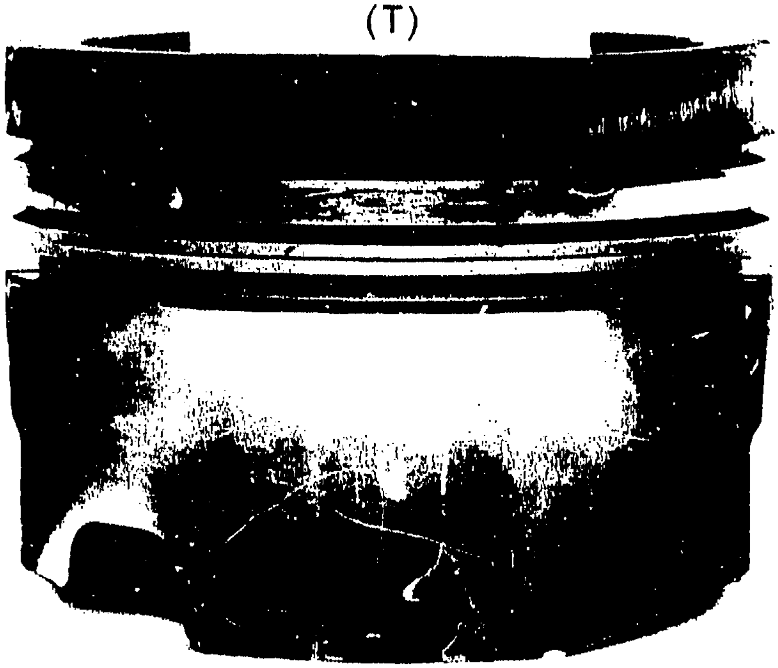
PISTON CONDITION Normal

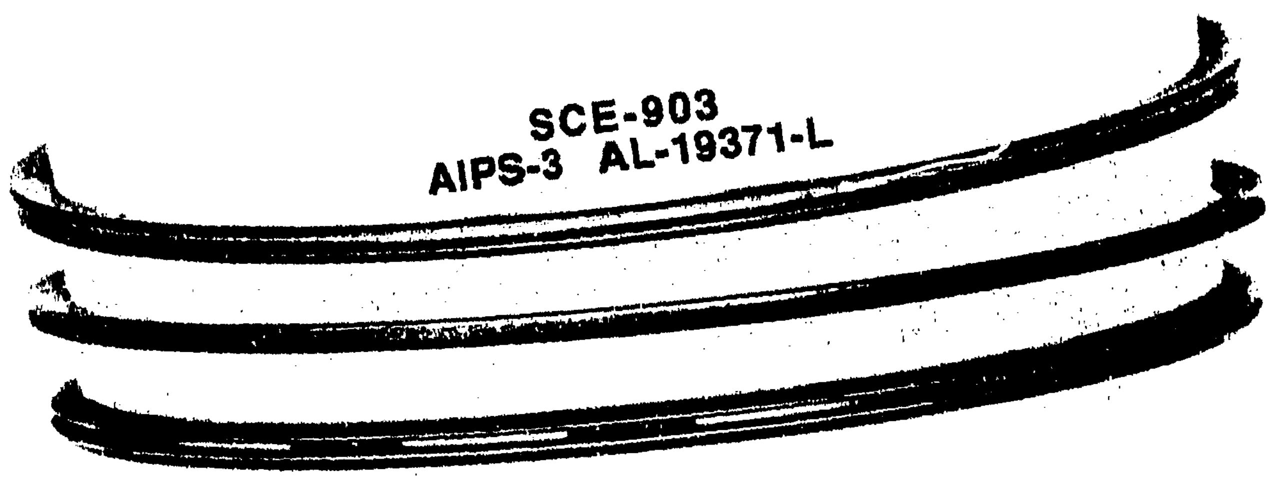
LINER CONDITION Normal

SCE-903
AIPS-3 AL-19371-L
(AT)

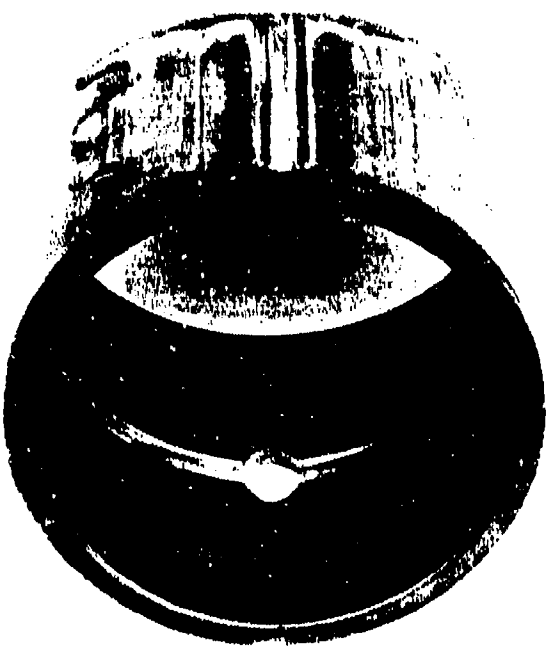


SCE-903
AIPS-3 AL-19371-L
(T)

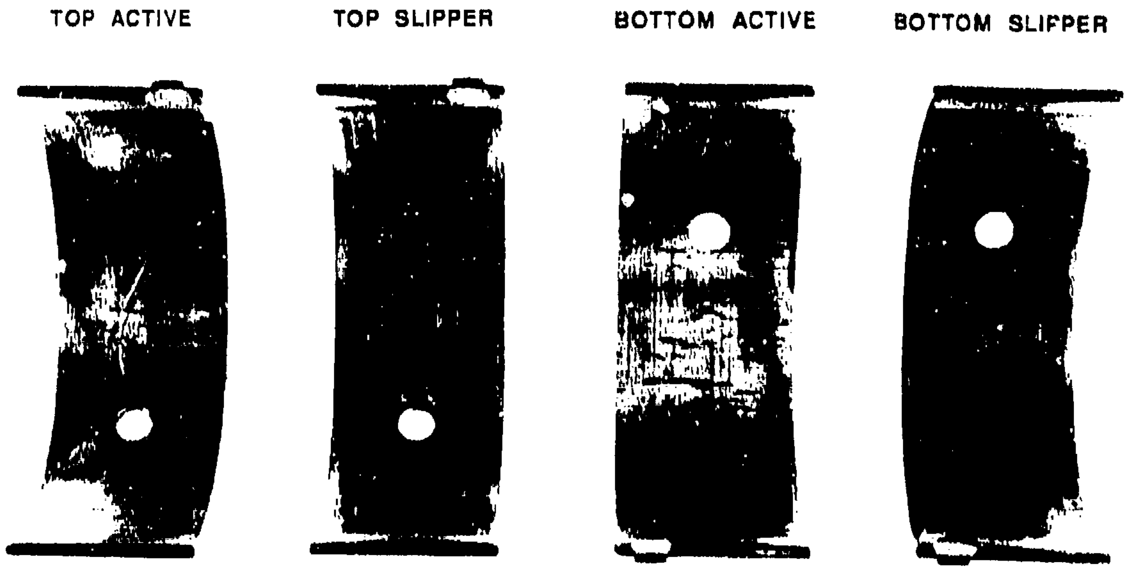



SCE-903
AIPS-3 AL-19371-L

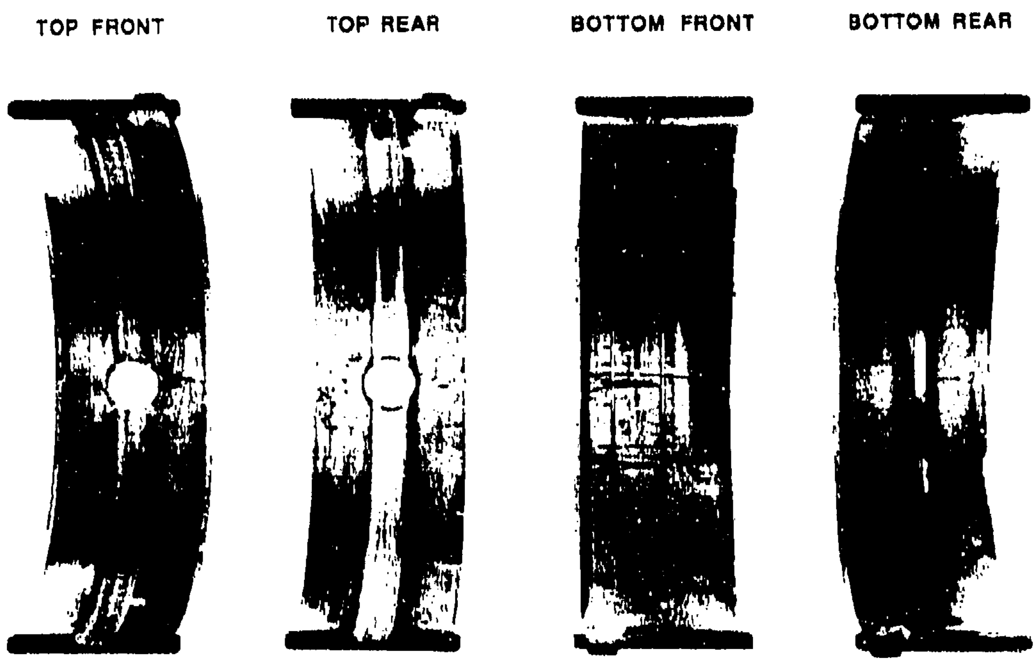
SCE-903
AIPS-3 AL-19371-L
TOP ROD BUSHING



SCE-903
AIPS-3 AL-19371-L
BOTTOM ROD BUSHING



SCE-903
AIPS-3 AL-19371-L
ROD BEARINGS



SCE-903
AIPS-3 AL-19371-L
MAIN BEARINGS

APPENDIX D

SCE-903 High-Temperature Lubricant Evaluation
Test No. AIPS-4

SCE-903 HIGH-TEMPERATURE LUBRICANT EVALUATION

Test Lubricant: AL-19346-L
Test Fuel: AL-19657-F
Test No.: AIPS-4
Date: 24 April 1991

Conducted For

U.S. Army Belvoir Research, Development and Engineering Center
Logistics Equipment Directorate
Fort Belvoir, Virginia 22060-5606

By

Belvoir Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78228-0510

TEST SUMMARY

The SCE-903 is a vee-configured two-cylinder engine, with one cylinder active and the second cylinder for balance. The SCE-903 is being used to screen candidate high-temperature lubricants for future low-heat rejection diesel engines. The target operating conditions are 340°F oil sump and 318°F oil gallery temperatures at 2600 rpm and a full-load air/fuel ratio of 28 to 1. The cylinder block is uncooled and the cylinder head temperature is 250°F during engine operation.

The AIPS-4 test candidate was an experimental 30 synthetic diesel engine oil. The lubricant evaluation lasted 200 hours, after which time the engine was disassembled for parts rating and inspection. The ratings revealed no cylinder liner scuffing or bore polish, and no ring face distress. All three rings were free with moderate to heavy groove and land deposits. The heaviest deposits were in the top groove and on the top land and also on the third groove and land. The connecting rod piston pin bushing, the main bearings, and connecting rod bearings appeared to be free of distress. The end-of-test lubricant inspection indicated there was reserve alkalinity remaining, and the oil had not started to degrade. Used oil wear metal contents by ICP were 72 ppm of iron and 32 ppm of copper.

SCE-903
OPERATING CONDITIONS SUMMARY

Date: 04/24/91 **Test No.: AIPS-4**

Lubricant: AL-19346-L **Fuel: AL-19657-F**

Test Hours: 200

	Mean	Standard Deviation
Engine Speed, rpm	2599	2
Torque, lb-ft	116.06	1.88
Observed Power, Bhp	57.43	0.93
Air/Fuel Ratio	27.14	1.75
Fuel Rate, lb/hr	20.75	0.45
BSFC, lb/Bhp-hr	0.361	0.0094
BMEP, psi	155.09	2.51
Oil Consumption Rate, lb/hr	0.0732	
BSOC, lb/Bhp-hr	0.0015	
Temperatures, °F		
Oil Sump	331	2.8
Oil After Cooler	316	3.2
Coolant Into Head	242	2.6
Coolant Out of Head	248	1.9
Exhaust	1106	10.8
Inlet Air	222	1.4
Fuel Inlet	103	5.3
Cylinder Liner, All Positions	477	7.1
Thrust Top	464	5.6
Upper Mid	508	21.1
Bottom	506	6.3
Antithrust		
Top	432	3.0
Pressures, psig		
Manifold	15.2	0.379
Oil Gallery	16.1	0.740
Exhaust Back	14.3	0.476

OIL PROPERTIES

Test No.: AIPS-4
Lubricant: AL-19346-L

Lubricant Analysis	AL-19346-L
K. Vis, 40°C, cSt	63.89
K. Vis, 100°C, cSt	9.83
Viscosity Index	138
App Vis, at -30°C, D 2602	>15000
App Vis, at -30°C, D 4684	29985
HTHS Vis at 150°C, cP, D 4683	3.73
Flash Point, °C	288
Pour Point, °C	-36
Sulfated Ash, wt%	0.86
TAN	0.4
TBN, D 664	6.2
N, wt%, D 4629	0.029
TFOUT, minutes, D 4742	>300
Elements, XRF, wt%	
S	0.21
Ca	0.27
Elements, ICP, ppm	
Ba	<1
B	<1
Mg	13
Mn	<1
Mo	<1
Ni	<1
P	6
Zn	3
Ca	2706
Cu	<1
Na	<1
IR Trace No.	16255
HPDSC, minutes, at	
180°C	>300
190°C	172
200°C	95
210°C	63

OIL PROPERTIES

Test No.: AIPS-4
Lubricant: AL-19346-L

Properties	Test Hours 0	50	75	100	150	200
K. Vis, 100°C, cSt	9.83	10.41	10.55	10.56	10.90	10.69
HTHS Vis at 150°C, cP, D 4683	3.73	3.897	3.966	3.925	3.877	4.069
TAN	0.4	1.04	0.92	1.43	1.1	2.05
TBN, D 664	6.2	4.55	3.54	3.54	2.71	2.36
TFOUT, minutes, D 4742	>300	>300	>300	>300	>300	>300
HPDSC at 190°C, minutes	172	55	ND*	71	54	44
TGA Soot, wt%	NIL	0.46	0.58	0.23	0.03	0.51
Coag Insols, wt%						
Pentane B	NIL	0.03	0.04	0.02	0.03	0.04
Toluene B	NIL	0.30	0.03	0.02	0.02	0 03
Elements, ICP, ppm						
Fe	NIL	33	31	31	58	72
Cu	NIL	36	31	26	30	32
Pb	NIL	48	38	38	51	71
Cr	NIL	<1	1	<1	2	2
Al	NIL	3	3	4	4	5
Si	ND	48	47	44	59	71
Sn	ND	5	4	2	4	6
Ca	2706	2695	2725	2780	2836	2411

* ND = Not Determined.

SCE-903
OIL CONSUMPTION AND WEAR METALS BY XRF

Lubricant: AL-19346-L

Test Time, hours	Total Oil Consumed		K. Vis, 100°C, cSt	Wear Metals, ppm	
	lb	kg		Fe	Cu
0	0.00	0.000	9.80	<20	<20
4	0.19	0.086	9.91	<20	<20
10	0.19	0.086	10.08	<20	<20
14	0.96	0.435	10.16	<20	<20
18	0.96	0.435	10.21	<20	<20
24	1.25	0.566	10.28	<20	21
30	1.79	0.811	10.41	<20	<20
36	2.45	1.110	10.49	<20	22
42	2.80	1.269	10.55	<20	28
48	3.30	1.495	10.59	28	26
50	3.61	1.636	10.39	<20	<20
56	4.50	2.039	10.54	21	21
62	4.68	2.121	10.58	33	24
67	5.31	2.406	10.60	27	21
73	6.05	2.741	10.59	25	<20
75	6.05	2.741	10.51	22	<20
79	6.65	3.013	10.60	26	<20
85	7.35	3.330	10.94	24	<20
91	7.92	3.589	10.50	29	<20
97	8.24	3.734	10.50	21	<20
100	8.57	3.883	10.45	22	<20
106	9.46	4.286	10.44	24	<20
112	9.58	4.341	10.43	29	<20
117	9.69	4.391	10.49	28	<20
123	10.19	4.617	10.52	25	<20
126	10.19	4.617	10.50	26	<20
131	10.53	4.771	10.59	35	<20
135	10.81	4.898	10.59	33	<20
141	11.10	5.029	10.59	34	<20
144	11.25	5.097	ND*	ND	ND
150	12.21	5.532	10.61	36	<20
153	12.21	5.532	ND	ND	ND
157	12.40	5.618	10.57	38	<20
163	12.39	5.614	10.62	35	<20
168	12.61	5.714	10.87	38	<20
174	13.06	5.917	10.84	40	<20
180	13.58	6.153	10.95	36	<20
183	13.58	6.153	ND	ND	ND
189	13.90	6.298	10.74	42	25
194	14.25	6.457	10.72	52	<20
200	14.64	6.633	10.69	46	<20
	lb/hr	kg/hr			
Average Oil Consumption Rate	0.0732	0.0332			

* ND = Not Determined.

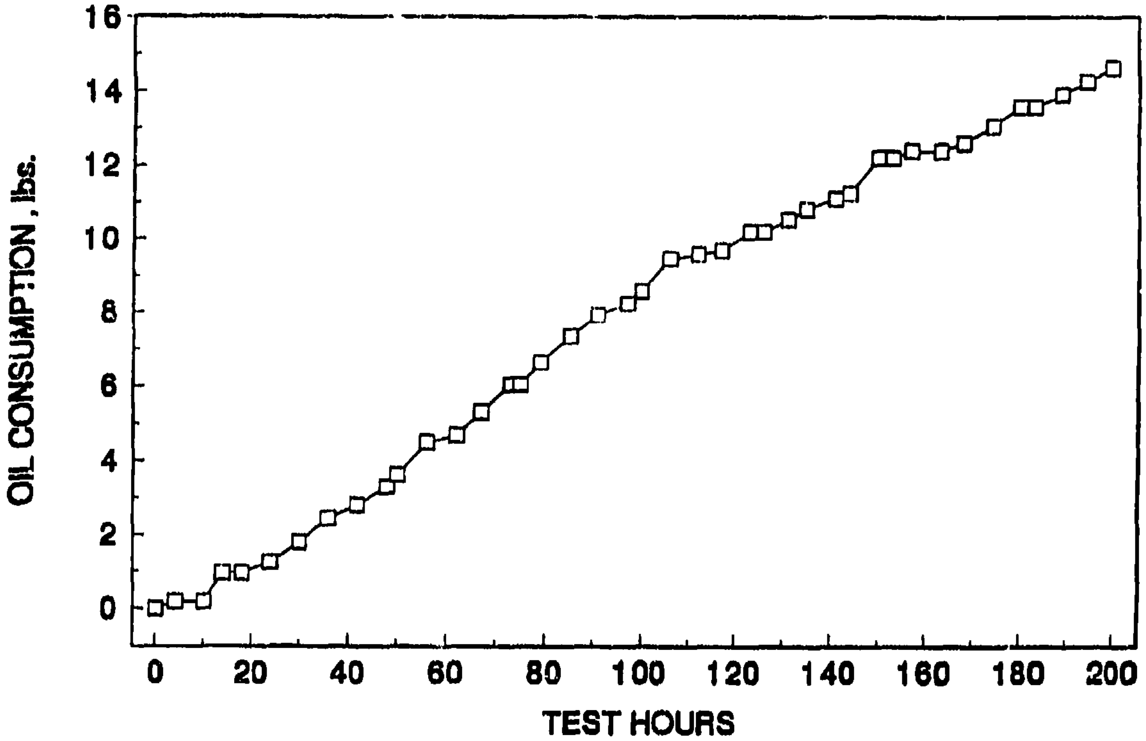


Figure D-1. AIPS-4, AL-19346, oil consumption

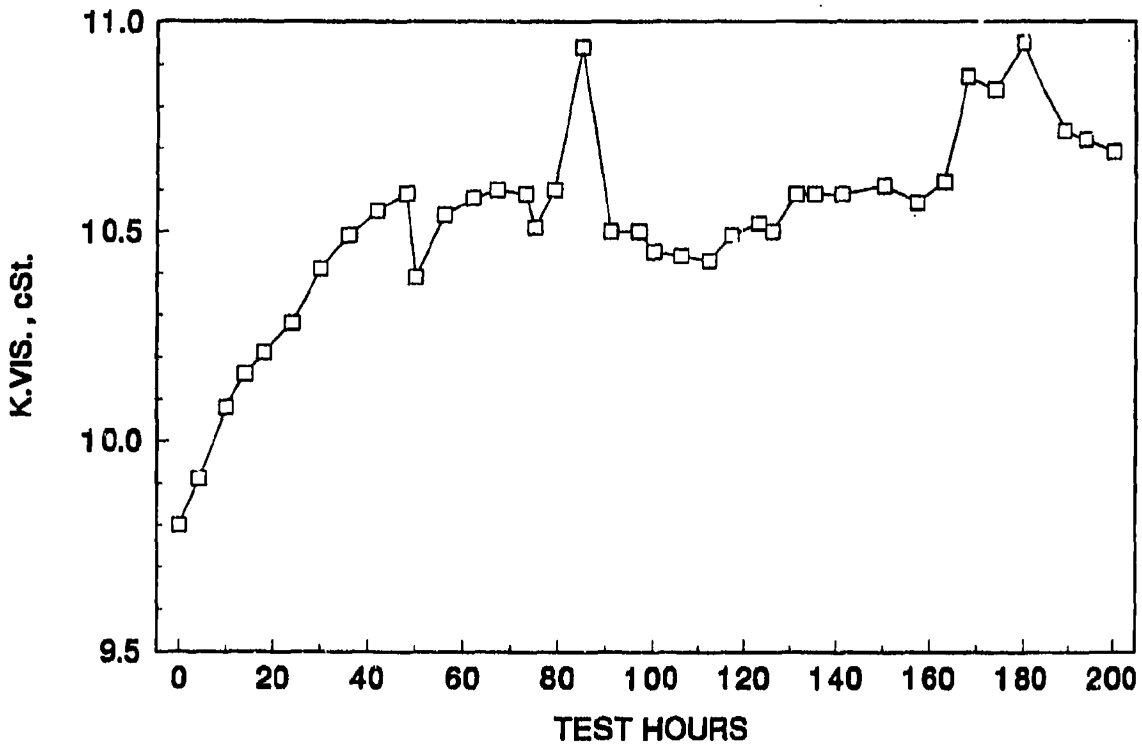


Figure D-2. AIPS-4, AL-19346, K. vis., 100°C

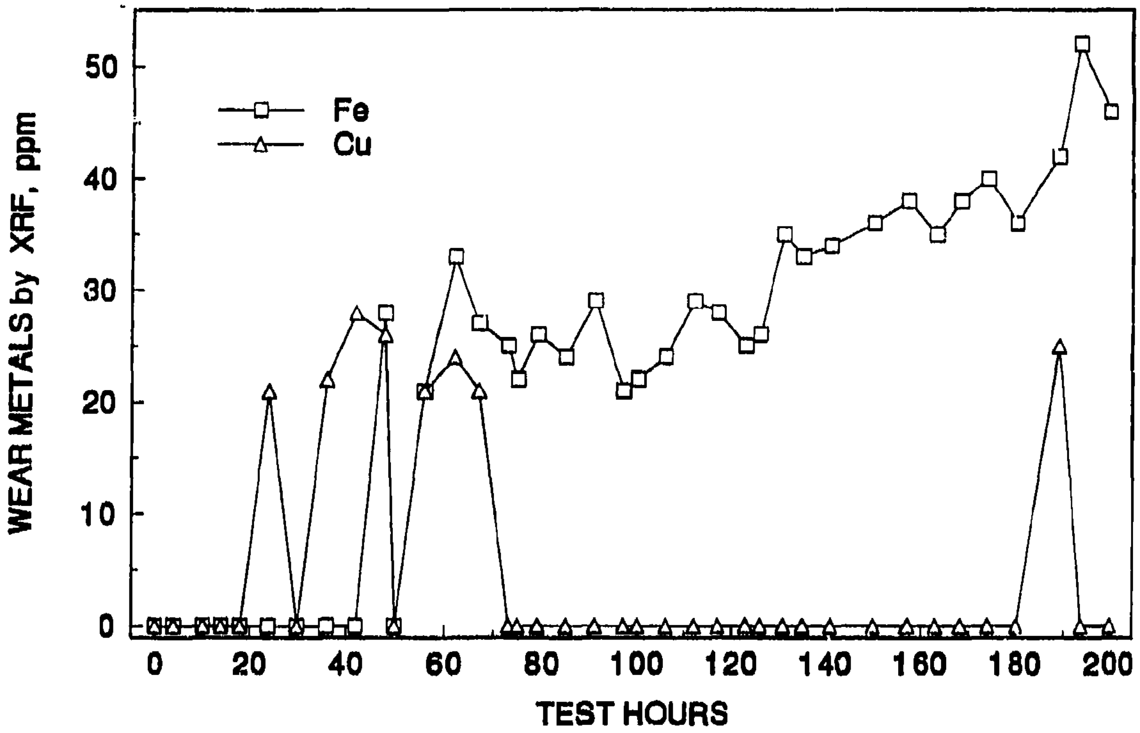


Figure D-3. <u>**AIPS-4, AL-19346, wear metals**</u>

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS*

Test No.: AIPS-4
Lubricant: AL-19346-L
Test Hours: 200

	Before		After		Change		Specified Limits	
	T-AT	F-B	T-AT	F-B	T-AT	F-B		
CYLINDER LINER**								
Inside Diameter								
Top	5.4992	5.4997	5.4997	5.4996	0.0005	-0.0001	5.4995 - 5.5010	Worn Limit: 5.505
Middle	5.4998	5.4997	5.5003	5.4997	0.0005	0.0000	5.4995 - 5.5010	Worn Limit: 5.505
Bottom	5.4993	5.4983	5.5000	5.4997	0.0007	0.0014	5.4995 - 5.5010	Worn Limit: 5.505
Taper	0.0001	0.0014	0.0003	0.0001	0.0002	-0.0013	0.0015 Max	
Out-of-Round								
Top	0.0005		0.0001		-0.0004		0.0020 Max	
Middle	0.0001		0.0006		0.0005		0.0020 Max	
Bottom	0.0010		0.0003		-0.0007		0.0020 Max	
PISTON DIAMETER								
At Skirt	5.4893		5.4893		0.0000		5.4890 - 5.4900	
PISTON PIN-BORE								
Bore	1.7489		1.7504		0.0015		1.7485 - 1.7489	Worn Limit: 1.7500
Pin	1.7488		1.7488		0.0000		1.7488 - 1.7490	Worn Limit: 1.7478
Clearance	0.0001		0.0016		0.0015		-0.0005 - 0.0001	Worn Limit: 0.0022
PISTON-CYLINDER LINER CLEARANCE								
Minimum	0.0090		0.0103		0.0013		0.0095 - 0.0120	Worn Limit: 0.0170
Maximum	0.0105		0.0110		0.0005		0.0095 - 0.0120	Worn Limit: 0.0170
PISTON RINGS								
Eng Gap								
Ring No. 1	0.0240		0.0230		-0.0010		0.0170 - 0.0270	
Ring No. 2	0.0240		0.0270		0.0030		0.0200 - 0.0300	
Ring No. 3	0.0220		0.0220		0.0000		0.0100 - 0.0250	
Ring Proudness								
Ring No. 1								
Measurement Point								
1	-0.0130		0.0020		0.0150			
2	-0.0125		0.0030		0.0155			
3	-0.0135		0.0010		0.0145			
4	-0.0130		0.0010		0.0140			
Ring No. 2								
Measurement Point								
1	-0.0060		0.0010		0.0070			
2	-0.0050		0.0040		0.0090			
3	-0.0050		-0.0050		0.0000			
4	-0.0060		-0.0040		0.0020			

* Measurements are in inches. Change = After - Before.
** T-AT = Thrust-Antithrust.
F-B = Front-Back.

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS* (CONT'D)

Test No.: AIPS-4
Lubricant: AL-19346-L
Test Hours: 200

	Before		After		Change		
	A	B	A	B	A	B	Specified Limits
BEARINGS**							
Main Bearing Journals							
1	3.7482	3.7480	3.7482	3.7479	0.0000	-0.0001	3.7490 - 3.7500 Worn Limit: 3.7470 Max
2	3.7489	3.7491	3.7489	3.7489	0.0000	-0.0002	3.7490 - 3.7500 Worn Limit: 3.7470 Max
Connecting Rod Bearing Journals							
1	3.1241	3.1241	3.1241	3.1241	0.0000	0.0000	3.1240 - 3.1250 Worn Limit: 3.1220
	F	BA	F	BA	F	BA	
Main Bearing Shells							
1	3.7561	3.7560	3.7557	3.7557	-0.0004	-0.0003	
2	3.7560	3.7556	3.7561	3.7556	0.0001	0.0000	
Connecting Rod Bearing Shells							
1	3.1286	3.1284	3.1295	3.1293	0.0009	0.0009	
	Min	Max	Min	Max	Min	Max	
Main Bearing Journal-Shell Clearances							
1	0.0078	0.0081	0.0075	0.0078	-0.0003	-0.0003	0.0015 - 0.0050 Worn Limit: 0.007
2	0.0065	0.0071	0.0067	0.0072	0.0002	0.0001	0.0015 - 0.0050 Worn Limit: 0.007
	Min	Max	Min	Max	Min	Max	
Connecting Rod Journal-Shell Clearances							
1	0.0043	0.0045	0.0052	0.0054	0.0009	0.0009	0.0015 - 0.0045 Worn Limit: 0.007
Main Bearing Weights, grams							
1 Upper	139.4652		139.4289		-0.0363		
1 Lower	159.6914		159.5697		-0.1217		
2 Upper	138.1230		138.1018		-0.0212		
2 Lower	160.1039		160.0685		-0.0354		
Connecting Rod Bearing Weight, grams							
1 Upper	84.6231		84.3373		-0.2858		
1 Lower	84.5880		84.5350		-0.0530		
	T	AT	T	AT	T	AT	
VALVES***							
Stem to Guide Clearance (Average)							
Intake	0.0028	0.0028	0.0029	0.0031	0.0001	0.0003	0.0015 - 0.0032
Exhaust	0.0028	0.0028	0.0029	0.0028	0.0001	0.0000	0.0015 - 0.0032
Recession							
Intake	-0.0168	-0.0188	-0.0179	-0.0228	-0.0011	-0.0040	-0.0050 - -0.0250
Exhaust	-0.0672	-0.0624	-0.0752	-0.0650	-0.0080	-0.0026	-0.0520 - -0.0720

* Measurements are in inches. Change = After - Before.
** A = Micrometer anvil parallel to weights; B = Micrometer anvil perpendicular to weights; F = Front; BA = Back.
*** T = Thrust; AT = Antithrust.

SCE-903
POST-TEST RATINGS OF ENGINE PARTS AND CONDITIONS

Test No.: AIPS-4
Lubricant: AL-19346-L
Test Hours: 200

PISTON	
Skirt Rating	Polished areas normal, with few fine to coarse vertical line cuttings.
Top Groove Fill, %	98
Second Groove Fill, %	<1
WDK Weighted Total Deposits	414
RINGS	
Ring Freedom	
No. 1	Free
No. 2	Free
No. 3	Free
Ring Distress Demerits	Some light discoloration, no apparent distress.

	T*	AT	Average
LINER			
Scuffing, %	0	0	0.0
Bore Polish, %	1	0	0.5
Distress	0	0	0.0

VALVES	
Head	
Intake	100% Light Carbon
Exhaust	100% Light Carbon
Tulip	
Intake	0.5% Carbon
Exhaust	1.0% Carbon
Face	
Intake	Clean, Good Condition
Exhaust	Trace Carbon Embedment
Stem	
Intake	T - 5% No. 9 Lacquer; AT - Clean
Exhaust	T - 5% No. 9 Lacquer, 5% No. 6 Lacquer, and 5% No. 2 Lacquer; AT - Clean

	Top	Bottom
BEARING DISTRESS, % Exposed Cu		
Front Main	0	1
Rear Main	0	0
Connecting Rod		
Active	1	0
Slipper	0	0
ROD BUSHING, % Wear Band		
Active	0	20
Slipper	ND**	ND

* T = Thrust; AT = Antithrust.
** ND = Not Determined.

LAB BFLRF	STAND NO. 1	TEST NO. 1-04	ENGINE	
OIL CODES AL-19346-L			FUEL BATCH	
DATE STARTED / /	DATE COMP 04/05/91	DATE RATED 04/17/91	RATER AB	TEST HRS 200
REFEREE INFORM.	COMPANY	DATE RATED	RATER	RATING NO

STAND LAST	TMC OIL	TEST NO	TEST TGF ___ TLHC ___	IND. TGF ___ TLHC ___
REFERENCE	DATE COMP	ENGINE NO	RAT. WDK _____ AVBSOC ___	AVE. WDK _____ AVBSOC ___

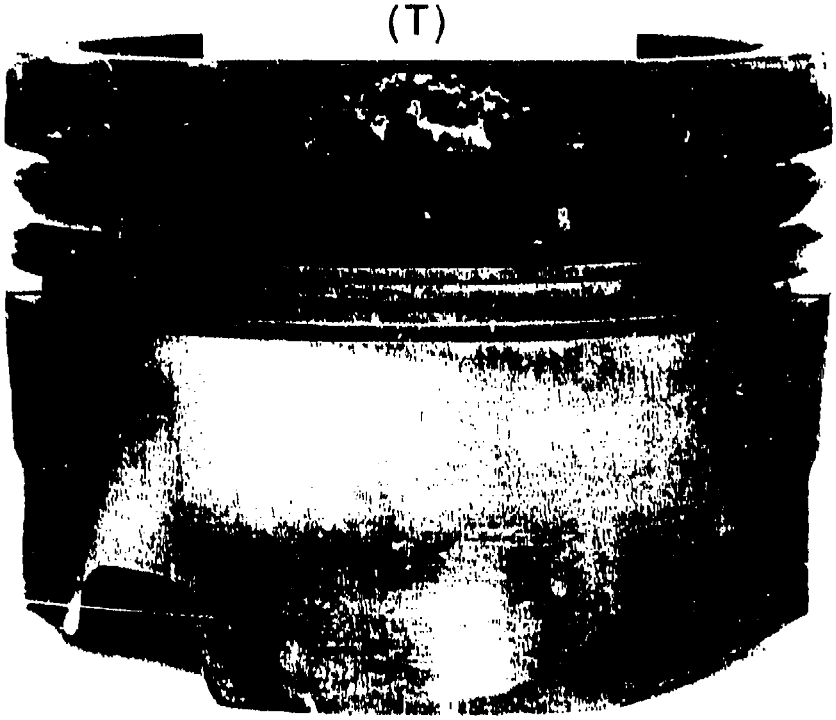
RATING SUMMARY

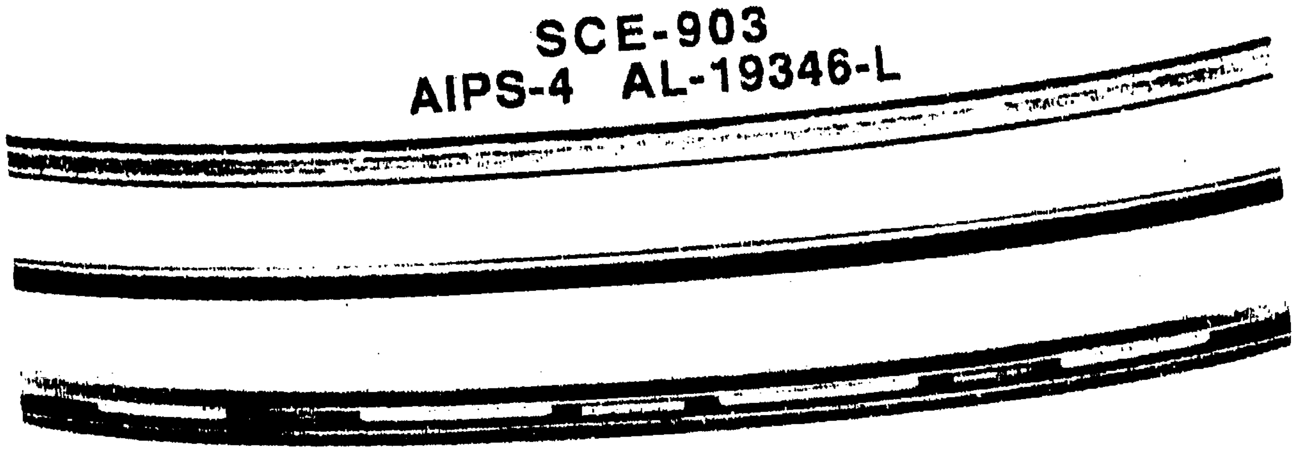
		GROOVES						LANDS						UPPER		UNDER		PIN BORES			
		NO.1		NO.2		NO.3		NO.1		NO.2		NO.3		SKIRT		CROWN		FRONT		REAR	
	dep factor	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM
c	hc-1.0	96	96.00					31	31.00												
a r	mc-0.5	4	2.00																		
b o	lc-.25			8	2.00			69	17.25	58	14.50										
n	total	100	98.000	8	2.000			100	48.250	58	14.500										
	8-9			18	1.620					22	1.980										
v	7-7.9																				
a	6-6.9									3	0.204										
r	5-5.9			58	2.900																
n	4-4.9					8	0.320					25	1.100	4	0.160						
i	3-3.9			16	0.480							40	1.280	4	0.128						
s	2-2.9					72	1.872					35	0.875	7	0.161			20	0.400	10	0.200
h	1-1.9					20	0.280									60	1.080	50	0.500	60	0.600
	0-0.9									17	0.034					40	0.200				
	total			92	5.000	100	2.472			42	2.218	100	3.255	100	0.449	100	1.280	100	0.900	100	0.800
rating		98.000		7.000		2.472		48.250		16.718		3.255		0.449		1.280		0.900		0.800	
WDK loc fct		1.5		1.5		25		1		1		25		50		20		0		0	
wt rating		147.000		10.500		61.800		48.250		16.718		81.375		22.450		25.600		0.000		0.000	

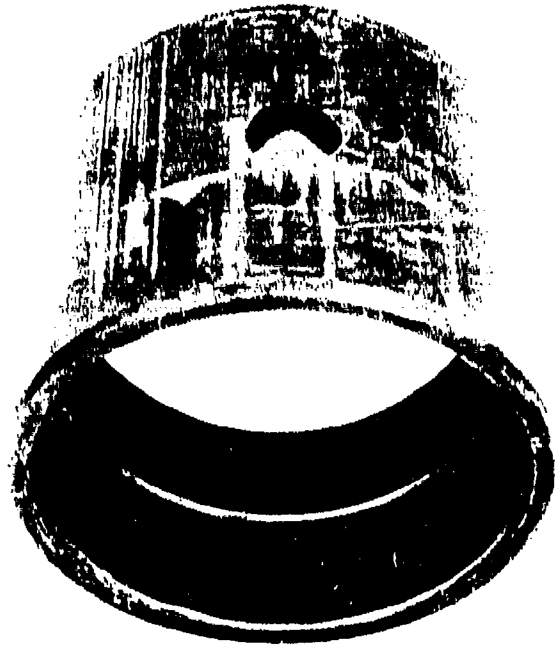
TGF%	INT GR FILL %	WDK	UN WEIGHTED DEP	T.L. HVY CRB %	T.L. FLAKED CRB %	ACC GR FILL %
98	<1	413.7	179.1	31	0	

SCE-903
AIPS-4 AL-19346-L
(AT)

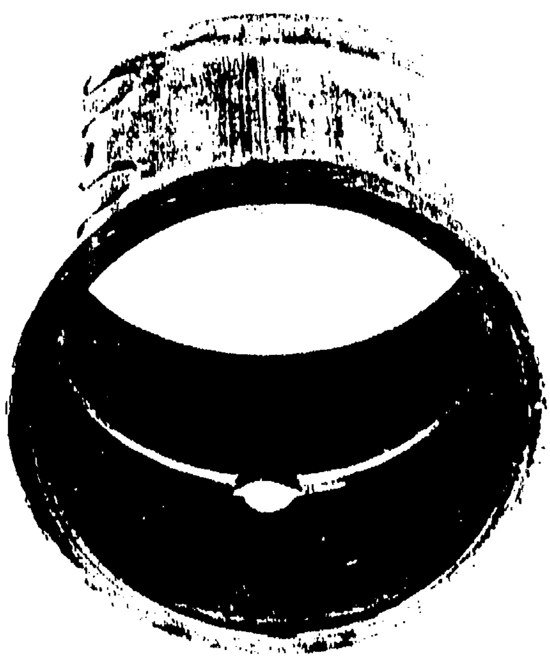
SCE-903
AIPS-4 AL-19346-L
(T)




SCE-903
AIPS-4 AL-19346-L

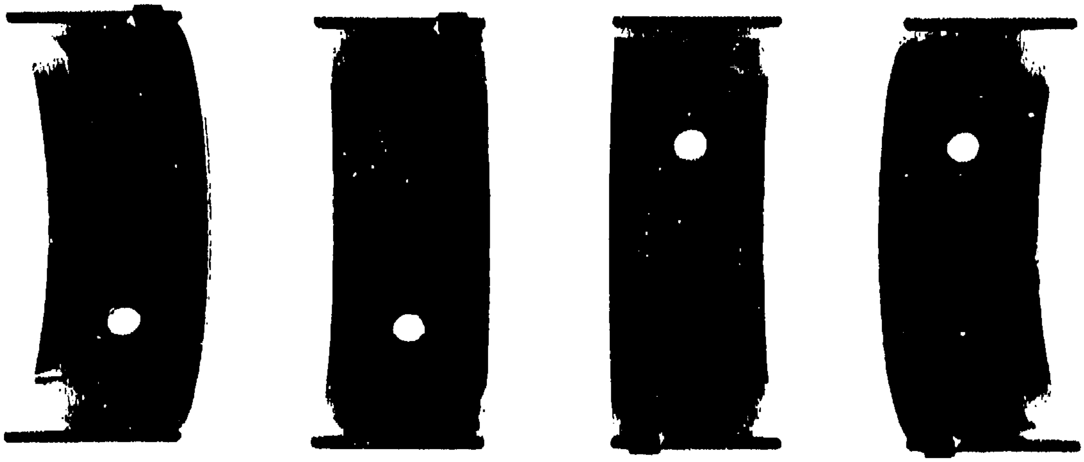


SCE-903
AIPS-4 AL-19346-L
TOP ROD BUSHING



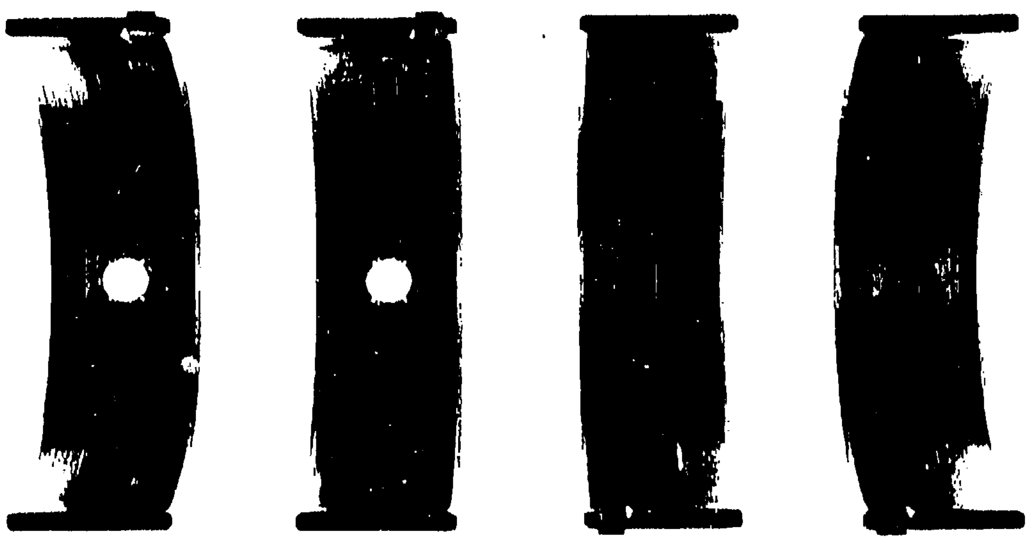
SCE-903
AIPS-4 AL-19346-L
BOTTOM ROD BUSHING

TOP ACTIVE TOP SLIPPER BOTTOM ACTIVE BOTTOM SLIPPER



SCE-903
AIPS-4 AL-19346-L
ROD BEARINGS

TOP FRONT TOP REAR BOTTOM FRONT BOTTOM REAR



SCE-903
AIPS-4 AL-19346-L
MAIN BEARINGS

APPENDIX E

SCE-903 High-Temperature Lubricant Evaluation
Test No. AIPS-5

SCE-903 HIGH-TEMPERATURE LUBRICANT EVALUATION

Test Lubricant: AL-19347-L
Test Fuel: AL-19709-F
Test No.: AIPS-5
Date: 17 December 1991

Conducted For

U.S. Army Belvoir Research, Development and
Engineering Center
Logistics Equipment Directorate
Fort Belvoir, Virginia 22060-5606

By

Belvoir Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78228-0510

TEST SUMMARY

The SCE-903 is a vee-configured two-cylinder engine, with one cylinder active and the second cylinder for balance. The SCE-903 is being used to screen candidate high-temperature lubricants for future low-heat rejection diesel engines. The target operating conditions are 340°F oil sump and 318°F oil gallery temperatures at 2600 rpm and a full-load air/fuel ratio of 28 to 1. The cylinder block is uncooled and the cylinder head temperature is 250°F during engine operation.

The AIPS-5 test candidate was an experimental 40 synthetic diesel engine oil. The lubricant evaluation lasted 100 hours, after which time the engine was disassembled for parts rating and inspection. The ratings revealed no cylinder liner scuffing, 5-percent bore polish, and no ring face distress. All three rings were free with moderate to heavy groove and land deposits. The heaviest deposit ratings were in the third groove and on the third land. The connecting rod piston pin bushing, the main bearings, and connecting rod bearings all revealed signs of distress and exposed copper. Of particular interest was the near catastrophic failure of the slipper piston pin bushing and the slipper piston connecting rod bearing shell. The end-of-test lubricant inspection indicated there was substantial oil degradation, apparently catalyzed by the copper from the bearings. There was a 100-percent increase in lubricant viscosity and an extremely high Total Acid Number. Used oil wear metal contents by ICP were 112 ppm of iron and 97 ppm of copper. Also in evidence was 323 ppm of zinc, in a lubricant that does not contain a zinc additive. It is speculated that the zinc is from the bearing material.

SCE-903
OPERATING CONDITIONS SUMMARY

Date: 12/17/91 | **Test No.: AIPS-5**

Lubricant: AL-19347-L | **Fuel: AL-19709-F**

Test Hours: 100

	Mean	Standard Deviation
Engine Speed, rpm	2608	2
Torque, lb-ft	112.43	1.39
Observed Power, Bhp	55.82	0.70
Air/Fuel Ratio	28.65	0.58
Fuel Rate, lb/hr	20.72	0.32
BSFC, lb/Bhp-hr	0.371	0.0064
BMEP, psi	150.24	1.86
Oil Consumption Rate, lb/hr	0.0861	
BSOC, lb/Bhp-hr	0.0015	
Temperatures, °F		
Oil Sump	331	1.6
Oil After Cooler	316	1.8
Coolant Into Head	244	2.5
Coolant Out of Head	250	2.2
Exhaust	1098	10.3
Inlet Air	221	2.8
Fuel Inlet	106	3.6
Cylinder Liner, All Positions	451	27.8
Thrust Top	439	65.9
Upper Mid	435	53.6
Bottom	507	9.0
Antithrust		
Top	423	26.3
Pressures, psig		
Manifold	15.5	0.177
Oil Gallery	17.0	0.628
Exhaust Back	14.7	0.500

OIL PROPERTIES

Test No.: AIPS-5
Lubricant: AL-19347-L

Lubricant Analysis	AL-19347-L
K. Vis, 40°C, cSt	105.39
K. Vis, 100°C, cSt	14.50
Viscosity Index	141
App Vis, at -30°C, D 2602	>15000
App Vis, at -30°C, D 4684	72609
HTHS Vis at 150°C, cP, D 4683	5.11
Flash Point, °C	286
Pour Point, °C	-33
Sulfated Ash, wt%	0.83
TAN	0.83
TBN, D 664	6.11
Gravity, °API	11.6
N, wt%, D 4629	0.03
TFOUT, minutes, D 4742	>300
Elements, XRF, wt%	
S	0.2
Ca	0.27
Ba	NA*
Zn	NA
P	NA
Elements, ICP 8A, ppm	
Ba	<1
B	<1
Mg	10
Mn	<1
Mo	<1
Ni	<1
P	2
Zn	<1
Elements, ICP, ppm	
Ca	2962
Cu	<1
Na	<1
IR Trace No.	16255
HPDSC, minutes, at	
180°C	>500
190°C	172
200°C	85
210°C	51

* NA = Not Applicable.

OIL PROPERTIES

Test No.: AIPS-5
Lubricant: AL-19347-L

Properties	Test Hours 0	Test Hours 100 EOT*
K. Vis, 40°C, cSt	105.39	314.70
K. Vis, 100°C, cSt	14.50	28.14
Viscosity Index	141	120
HTHS Viscosity, 150°C, cP, D 4683	5.11	8.59
Flash Point, °C	286	272
TAN	0.83	20.9
TBN, D 664	6.11	0
Sulfated Ash, wt%	0.83	1.39
TFOUT, minutes, D 4742	>300	35
Coag Insols, wt%		
Pentane B	ND**	1.02
Toluene B	ND	0.40
Elements, ICP, ppm		
Ca	2962	2694
Mg	10	17
P	2	29
Zn	<1	323
Ag	[illegible]	<1
Al	ND	6
B	<1	<1
Ba	<1	<1
Cr	ND	4
Cu	<1	97
Fe	ND	112
Na	<1	7
Ni	<1	4
Pb	ND	119
Si	ND	104
Sn	ND	25

* EOT = End-of-test.
** ND = Not Determined.

SCE-903
OIL CONSUMPTION AND WEAR METALS BY XRF

Lubricant: AL-19347-L

Test Time, hours	Total Oil Consumed		K. Vis, 100°C, cSt	Wear Metals, ppm	
	lb	kg		Fe	Cu
0	0.00	0.000	14.21	<20	<20
6	0.00	0.000	14.91	<20	<20
12	0.94	0.426	15.38	<20	<20
15	0.96	0.435	ND*	ND	ND
21	0.96	0.435	15.37	20	<20
25	0.96	0.435	15.60	26	<20
31	1.33	0.602	15.82	26	<20
37	2.14	0.971	16.34	28	<20
43	2.82	1.279	16.51	20	<20
49	3.32	1.506	16.87	25	<20
51	3.91	1.773	ND	ND	ND
57	3.92	1.778	16.75	27	<20
63	4.38	1.986	17.15	35	24
69	4.71	2.136	17.69	40	<20
70	5.45	2.472	ND	ND	ND
76	5.45	2.472	17.87	34	23
82	5.57	2.526	18.52	43	22
88	6.31	2.862	19.24	39	24
94	6.98	3.166	20.34	45	29
100	8.61	3.905	30.72	74	70

	lb/hr	kg/hr
Average Oil Consumption Rate	0.0861	0.0390

* ND = Not Determined.

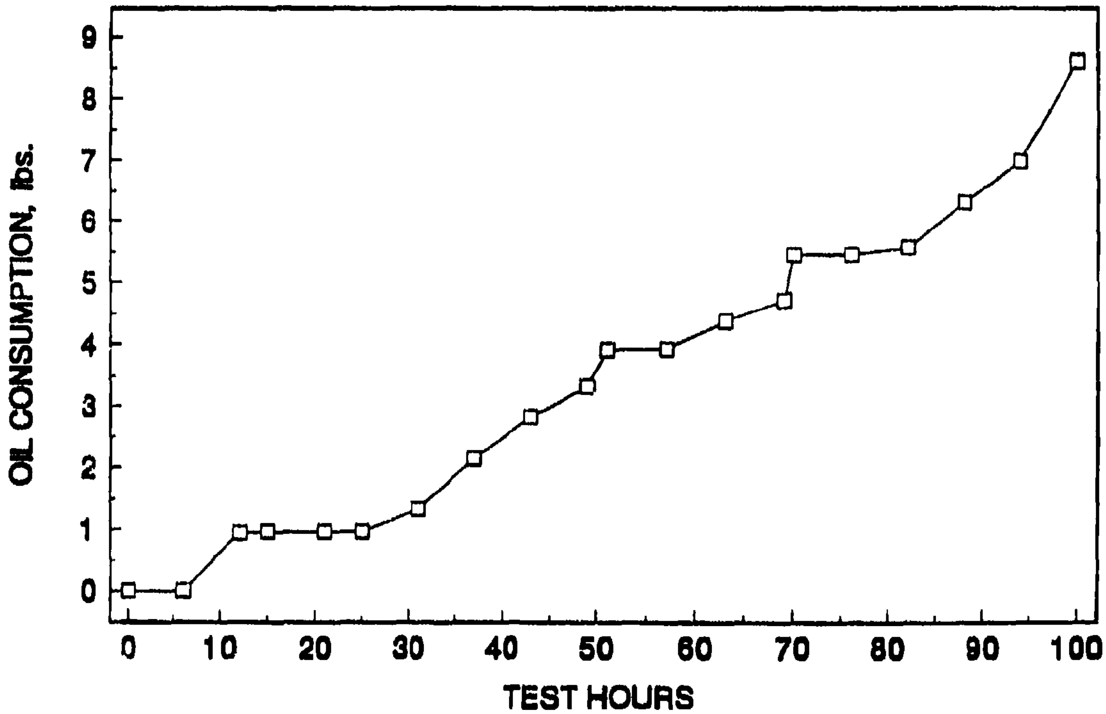


Figure E-1. AIPS-5, AL-19347, oil consumption

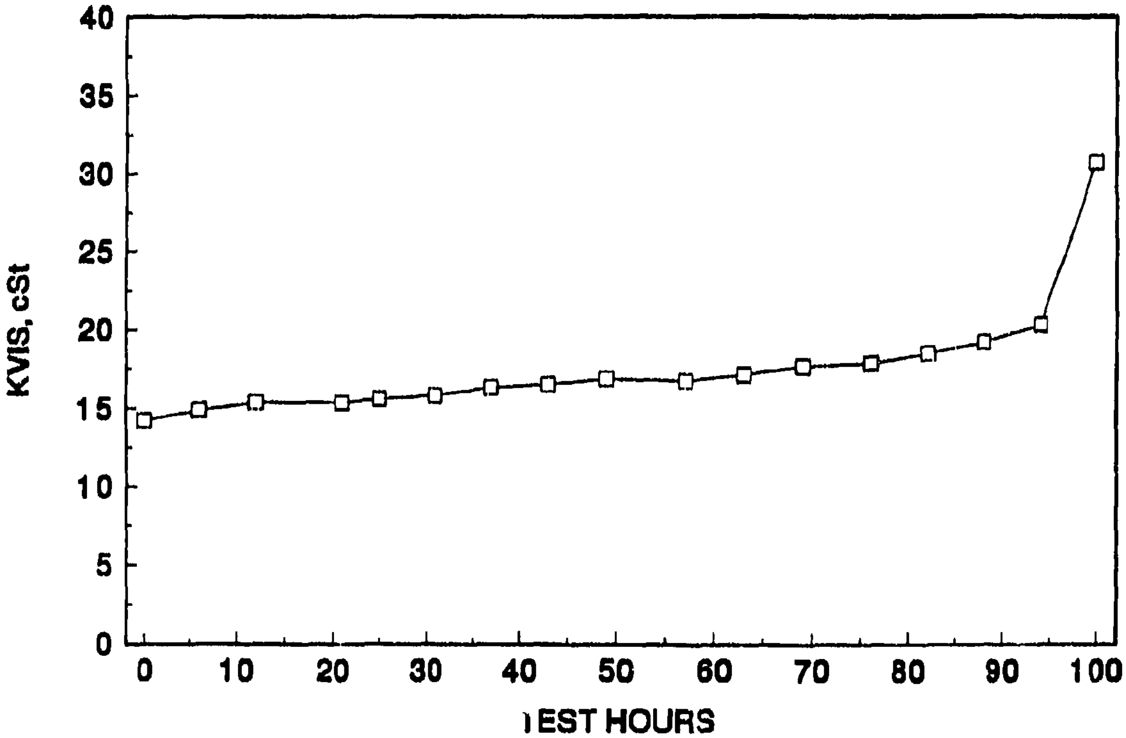


Figure E-2. AIPS-5, AL-19347, K. vis., 100°C

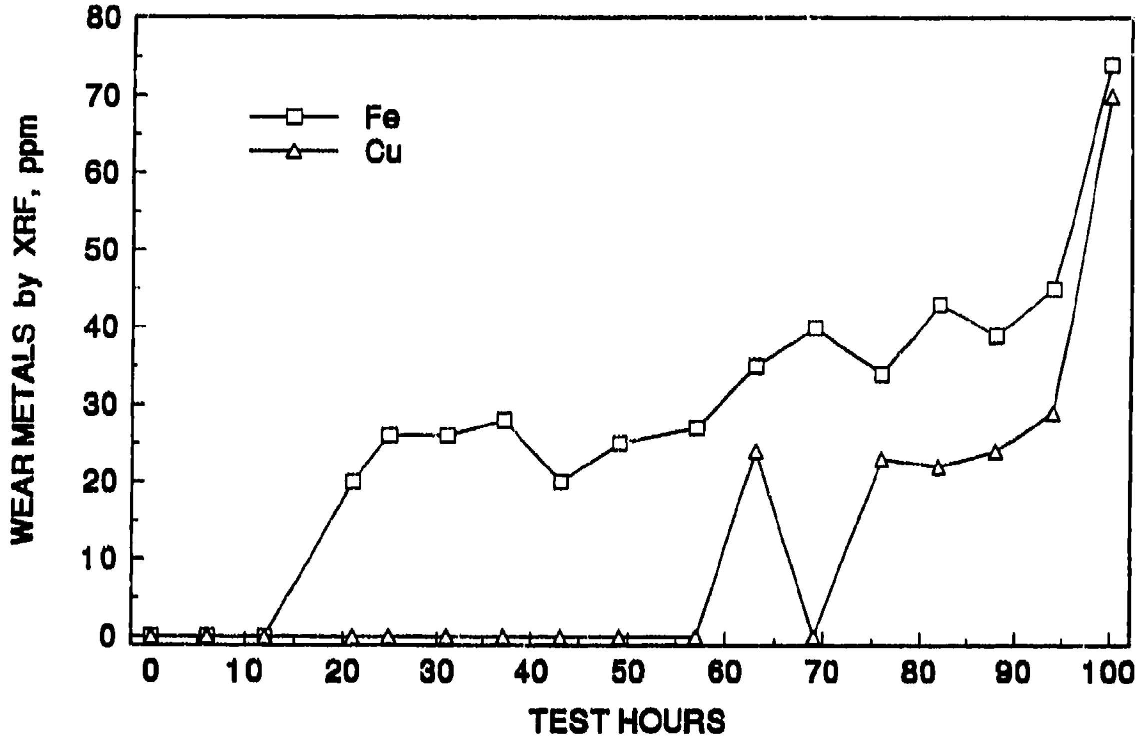


Figure E-3. <u>AIPS-5, AL-19347, wear metals</u>

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS*

Test No.: AIPS-5
Lubricant: AL-19347-L
Test Hours: 100

	Before		After		Change		Specified Limits	
	T-AT	F-B	T-AT	F-B	T-AT	F-B		
CYLINDER LINER**								
Inside Diameter								
Top	5.4999	5.5002	5.5003	5.5003	0.0004	0.0001	5.4995 - 5.5010	Worn Limit: 5.505
Middle	5.5005	5.5002	5.5010	5.0001	0.0005	-0.0001	5.4995 - 5.5010	Worn Limit: 5.505
Bottom	5.5002	5.4991	5.5009	5.4988	0.0007	-0.0003	5.4995 - 5.5010	Worn Limit: 5.505
Taper	0.0003	0.0011	0.0006	0.0015	0.0003	0.0004	0.0015 Max	
Out-of-Round								
Top	0.0003		0.0000		-0.0003		0.0020 Max	
Middle	0.0003		0.0009		0.0006		0.0020 Max	
Bottom	0.0011		0.0021		0.0010		0.0020 Max	
PISTON DIAMETER								
At Skirt	5.4898		5.4898		0.0000		5.4890 - 5.4900	
PISTON PIN-BORE								
Bore	1.7491		1.7502		0.0011		1.7485 - 1.7489	Worn Limit: 1.7500
Pin	1.7489		1.7488		-0.0001		1.7488 - 1.7490	Worn Limit: 1.7478
Clearance	0.0002		0.0014		0.0012		-0.0005 - 0.0001	Worn Limit: 0.0022
PISTON-CYLINDER LINER CLEARANCE								
Minimum	0.0093		0.0090		-0.0003		0.0095 - 0.0120	Worn Limit: 0.0170
Maximum	0.0107		0.0112		0.0012		0.0095 - 0.0120	Worn Limit: 0.0170
PISTON RINGS								
Eng Gap								
Ring No. 1	0.0240		0.0240		0.0000		0.0170 - 0.0270	
Ring No. 2	0.0260		0.0260		0.0000		0.0200 - 0.0300	
Ring No. 3	0.0210		0.0220		0.0010		0.0100 - 0.0250	
Ring Proudness								
Ring No. 1								
Measurement Point								
1	-0.0105		-0.0020		0.0085			
2	-0.0100		-0.0010		0.0090			
3	-0.0115		0.0010		0.0125			
4	-0.0120		-0.0090		0.0030			
Ring No. 2								
Measurement Point								
1	-0.0040		0.0030		0.0070			
2	-0.0045		-0.0010		0.0035			
3	-0.0050		-0.0040		0.0010			
4	-0.0050		-0.0010		0.0040			

* Measurements are in inches. Change = After - Before.
** T-AT = Thrust-Antithrust.
F-B = Front-Back.

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS* (CONT'D)

Test No.: AIPS-5
Lubricant: AL-19347-L
Test Hours: 100

	Before		After		Change		Specified Limits
BEARINGS**	A	B	A	B	A	B	
Main Bearing Journals							
1	3.7482	3.7479	3.7482	3.7479	0.0000	0.0000	3.7490 - 3.7500 Worn Limit: 3.7470 Max
2	3.7489	3.7489	3.7489	3.7489	0.0000	0.0000	3.7490 - 3.7500 Worn Limit: 3.7470 Max
Connecting Rod Bearing Journals							
1	3.1241	3.1241	3.1241	3.1241	0.0000	0.0000	3.1240 - 3.1250 Worn Limit: 3.1220
	F	BA	F	BA	F	BA	
Main Bearing Shells							
1	3.7564	3.7566	3.7571	3.7571	0.0007	0.0005	
2	3.7564	3.7560	3.7573	3.7567	0.0009	0.0007	
Connecting Rod Bearing Shells							
1	3.1287	3.1288	3.1300	3.1299	0.0013	0.0011	
	Min	Max	Min	Max	Min	Max	
Main Bearing Journal-Shell Clearances							
1	0.0082	0.0087	0.0089	0.0092	0.0007	0.0005	0.0015 - 0.0050 Worn Limit: 0.007
2	0.0071	0.0075	0.0078	0.0084	0.0007	0.0009	0.0015 - 0.0050 Worn Limit: 0.007
	Min	Max	Min	Max	Min	Max	
Connecting Rod Journal-Shell Clearances							
1	0.0046	0.0047	0.0058	0.0059	0.0012	0.0012	0.0015 - 0.0045 Worn Limit: 0.007
Main Bearing Weights, grams							
1 Upper	140.1495		139.1140		-1.0355		
1 Lower	160.2580		158.9395		-1.3185		
2 Upper	140.1180		139.1341		-0.9839		
2 Lower	159.9669		158.5372		-1.4297		
Connecting Rod Bearing Weight, grams							
1 Upper	84.4378		83.5101		-0.9277		
1 Lower	84.2539		83.4520		-0.8019		
	T	AT	T	AT	T	AT	
VALVES***							
Stem to Guide Clearance (Average)							
Intake	0.0027	0.0026	0.0028	0.0028	0.0001	0.0002	0.0015 - 0.0032
Exhaust	0.0023	0.0024	0.0031	0.0036	0.0008	0.0012	0.0015 - 0.0032
Recession							
Intake	-0.0091	-0.0081	-0.0118	-0.0136	-0.0027	-0.0055	-0.0050 - -0.0250
Exhaust	-0.0717	-0.0611	-0.0760	-0.0720	-0.0043	-0.0109	-0.0520 - -0.0720

* Measurements are in inches. Change = After - Before.

** A = Micrometer anvil parallel to weights; B = Micrometer anvil perpendicular to weights; F = Front; BA = Back.

*** T = Thrust; AT = Antithrust.

SCE-903
POST-TEST RATINGS OF ENGINE DEPOSITS AND CONDITIONS

Test No.: AIPS-5
Lubricant: AL-19347-L
Test Hours: 100

PISTON					
Skirt Rating	Polished areas normal, with few vertical line cuttings.				
Top Groove Fill, %	13				
Second Groove Fill, %	14				
WDK Weighted Total Deposits	481.7				
RINGS					
Ring Freedom					
No. 1	Free				
No. 2	Free				
No. 3	Free				
Ring Distress Demerits	Some light discoloration, no apparent distress.				
	T*	AT	Average		
LINER					
Scuffing, %	0	0	0.0		
Bore Polish, %	3	7	5.0		
Distress	0	0	0.0		
VALVES					
Head					
Intake	100% Light Carbon				
Exhaust	100% Light Carbon				
Tulip					
Intake	T and AT - 0.5% Carbon				
Exhaust	T and AT - 0.5% Carbon				
Face					
Intake	T and AT - Good Condition				
Exhaust	T and AT - Good Condition				
Stem					
Intake	T and AT - Clean				
Exhaust	T - 6% No. 9 Lacquer; AT - 26% No. 9 Lacquer				

	Top	Bottom
BEARING DISTRESS,		
% Exposed Cu		
Front Main	7	12
Rear Main	3	6
Connecting Rod		
Active	11	10
Slipper	35, medium abrasive scratches	55, medium abrasive scratches
ROD BUSHING, % Wear Band		
Active	0	70
Slipper	Foreign material embedded	Foreign material embedded

* T = Thrust; AT = Antithrust.
** ND = Not Determined.

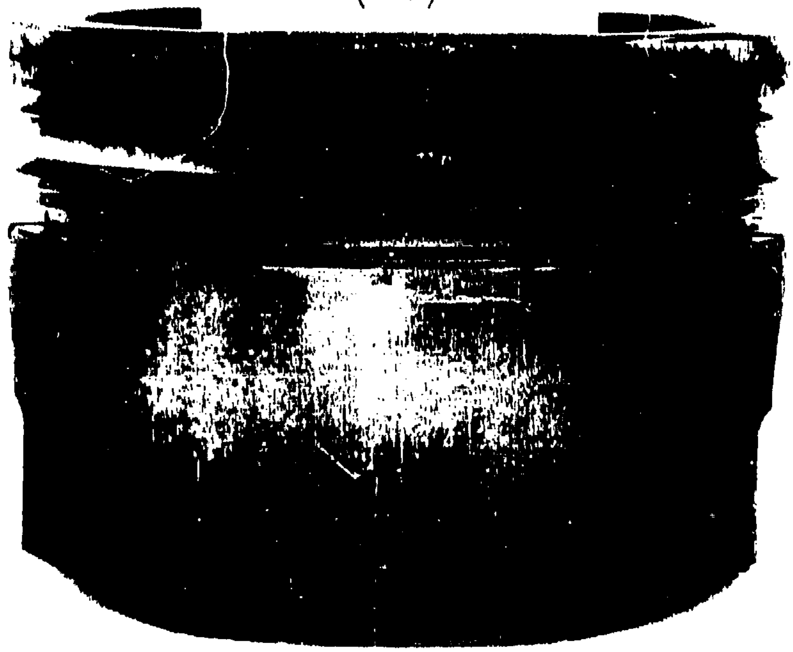
LAB SwRI	STAND NO. 1	TEST NO. 1-5	ENGINE SC-903
OIL CODES AL-19347-L			FUEL BATCH
DATE STARTED / /	DATE COMP 12/17/91	DATE RATED 01/14/92	RATER AB · TEST HRS 100
REFEREE INFORM. COMPANY	DATE RATED	RATER	RATING NO
STAND LAST REFERENCE · TMC OIL / DATE COMP	TEST NO / ENGINE NO	TEST TGF ___ TLHC ___ / RAT. WDK ___ AVBSOC ___	IND. TGF ___ TLHC ___ / AVE. WDK ___ AVBSOC ___

RATING SUMMARY

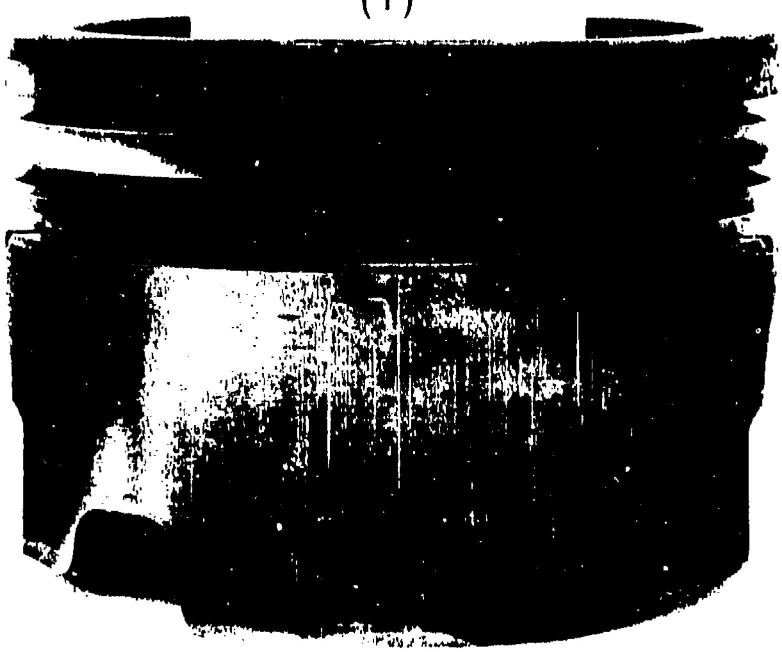
		GROOVES						LANDS						UPPER SKIRT		UNDER CROWN		PIN BORES			
	dep	NO.1		NO.2		NO.3		NO.1		NO.2		NO.3						FRONT		REAR	
	factor	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM
carbon	hc-1.0	4	4.00					66	66.00												
	mc-0.5	7	3.50																		
	lc-.25	89	22.25	57	14.25			36	9.00	46	11.50										
	total	100	29.750	57	14.250			100	73.000	46	11.500										
varnish	8-9			43	3.700					25	2.250	50	4.500								
	7-7.9											45	3.195			10	0.730				
	6-6.9									2	0.130					5	0.300				
	5-5.9																				
	4-4.9											5	0.210								
	3-3.9																				
	2-2.9					55	1.420			17	0.408			15	0.300	65	1.820	25	0.620	15	0.300
	1-1.9					45	0.450							5	0.060	15	0.150	55	0.770	50	0.600
	0-0.9															5	0.025	20	0.060	35	0.105
	total			43	3.700	100	1.870			54	2.788	100	7.905	100	0.360	100	3.025	100	1.450	100	1.005
rating		29.750		17.950		1.870		73.000		14.288		7.905		0.360		3.025		1.450		1.005	
WDK loc fct		1.5		1.5		25		1		1		25		50		20		0		0	
wt rating		44.625		26.925		46.750		73.000		14.288		197.625		18.000		60.500		0.000		0.000	

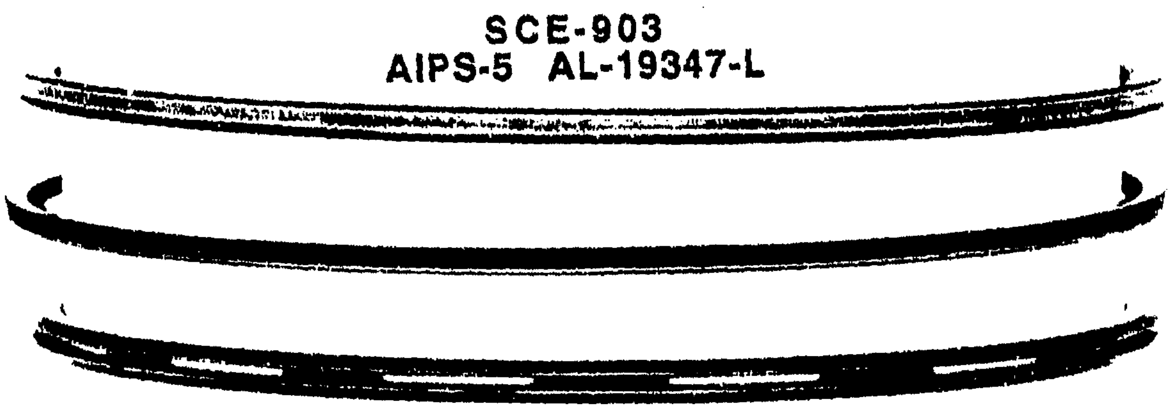
TGF%	INT GR FILL %	WDK	UN WEIGHTED DEP	T.L. HVY CRB %	T.L. FLAKED CRB %	ACC GR FILL %
13	14	481.7	150.6	64		

SCE-903
AIPS-5 AL-19347-L
(AT)

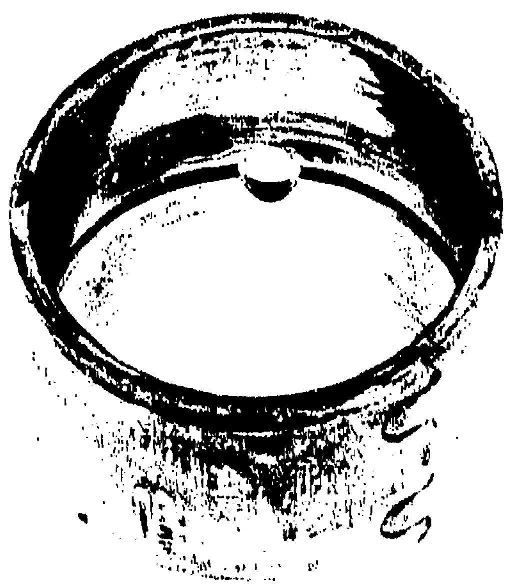


SCE-903
AIPS-5 AL-19347-L
(T)



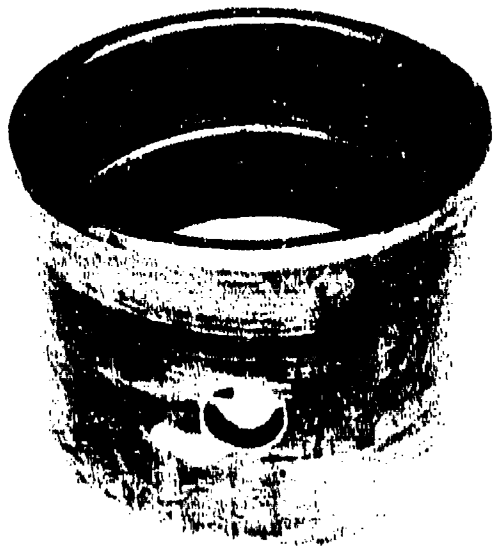

SCE-903
AIPS-5 AL-19347-L

SCE-903
AIPS-5 AL-19347-L
ACTIVE
TOP ROD BUSHING

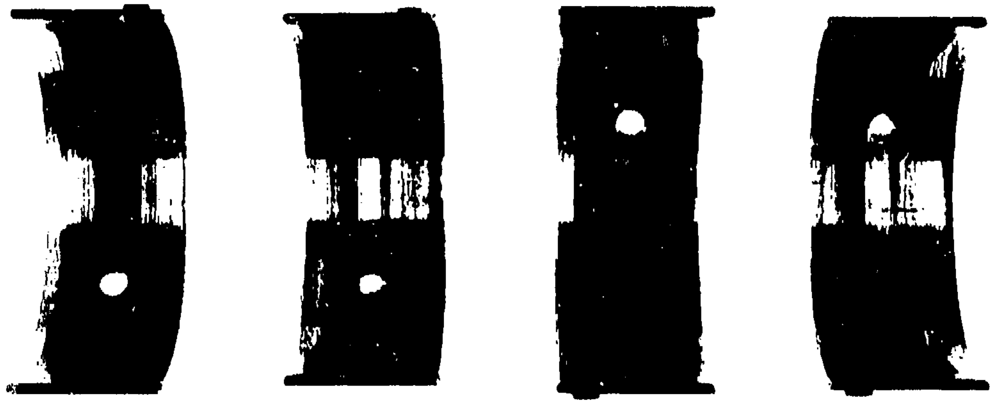


SCE-903
AIPS-5 AL-19347-L
ACTIVE
BOTTOM ROD BUSHING

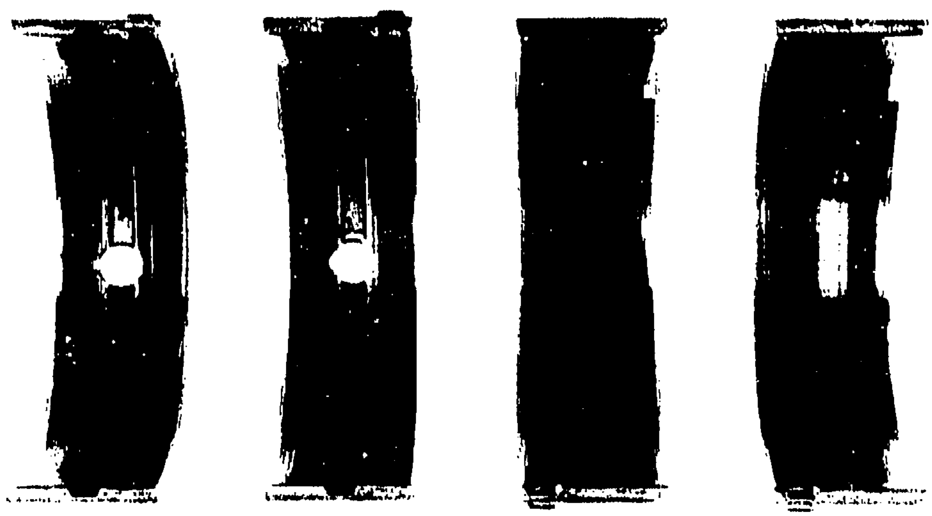
SCE-903
AIPS-5 AL-19347-L
SLIPPER
TOP ROD BUSHING



SCE-903
AIPS-5 AL-19347-L
SLIPPER
BOTTOM ROD BUSHING



SCE-903
AIPS-5 AL-19347-L
ROD BEARINGS



SCE-903
AIPS-5 AL-19347-L
MAIN BEARINGS

APPENDIX F

SCE-903 High-Temperature Lubricant Evaluation
Test No. AIPS-6

SCE-903 HIGH-TEMPERATURE LUBRICANT EVALUATION

Test Lubricant: AL-19372-L
Test Fuel: AL-19709-F
Test No.: AIPS-6
Date: 13 May 1992

Conducted For

U.S. Army Belvoir Research, Development and Engineering Center
Logistics Equipment Directorate
Fort Belvoir, Virginia 22060-5606

By

Belvoir Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78228-0510

TEST SUMMARY

The SCE-903 is a vee-configured two-cylinder engine, with one cylinder active and the second cylinder for balance. The SCE-903 is being used to screen candidate high temperature lubricants for future low-heat rejection diesel engines. The target operating conditions are 340°F oil sump and 318°F oil gallery temperatures at 2600 rpm and a full-load air/fuel ratio of 28 to 1. The cylinder block is uncooled and the cylinder head temperature is 250°F during engine operation.

The AIPS-6 test candidate was a commercially available 15W-40 mineral-based diesel engine oil. The lubricant evaluation lasted 49 hours, after which time the engine was disassembled for parts rating and inspection. The ratings revealed no cylinder liner scuffing, 2.5-percent bore polish, and no ring face distress. All three rings were free with moderate to heavy groove and land deposits. The connecting rod piston pin bushing appeared to have some distress. There was not any bearing distress evident, likely due to the shortness of the test. The end-of-test lubricant inspection revealed oil degradation, with a 84-percent viscosity increase and a Total Acid Number increase. This test, which was a repeat of AIPS-2, revealed oil degradation rates similar to the earlier test, until later on in the test when oil leaks resulted in large additions of makeup oil. Used oil wear metal contents by ICP were 38 ppm of iron and 32 ppm of copper.

SCE-903
OPERATING CONDITIONS SUMMARY

Date: 05/13/92 **Test No.: AIPS-6**

Lubricant: AL-19372-L **Fuel: AL-19709-F**

Test Hours: 49

	Mean	Standard Deviation
Engine Speed, rpm	2600	0.20
Torque, lb-ft	113.06	0.59
Observed Power, Bhp	56.08	0.29
Air/Fuel Ratio	28.24	4.31
Fuel Rate, lb/hr	20.69	0.24
BSFC, lb/Bhp-hr	0.369	0.0045
BMEP, psi	151.38	0.79
Oil Consumption Rate, lb/hr	0.345	
BSOC, lb/Bhp-hr	0.0064	
Temperatures, °F		
Oil Sump	333	4.57
Oil After Cooler	316	2.81
Coolant Into Head	245	0.43
Coolant Out of Head	249	0.43
Exhaust	1100	13.50
Inlet Air	221	0.81
Fuel Inlet	109	2.44
Cylinder Liner, All Positions	470	34.04
Thrust Top	488	17.59
Upper Mid	462	8.07
Bottom	422	11.02
Antithrust		
Top	506	9.92
P-Tube Oil	312	6.43
Main Bearing, Bottom	325	17.48
Main Bearing, Side	318	6.39
Pressures, psig		
Manifold	15.7	2.13
Oil Gallery	20.9	2.06
Exhaust Back	15.4	0.19

OIL PROPERTIES

Test No.: AIPS-6
Lubricant: AL-19372-L

Lubricant Analysis	AL-19372-L
K. Vis, 40°C, cSt	97.9
K. Vis, 100°C, cSt	14.59
Viscosity Index	155
App Vis, at -15°C, D 2602	>15000
App Vis, at -20°C, D 4684	113652
HTHS Vis at 150°C, cP, D 4624	3.86
Flash Point, °C	221
Pour Point, °C	-19
Sulfated Ash, wt%	0.91
TAN	3.19
TBN, D 664	6.33
Gravity, °API	21.7
Carbon Residue Ramsbottom, wt%	3.59
N, wt%, D 4629	0.098
TFOUT, minutes, D 4742	200
IR Trace No.	20
Elements, XRF, wt%	
S	1.1
Ca	0.18
Ba	ND*
Zn	0.15
P	0.12
Elements, ICP 8A, ppm	
Ba	<1
B	8
Mg	4
Mn	<1
Mo	1
Ni	<1
P	1029
Zn	1431
HPDSC, minutes, at	
180°C	57
190°C	34
200°C	20
210°C	10

* ND = Not Determined.

OIL PROPERTIES

Test No.: AIPS-6
Lubricant: AL-19372-L

Properties	Test Hours 0	Test Hours 49
K. Vis, 40°C, cSt	97.9	23.46
K. Vis, 100°C, cSt	14.59	26.89
Viscosity Index	155	148
HTHS Vis at 150°C, cP, D 4624	3.86	6.46
Flash Point, °C	221	222
TAN	3.19	5.02
TBN, D 664	6.33	2.49
Sulfated Ash, wt%	0.91	1.44
Carbon Residue Ramsbottom, wt%	3.59	2.78
N, wt%, D 4629	0.098	0.139
TFOUT, minutes, D 4742	200	128
TGA Soot, wt%	ND	1.6
Coag Insols, wt%		
Pentane B	ND*	0.02
Toluene B	ND	0.01
Differential IR		
Oxidation, A/cm	ND	42
Nitration, A/cm	ND	14
Elements, XRF, wt%		
S	1.10	1.20
Ca	0.18	0.26
Ba	ND	NIL
Zn	0.15	0.21
P	0.12	ND
Elements, XRF, ppm		
Fe	ND	32
Cu	ND	15
Pb	ND	12
Elements, ICP, ppm		
Ca	ND	3521
Mg	4	9
P	1029	1832
Zn	1431	2388
Ag	ND	<1
Al	ND	5
B	8	7
Ba	<1	<1
Cr	ND	<1
Cu	ND	32
Fe	ND	38
Na	ND	32
Ni	<1	<1
Pb	ND	19
Si	ND	36
Sn	ND	<1

* ND = Not Determined.

SCE-903
OIL CONSUMPTION AND WEAR METALS BY ICP

Lubricant: AL-19372-L

Test Time, hours	Total Oil Consumed		K. Vis, 100°C, cSt	Wear Metals, ppm		
	lb	kg		Fe	Cu	Pb
0	0.00	0.000	14.38	2	<1	<1
6	0.83	0.376	18.00	39	36	ND
12	2.99	1.356	22.45	49	50	29
18	4.72	2.141	26.74	52	37	27
20	6.92	3.138	ND*	ND	ND	ND
25	7.99	3.624	27.39	49	31	23
29	9.02	4.091	30.11	71	33	24
35	10.83	4.912	32.81	57	36	24
41	13.43	6.091	36.26	58	42	26
43	15.50	7.029	ND	ND	ND	ND
49	16.92	7.673	31.36	47	33	18
	lb/hr	kg/hr				
Average Oil Consumption Rate	0.345	0.157				

* ND = Not Determined.

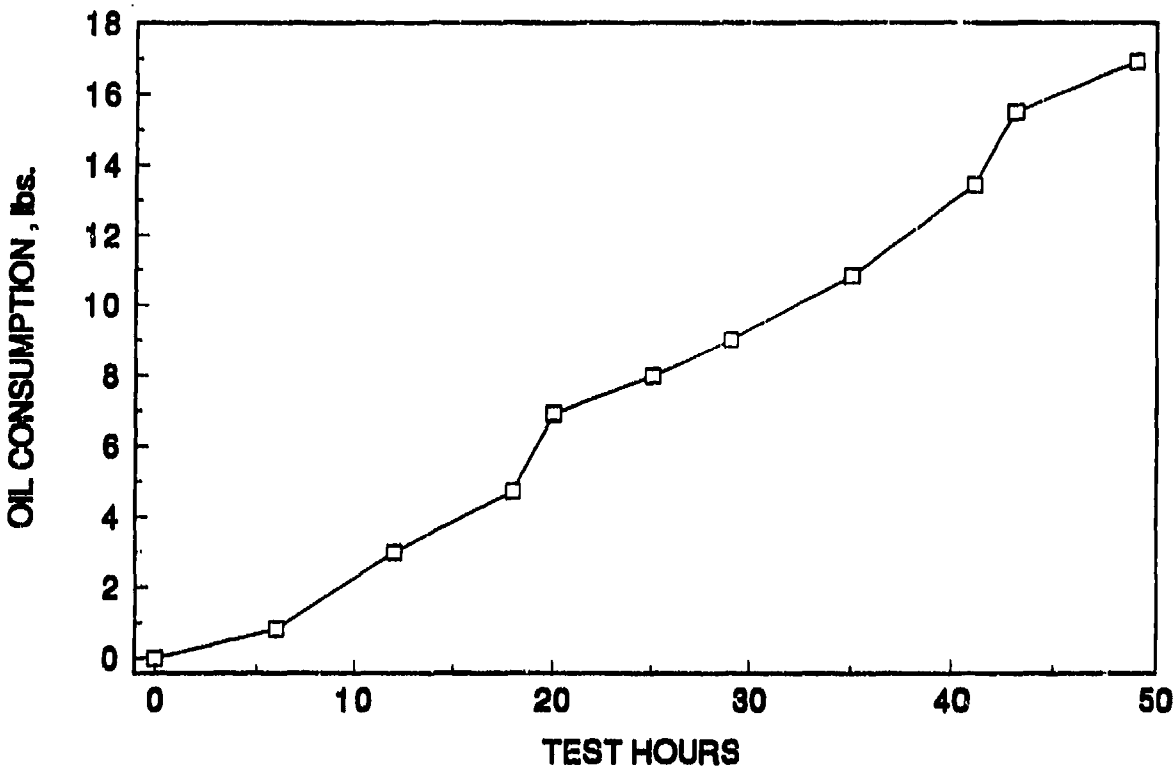


Figure F-1. AIPS-6, AL-19372, oil consumption

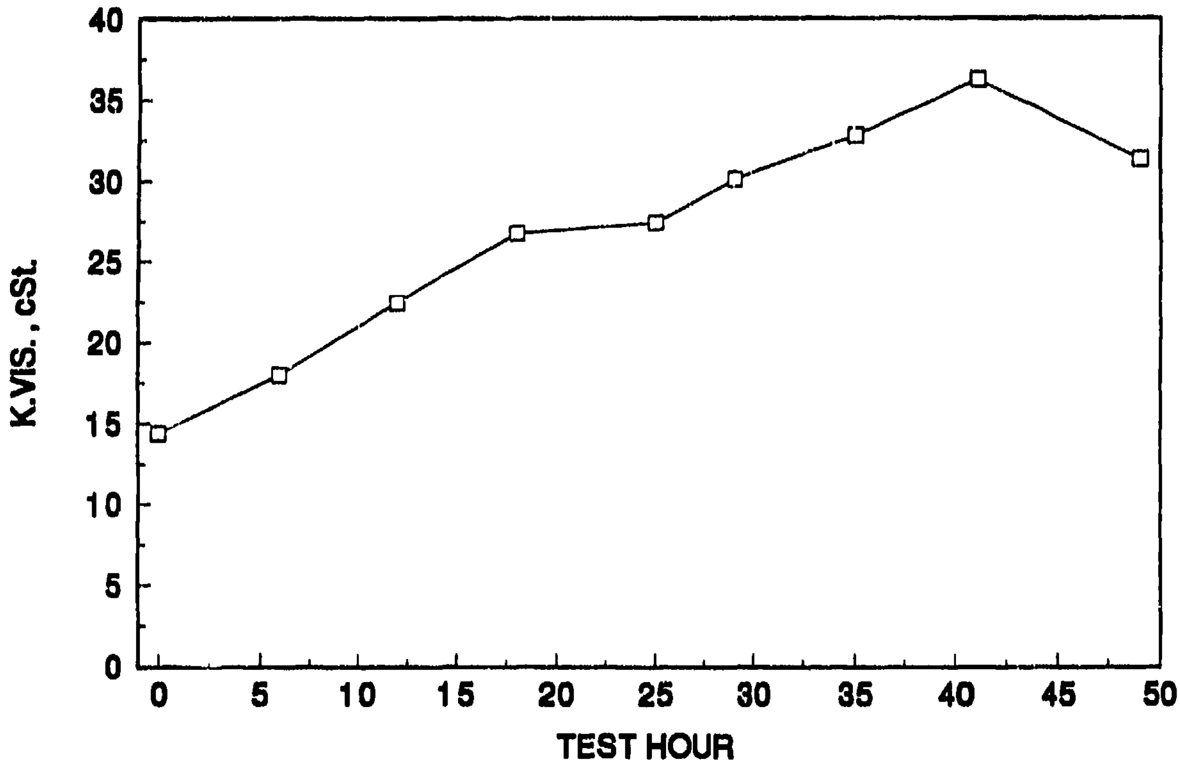


Figure F-2. AIPS-6, AL-19372, K. vis., 100°C

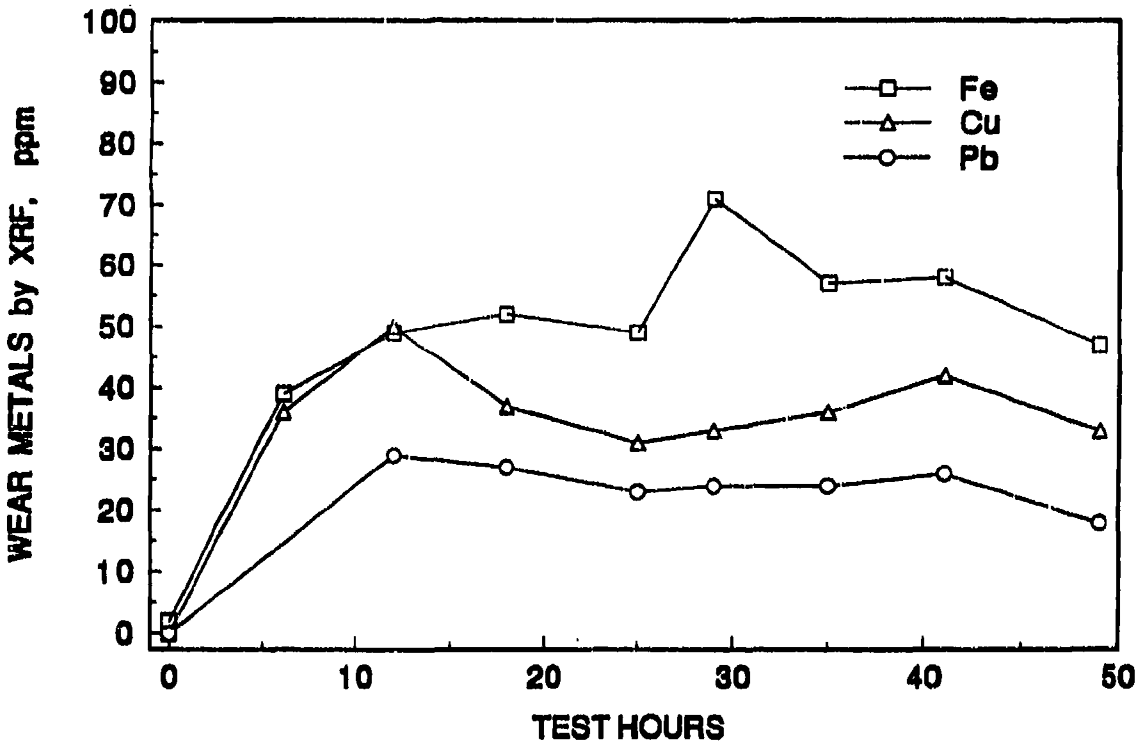


Figure F-3. AIPS-6, AL-19372, wear metals

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS*

Test No.: AIPS-6
Lubricant: AL-19372-L
Test Hours: 49

	Before		After		Change		Specified Limits	
	T-AT	F-B	T-AT	F-B	T-AT	F-B		
CYLINDER LINER**								
Inside Diameter								
Top	5.5006	5.5004	5.5005	5.5005	-0.0001	0.0001	5.4995 - 5.5010	Worn Limit: 5.505
Middle	5.5010	5.5003	5.5009	5.5003	-0.0001	0.0000	5.4995 - 5.5010	Worn Limit: 5.505
Bottom	5.5001	5.4990	5.5006	5.4995	0.0005	0.0005	5.4995 - 5.5010	Worn Limit: 5.505
Taper	0.0005	0.0014	0.0001	0.0010	-0.0004	-0.0004	0.0015 Max.	
Out-of-Round								
Top	0.0002		0.0000		-0.0002		0.0020 Max	
Middle	0.0007		0.0006		-0.0001		0.0020 Max	
Bottom	0.0011		0.0011		0.0000		0.0020 Max	
PISTON DIAMETER								
At Skirt	5.4898		5.4895		-0.0003		5.4890 - 5.4900	
PISTON PIN-BORE								
Bore	1.7492		1.7498		0.0006		1.7485 - 1.7489	Worn Limit: 1.7500
Pin	1.7488		1.7488		0.0000		1.7488 - 1.7490	Worn Limit: 1.7478
Clearance	0.0004		0.0010		0.0006		-0.0005 - 0.0001	Worn Limit: 0.0022
PISTON-CYLINDER LINER CLEARANCE								
Minimum	0.0092		0.0100		0.0008		0.0095 - 0.0120	Worn Limit: 0.0170
Maximum	0.0108		0.0114		0.0006		0.0095 - 0.0120	Worn Limit: 0.0170
PISTON RINGS								
Eng Gap								
Ring No. 1	0.0250		0.0270		0.0020		0.0170 - 0.0270	
Ring No. 2	0.0250		0.0270		0.0020		0.0200 - 0.0300	
Ring No. 3	0.0260		0.0280		0.0020		0.0100 - 0.0250	
Ring Proudness								
Ring No. 1								
Measurement Point								
1	-0.0120		-0.0050		0.0070			
2	-0.0125		0.0030		0.0155			
3	-0.0140		0.0020		0.0160			
4	-0.0130		-0.0040		0.0090			
Ring No. 2								
Measurement Point								
1	-0.0040		0.0100		0.0140			
2	-0.0045		0.0030		0.0075			
3	-0.0060		0.0020		0.0080			
4	-0.0050		0.0080		0.0130			

* Measurements are in inches. Change = After - Before.
** T-AT = Thrust-Antithrust.
F-B = Front-Back.

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS* (CONT'D)

Test No.: AIPS-6
Lubricant: AL-19372-L
Test Hours: 49

	Before		After		Change		
	A	B	A	B	A	B	Specified Limits
BEARINGS**							
Main Bearing Journals							
1	3.7482	3.7479	3.7482	3.7479	0.0000	0.0000	3.7490 - 3.7500 Worn Limit: 3.7470 Max
2	3.7489	3.7489	3.7489	3.7489	0.0000	0.0000	3.7490 - 3.7500 Worn Limit: 3.7470 Max
Connecting Rod Bearing Journals							
1	3.1241	3.1241	3.1241	3.1240	0.0000	-0.0001	3.1240 - 3.1250 Worn Limit: 3.1220
	F	BA	F	BA	F	BA	
Main Bearing Shells							
1	3.7554	3.7555	3.7554	3.7553	0.0000	-0.0002	
2	3.7557	3.7552	3.7555	3.7548	-0.0002	-0.0004	
Connecting Rod Bearing Shells							
1	3.1287	3.1287	3.1286	3.1285	-0.0001	-0.0002	
	Min	Max	Min	Max	Min	Max	
Main Bearing Journal-Shell Clearances							
1	0.0072	0.0076	0.0071	0.0075	-0.0001	-0.0001	0.0015 - 0.0050 Worn Limit: 0.007
2	0.0063	0.0068	0.0059	0.0066	-0.0004	-0.0002	0.0015 - 0.0050 Worn Limit: 0.007
	Min	Max	Min	Max	Min	Max	
Connecting Rod Journal-Shell Clearances							
1	0.0046	0.0046	0.0044	0.0046	-0.0002	0.0000	0.0015 - 0.0045 Worn Limit: 0.007
Main Bearing Weights, grams							
1 Upper	137.9580		137.9301		-0.0279		
1 Lower	160.1805		160.1389		-0.0416		
2 Upper	138.2421		138.2236		-0.0185		
2 Lower	160.0496		160.0100		-0.0396		
Connecting Rod Bearing Weight, grams							
1 Upper	84.6727		84.6095		-0.0632		
1 Lower	84.6574		84.6442		-0.0132		
	T	AT	T	AT	T	AT	
VALVES***							
Stem to Guide Clearance (Average)							
Intake	0.0026	0.0026	0.0024	0.0025	-0.0002	-0.0001	0.0015 - 0.0032
Exhaust	0.0022	0.0023	0.0023	0.0022	0.0001	-0.0001	0.0015 - 0.0032
Recession							
Intake	-0.0145	-0.0126	-0.0147	-0.0149	-0.0002	-0.0023	-0.0050 - -0.0250
Exhaust	-0.0662	-0.0689	-0.0718	-0.0703	-0.0056	-0.0014	-0.0520 - -0.0720

* Measurements are in inches. Change = After - Before.
** A = Micrometer anvil parallel to weights; B = Micrometer anvil perpendicular to weights; F = Front; BA = Back.
*** T = Thrust; AT = Antithrust.

SCE-903
POST-TEST RATINGS OF ENGINE DEPOSITS AND CONDITIONS

Test No.: AIPS-6
Lubricant: AL-19372-L
Test Hours: 49

PISTON			
Skirt Rating	Polished areas normal, with few vertical line cuttings.		
Top Groove Fill, %	41		
Second Groove Fill, %	53		
WDK Weighted Total Deposits	484.8		
RINGS			
Ring Freedom			
No. 1	Free		
No. 2	Free		
No. 3	Free		
Ring Distress Demerits	Some light discoloration, no apparent distress.		
LINER	Few vertical scratches.		
	T*	AT	Average
Scuffing, %	0	0	0.0
Bore Polish, %	3	2	2.5
Distress	0	0	0.0
VALVES			
Head			
Intake	100% Light Carbon		
Exhaust	100% Light Carbon		
Tulip			
Intake	T and AT - 0.5% Carbon		
Exhaust	T and AT - 0.5% Carbon		
Face			
Intake	T and AT - Good Condition		
Exhaust	T and AT - Good Condition		
Stem			
Intake	T and AT - Clean		
Exhaust	T - Clean; AT - 30% No. 9 Lacquer, 20% No. 4 Lacquer		

	Top	Bottom
BEARING DISTRESS,		
% Exposed Cu		
Front Main	0	0
Rear Main	0	0
Connecting Rod		
Active	0	0
Slipper	0	0
ROD BUSHING, % Wear Band		
Active	0	15
Slipper	ND**	ND

* T = Thrust; AT = Antithrust.
** ND = Not Determined.

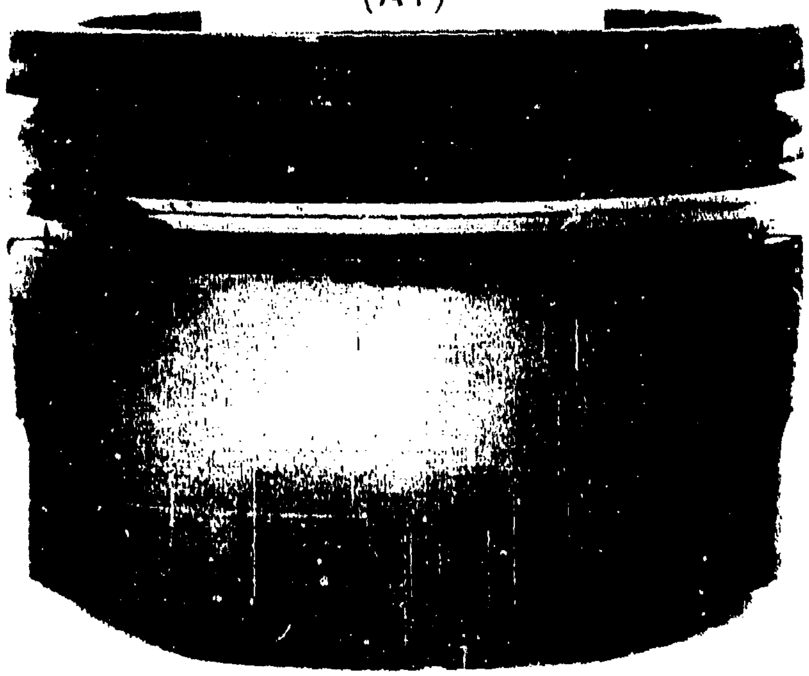
LAB SwRI	STAND NO. 1	TEST NO. 1-6	ENGINE
OIL CODES AL-19372-L			FUEL BATCH
DATE STARTED / /	DATE COMP 04/17/92	DATE RATED 05/01/92	RATER AB / TEST HRS 49
REFEREE INFORM. COMPANY	DATE RATED	RATER	RATING NO
STAND LAST REFERENCE	TMC OIL / DATE COMP	TEST NO / ENGINE NO	TEST TGF __ TLHC __ RAT. WDK __ AVBSOC __ / IND. TGF __ TLHC __ AVE. WDK __ AVBSOC __

RATING SUMMARY

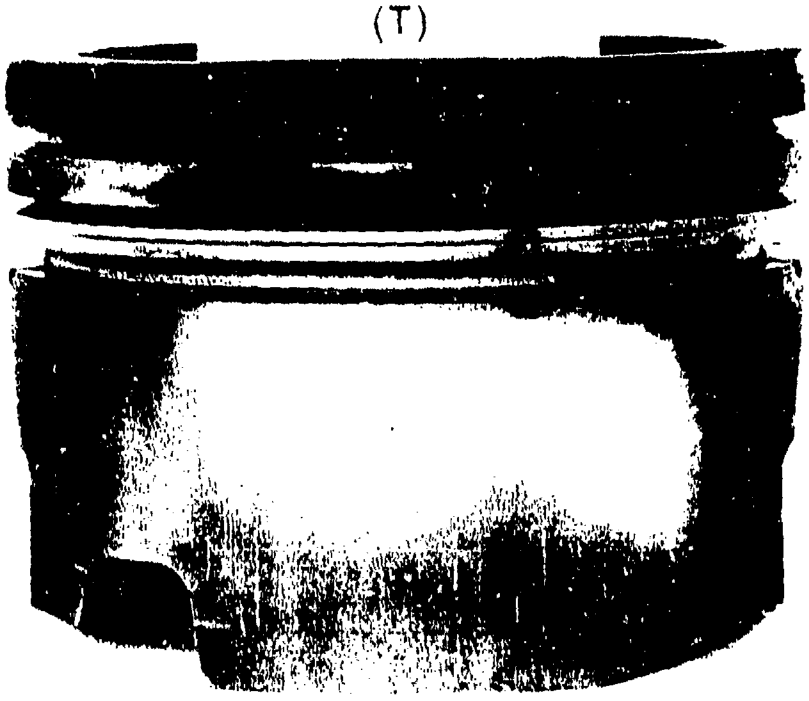
		GROOVES						LANDS						UPPER		UNDER		PIN BORES			
	dep	NO.1		NO.2		NO.3		NO.1		NO.2		NO.3		SKIRT		CROWN		FRONT		REAR	
	factor	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM
carbon	hc-1.0	4	4.00	40	40.00			5	5.00	50	50.00										
	mc-0.5	1	0.50																		
	lc-.25	65	16.25	42	10.50			95	23.75	36	9.00	9	2.25								
	total	70	20.750	82	50.500			100	28.750	86	59.000	9	2.250								
varnish	8-9			5	0.450					1	0.090	2	0.180			20	1.640				
	7-7.9			9	0.686					2	0.140										
	6-6.9																				
	5-5.9																				
	4-4.9											6	0.252			15	0.600				
	3-3.9									4	0.126			15	0.480						
	2-2.9			4	0.088	35	0.875			7	0.154	83	2.158	18	0.450	45	1.260				
	1-1.9					65	0.845							5	0.050	20	0.240	40	0.400	100	1.000
	0-0.9																	40	0.200		
	total			18	1.224	100	1.720			14	0.508	91	2.590	100	0.980	100	3.740	100	0.600	100	1.000
rating		20.750		51.724		1.720		28.750		59.508		4.840		0.980		3.740		0.600		1.000	
WDK loc fct		1.5		1.5		25		1		1		25		50		20		0		0	
wt rating		31.125		77.586		43.000		28.750		59.508		121.000		49.000		74.800		0.000		0.000	

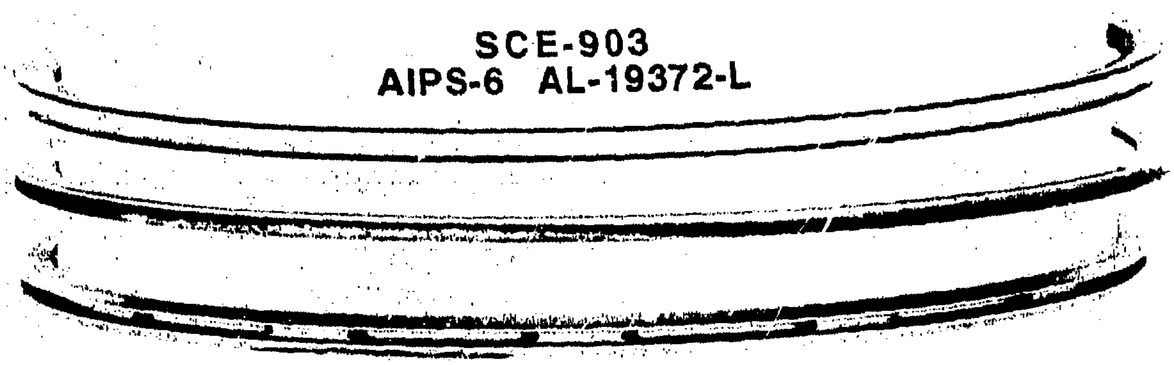
TGF%	INT GR FILL %	WDK	UN WEIGHTED DEP	T.L. HVY CRB %	T.L. FLAKED CRB %	ACC GR FILL %
41	53	484.8	173.6	5	0	

SCE-903
AIPS-6 AL-19372-L
(AT)

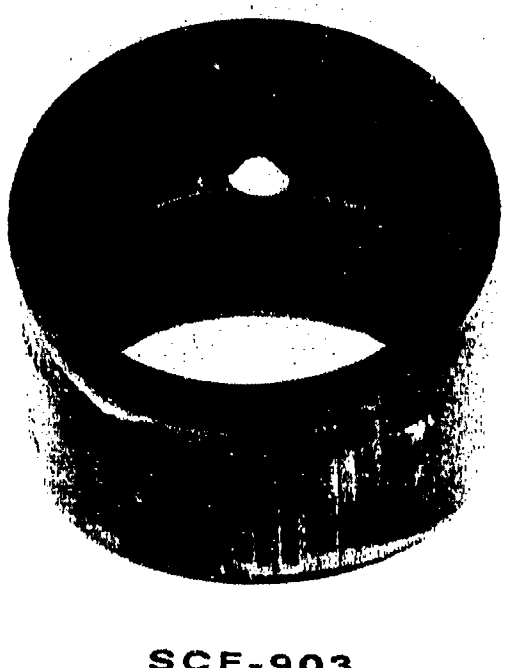


SCE-903
AIPS-6 AL-19372-L
(T)



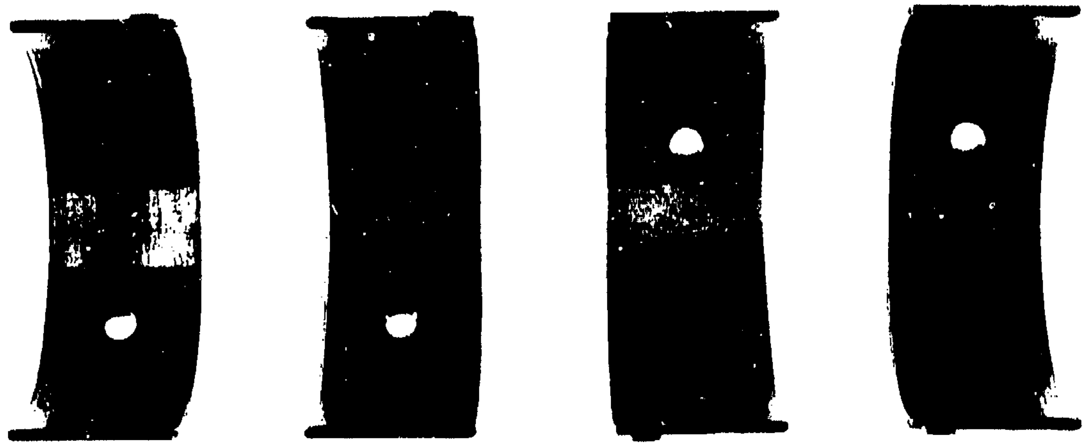

SCE-903
AIPS-6 AL-19372-L

SCE-903
AIPS-6 AL-19372-L
ACTIVE
TOP ROD BUSHING



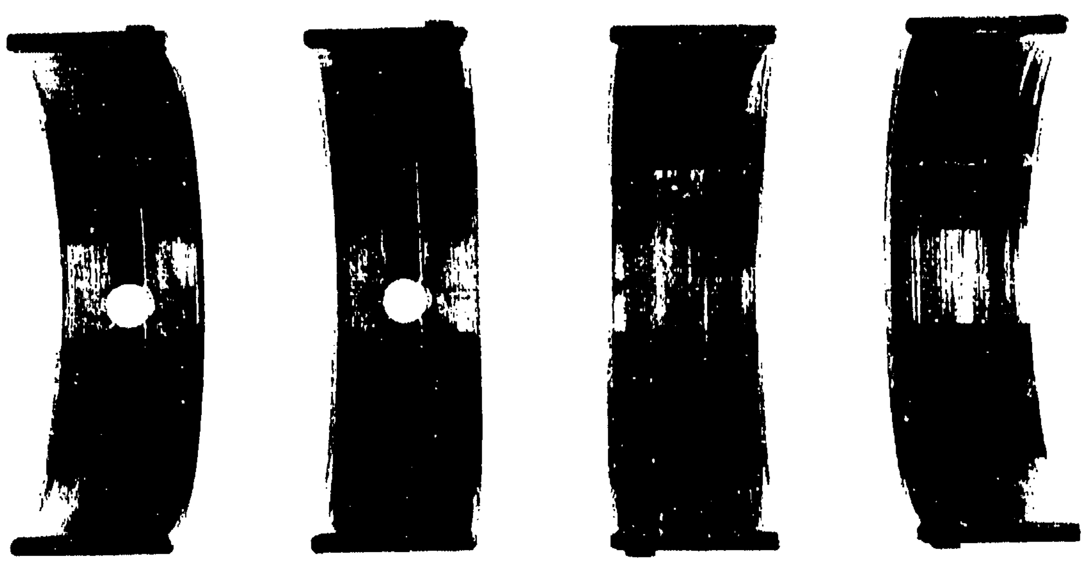
SCE-903
AIPS-6 AL-19372-L
ACTIVE
BOTTOM ROD BUSHING

TOP ACTIVE TOP SLIPPER BOTTOM ACTIVE BOTTOM SLIPPER



SCE-903
AIPS-6 AL-19372-L
ROD BEARINGS

TOP FRONT TOP REAR BOTTOM FRONT BOTTOM REAR



SCE-903
AIPS-6 AL-19372-L
MAIN BEARINGS

APPENDIX G

SCE-903 High-Temperature Lubricant Evaluation
Test No. AIPS-7

SCE-903 HIGH-TEMPERATURE LUBRICANT EVALUATION

Test Lubricant: AL-19902-L
Test Fuel: AL-19709-F
Test No.: AIPS-7
Date: 07 July 1992

Conducted For

U.S. Army Belvoir Research, Development and
Engineering Center
Logistics Equipment Directorate
Fort Belvoir, Virginia 22060-5606

By

Belvoir Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78228-0510

TEST SUMMARY

The SCE-903 is a vee-configured, two-cylinder engine, with one cylinder active and the second cylinder for balance. The SCE-903 engine is being used to screen candidate high-temperature lubricants for future low-heat rejection diesel engines. The target operating conditions are 340°F oil sump and 318°F oil gallery temperatures at 2600 rpm and a full-load air/fuel ratio of 28 to 1. The cylinder block is uncooled, and the cylinder head temperature is 250°F during engine operation.

The AIPS-7 test candidate was an experimental SAE XW-30 synthetic-based diesel engine oil. The lubricant evaluation lasted 75 hours, after which time the engine was disassembled for parts rating and inspection. The evaluation was terminated due to a 66-cSt viscosity measurement at 73 hours. The ratings revealed no cylinder liner scuffing, 2.0-percent bore polish, and no ring face distress. The compression ring and scraper ring were free, while the oil control ring was 20 percent cold stuck. All three rings had moderate to heavy groove and land deposits. The connecting rod piston pin bushing had 10 percent exposed copper on the top half and 90 percent heat fatigue with flaking and pitting on the bottom half. No significant bearing distress was evident, other than 5 percent flaking of the overlay on the bottom half of the active connecting rod bearing. The end of test lubricant inspection revealed oil degradation, with a 60 percent viscosity increase of the bulk oil, with higher viscosities in those areas in which the lubricant was able to accumulate and stratify, and a Total Acid Number increase. Used oil wear metal contents by ICP were 62 ppm of iron, 245 ppm of copper, and 170 ppm of lead. The high values of copper and lead are evidence of possible bearing corrosion.

SCE-903
OPERATING CONDITIONS SUMMARY

Date: 07/07/92 **Test No.: AIPS-7**

Lubricant: AL-19902-L **Fuel: AL-19709-F**

Test Hours: 75

	Mean	Standard Deviation
Engine Speed, rpm	2603	3.4
Torque, lb-ft	114	2.2
Observed Power, Bhp	57	1.1
Air/Fuel Ratio	29.63.5	
Fuel Rate, lb/hr	20.40.2	
Oil Flow, gpm	5.3	1.7
BSFC, lb/Bhp-hr	0.360	0.007
BMEP, psi	152.3	3.0
Oil Consumption Rate, lb/hr	0.136	
BSOC, lb/Bhp-hr	0.0024	
Temperatures, °F		
Oil Sump	333	4.3
Oil After Cooler	319	5.2
Coolant Into Head	242	1.2
Coolant Out of Head	248	4.3
Exhaust	1121	22.0
Inlet Air	220	0.8
Fuel Inlet	120	3.0
Cylinder Liner, All Positions	469	26.0
Thrust Top	483	10.0
Lower Mid	459	4.3
Bottom	434	4.8
Antithrust		
Top	500	9.1
P-Tube Oil	319	4.8
Main Bearing, Bottom	330	5.7
Main Bearing, Side	323	5.0
Pressures, psig		
Manifold	15.90.2	
Oil Gallery	16.51.4	
Exhaust Back	15.90.6	

OIL PROPERTIES

Test No.: AIPS-7
Lubricant: AL-19902-L

Lubricant Analysis	AL-19902-L
K. Vis, 40°C, cSt	75.33
K. Vis, 100°C, cSt	10.94
Viscosity Index	134
HTHS Vis at 150°C, cP, D 4683	4.49
Flash Point, °C	212
Pour Point, °C	-33
Sulfated Ash, wt%	1.43
TAN	2.5
TBN, D 4739	7.8
Gravity, °API	19.5
N, wt%, D 4629	0.189
TFOUT, minutes, D 4742	>300
Elements, ICP 8A, ppm	
Ca	2921
Mg	13
P	9136
Zn	939
Ag	1
Al	1
B	<1
Ba	<1
Cr	<1
Cu	<1
Fe	5
Na	16
Ni	<1
Pb	<1
Si	<1
Sn	<1
HPDSC, minutes, at 190°C	>300

OIL PROPERTIES

Test No.: AIPS-7
Lubricant: AL-19902-L

Properties	Test Hours 0	55	75
K. Vis, 40°C, cSt	75.33	ND*	306.6
K. Vis, 100°C, cSt	10.94	21.89	27.55
Viscosity Index	134	ND	120
HTHS Vis at 150°C, cP, D 4624	4.49	6.4	7.21
Flash Point, °C	213	ND	285
TAN	2.5	4.01	4.81
TBN, D 664	7.8	1.73	1.64
Sulfated Ash, wt%	1.43	ND	2.14
TFOUT, minutes, D 4742	>300	>300	>300
TGA Soot, wt%	NIL	0.8	0.9
Coag Insols, wt%			
Pentane B	ND	ND	1.00
Toluene B	ND	ND	0.66
HPDSC at 190°C, minutes	>300	ND	33
Elements, ICP, ppm			
Ca	2921	4249	4626
Mg	13	22	22
P	9136	4620	4155
Zn	939	1284	1326
Ag	1	2	<1
Al	1	6	10
B	<1	2	<1
Ba	<1	<1	<1
Cr	<1	<1	<1
Cu	<1	245	245
Fe	5	52	62
Na	16	22	23
Ni	<1	<1	7
Pb	<1	105	170
Si	<1	55	86
Sn	<1	17	18
K. Vis, 100°C, cSt			
Oil Pan Residue	ND	ND	59.30
Valve Deck Residue	ND	ND	38.93

* ND = Not Determined.

SCE-903
OIL CONSUMPTION AND WEAR METALS BY ICP

Lubricant: AL-19902-L

Test Time, hours	Total Oil Consumed		K. Vis, 100°C, cSt	Wear Metals, ppm, ICP		
	lb	kg		Fe	Cu	Pb
0	0.00	0.000	10.94	5	<1	<1
5	0.00	0.000	12.86	17	28	38
11	0.00	0.000	13.21	21	111	42
17	1.68	0.762	14.32	30	134	48
23	2.64	1.197	15.22	33	159	49
30	2.59	1.175	16.50	37	182	60
36	5.24	2.374	18.55	43	197	81
43	5.19	2.354	18.39	42	200	72
49	6.20	2.812	20.51	47	232	95
55	6.88	3.120	21.89	52	245	105
60	7.22	3.274	23.04	55	272	111
66	7.17	3.252	26.50	61	267	145
73	9.82	4.454	66.21	70	293	209
75	10.19	4.621	26.92	62	245	170
	lb/hr	kg/hr				
Average Oil Consumption Rate	0.136	0.0616				

* ND = Not Determined.

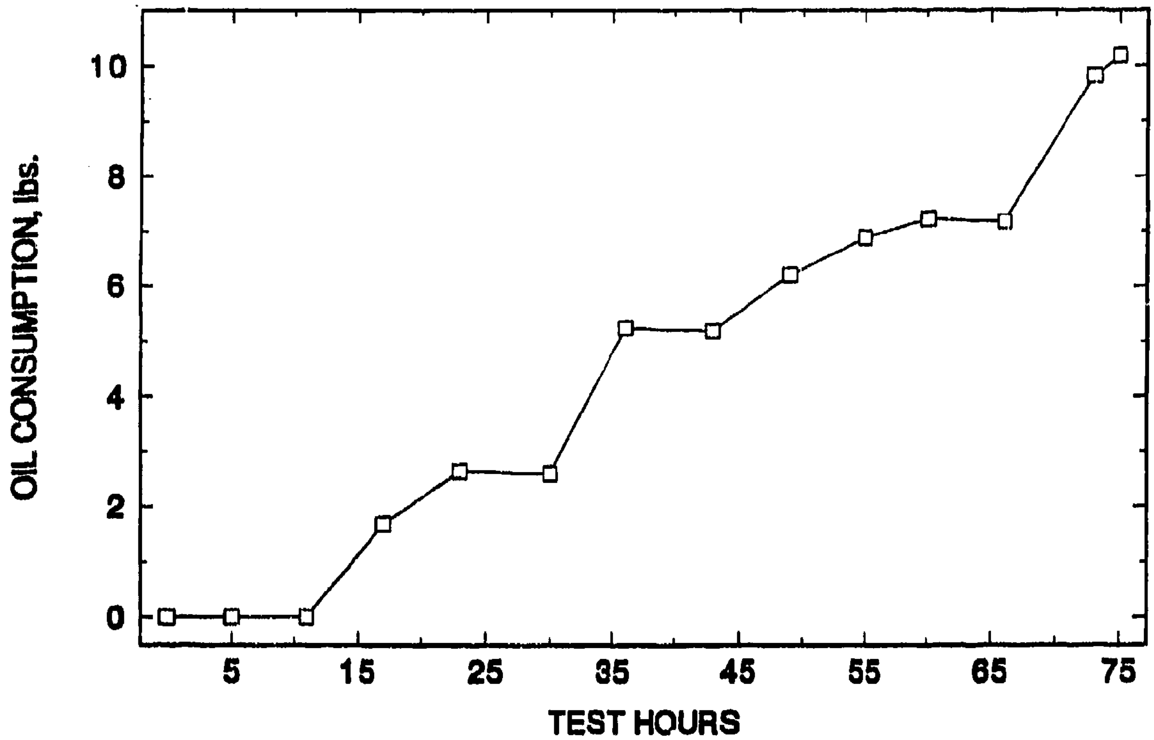


Figure G-1. **AIPS-7, AL-19902, oil consumption**

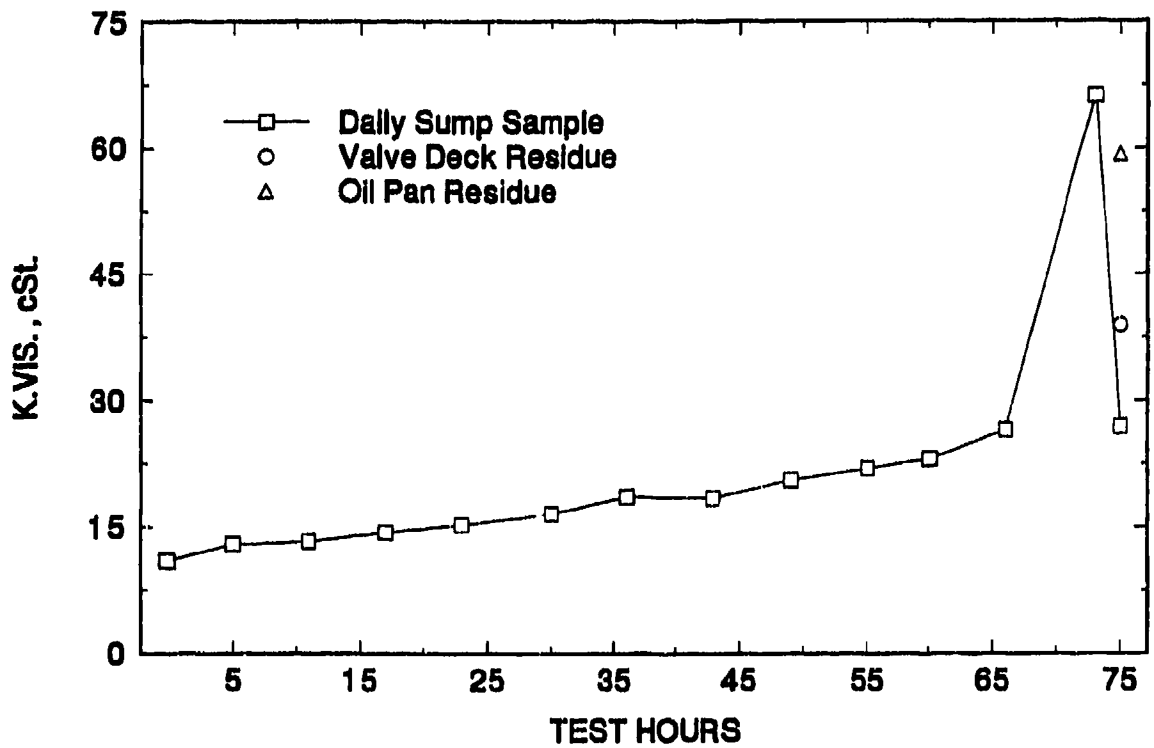


Figure G-2. **AIPS-7, AL-19902, K. vis., 100°C**

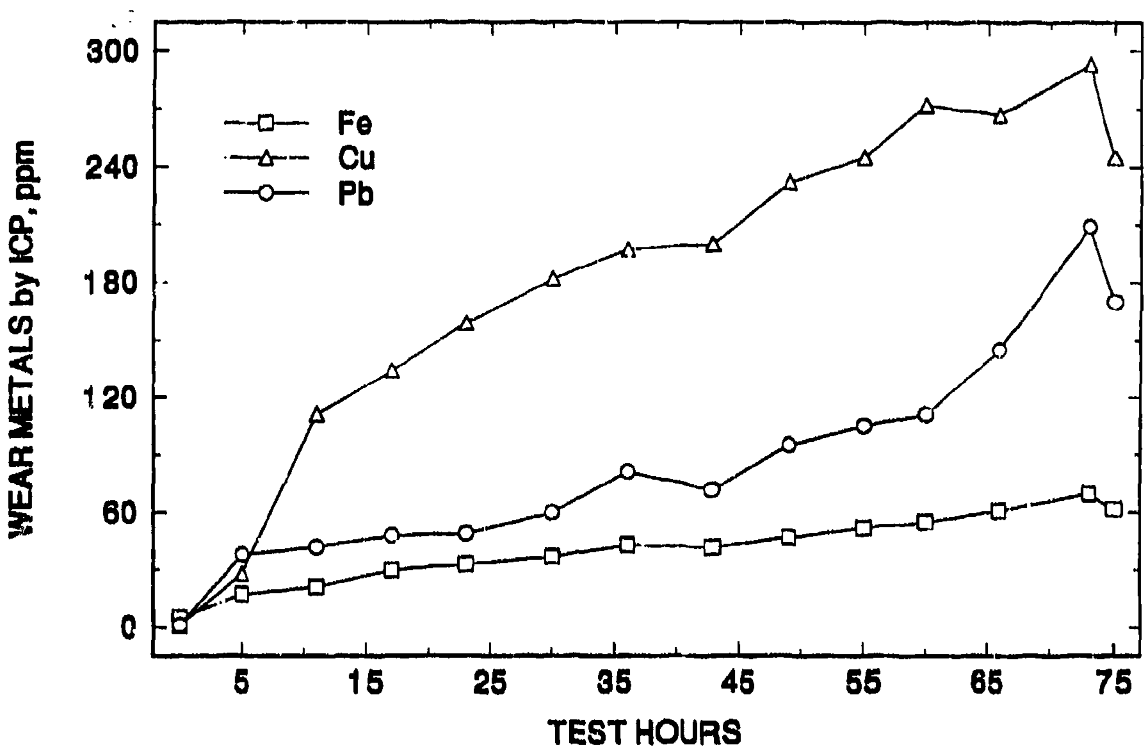


Figure G-3. AIPS-7, AL-19902, wear metals

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS*

Test No.: AIPS-7
Lubricant: AL-19902-L
Test Hours: 75

	Before T-AT	Before F-B	After T-AT	After F-B	Change T-AT	Change F-B	Specified Limits	
CYLINDER LINER**								
Inside Diameter								
Top	5.5005	5.5005	5.5007	5.5002	0.0002	-0.0003	5.4995 - 5.5010	Worn Limit: 5.505
Middle	5.5009	5.5003	5.5011	5.5002	0.0002	-0.0001	5.4995 - 5.5010	Worn Limit. 5.505
Bottom	5.5006	5.4995	5.5008	5.4992	0.0002	-0.0003	5.4995 - 5.5010	Worn Limit: 5.505
Taper	0.0001	0.0010	0.0001	0.0010	-0.000	0.0000	0.0015 Max.	
Out-of-Round								
Top	0.0000		0.0005		0.0005		0.0020 Max.	
Middle	0.0006		0.0009		0.0003		0.0020 Max.	
Bottom	0.0011		0.0016		0.0005		0.0020 Max.	
PISTON DIAMETER								
At Skirt	5.4895		5.4895		0.0000		5.4890 - 5.4900	
PISTON PIN-BORE								
Bore	1.7493		1.7500		0.0007		1.7485 - 1.7489	Worn Limit: 1.7500
Pin	1.7488		1.7488		0.0000		1.7488 - 1.7490	Worn Limit: 1.7478
Clearance	0.0005		0.0012		0.0007		-0.0005 - 0.0001	Worn Limit: 0.0022
PISTON-CYLINDER LINER CLEARANCE								
Minimum	0.0100		0.0097		-0.0003		0.0095 - 0.0120	Worn Limit: 0.0170
Maximum	0.0114		0.0116		0.0002		0.0095 - 0.0120	Worn Limit: 0.0170
PISTON RINGS								
Eng Gap								
Ring No. 1	0.0250		0.0240		-0.0010		0.0170 - 0.0270	
Ring No. 2	0.0250		0.0250		0.0000		0.0200 - 0.0300	
Ring No. 3	0.0240		0.0230		-0.0010		0.0100 - 0.0250	
Ring Proudness								
Ring No. 1								
Measurement Point								
1	-0.0110		0.0000		0.0110			
2	-0.0105		0.0050		0.0155			
3	-0.0130		0.0020		0.0150			
4	-0.0100		0.0020		0.0120			
Ring No. 2								
Measurement Point								
1	-0.0030		0.0120		0.0150			
2	-0.0030		0.0140		0.0170			
3	-0.0055		0.0130		0.0185			
4	-0.0030		0.0140		0.0170			

* Measurements are in inches. Change = After - Before.
** T-AT = Thrust-Antithrust.
F-B = Front-Back.

SCE-903
BEFORE AND AFTER TEST MEASUREMENTS* (CONT'D)

Test No.: AIPS-7
Lubricant: AL-19902-L
Test Hours: 75

	Before A	Before B	After A	After B	Change A	Change B	Specified Limits	
BEARINGS**								
Main Bearing Journals								
1	3.7482	3.7479	3.7482	3.7479	-0.0001	0.0000	3.7490 - 3.7500	Worn Limit: 3.7470 Max.
2	3.7489	3.7489	3.7486	3.7489	-0.0003	0.0000	3.7490 - 3.7500	Worn Limit: 3.7470 Max.
Connecting Rod Bearing Journals								
1	3.1241	3.1240	3.1241	3.1239	0.0000	-0.0001	3.1240 - 3.1250	Worn Limit: 3.1220
	F	BA	F	BA	F	BA		
Main Bearing Shells								
1	3.7558	3.7557	3.7556	3.7555	-0.0002	-0.0002		
2	3.7561	3.7558	3.7557	3.7553	-0.0004	-0.0005		
Connecting Rod Bearing Shells								
1	3.1291	3.1288	3.1298	3.1297	0.0007	0.0009		
	Min	Max	Min	Max	Min	Max		
Main Bearing Journal-Shell Clearances								
1	0.0075	0.0079	0.0074	0.0077	-0.0001	-0.0002	0.0015 - 0.0050	Worn Limit: 0.007
2	0.0069	0.0072	0.0064	0.0071	-0.0005	-0.0001	0.0015 - 0.0050	Worn Limit: 0.007
	Min	Max	Min	Max	Min	Max		
Connecting Rod Journal-Shell Clearances								
1	0.0047	0.0051	0.0056	0.0059	0.0009	0.0008	0.0015 - 0.0045	Worn Limit: 0.007
Main Bearing Weights, grams								
1 Upper	139.6519		139.6145		-0.0374			
1 Lower	159.7219		159.5869		-0.1350			
2 Upper	139.2799		139.2693		-0.0106			
2 Lower	160.0191		159.9445		-0.0746			
Connecting Rod Bearing Weight, grams								
1 Upper	83.7422		83.3883		-0.3539			
1 Lower	83.5570		83.5309		-0.0261			
	T	AT	T	AT	T	AT		
VALVES***								
Stem to Guide Clearance (Average)								
Intake	0.0022	0.0022	0.0027	0.0028	0.0005	0.0006	0.0015 - 0.0032	
Exhaus	0.0021	0.0019	0.0024	0.0022	0.0003	0.0003	0.0015 - 0.0032	
Recession								
Intake	-0.0142	-0.0148	-0.0184	-0.0195	-0.0042	-0.0047	-0.0050 - -0.0250	
Exhaus	-0.0715	-0.0709	-0.0773	-0.0742	-0.0058	-0.0033	-0.0520 - -0.0720	

* Measurements are in inches. Change = After - Before.
** A = Micrometer anvil parallel to weights; B = Micrometer anvil perpendicular to weights; F = Front; BA = Back.
*** T = Thrust; AT = Antithrust.

SCE-903
POST-TEST RATINGS OF ENGINE DEPOSITS AND CONDITIONS

Test No.: AIPS-7
Lubricant: AL-19902-L
Test Hours: 75

PISTON				
Skirt Rating	Polished areas normal, with few vertical line cuttings.			
Top Groove Fill, %	57			
Second Groove Fill, %	76			
WDK Weighted Total Deposits	1875.5			
RINGS				
Ring Freedom				
No. 1	Free			
No. 2	Free			
No. 3	20% Cold Stuck			
Ring Distress Demerits	Some discoloration, some carbon deposits, no apparent distress.			
LINER				
	T*	AT	Average	
Scuffing, %	0	0	0.0	
Bore Polish, %	1	3	2.0	
Distress	0	0	0.0	
VALVES				
Head				
Intake	100% Light Carbon			
Exhaust	100% Light Carbon			
Tulip				
Intake	T and AT - 0.25% Carbon			
Exhaust	T and AT - 0.5% Carbon			
Face				
Intake	T and AT - Trace of carbon and ash embedded			
Exhaust	T and AT - Light amount of carbon and ash embedded			
Stem				
Intake	T - 20% No. 6 Lacquer, AT - Clean			
Exhaust	T - 10% No. 9 Lacquer and 15% No. 3 Lacquer AT - 20% No. 9 and 10% No. 7 and 20% No. 4 and 25% No. 2 Lacquer			

	Top	Bottom
BEARING DISTRESS,		
% Exposed Cu		
Front Main	0, Few Debris Scratches	0, Few Debris Scratches
Rear Main	0, Few Debris Scratches	0, Few Debris Scratches
Connecting Rod		
Active	0, Few Debris Scratches	0, Few Debris Scratches 5% Flaking of Overlay
Slipper	0, Few Debris Scratches	0, Few Debris Scratches
ROD BUSHING, % Wear Band		
Active	10% Exposed Copper	90% Heat Fatigued, Sings of Flaking and Pitting
Slipper	0	0

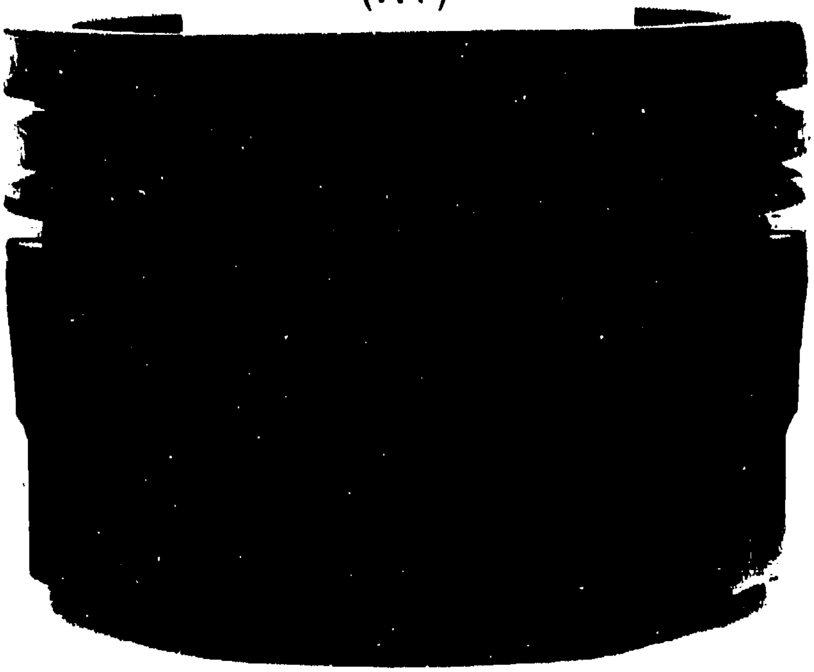
LAB SwRI	STAND NO. 1	TEST NO. 1-07	ENGINE	
OIL CODES AL-19902-L	FUEL CODE AL-19709-F		FUEL BATCH	
DATE STARTED / /	DATE COMP 07/07/92	DATE RATED 07/23/92	RATER AB	TEST HRS 75
REFEREE INFORM. [illegible]				
STAND LAST REFERENCE	TMC OIL / DATE COMP	TEST NO / ENGINE NO	TEST TGF ___ TLHC ___ / RAT. WDK ___ AVBSOC ___	IND. TGF ___ TLHC ___ / AVE. WDK ___ AVBSOC ___

RATING SUMMARY

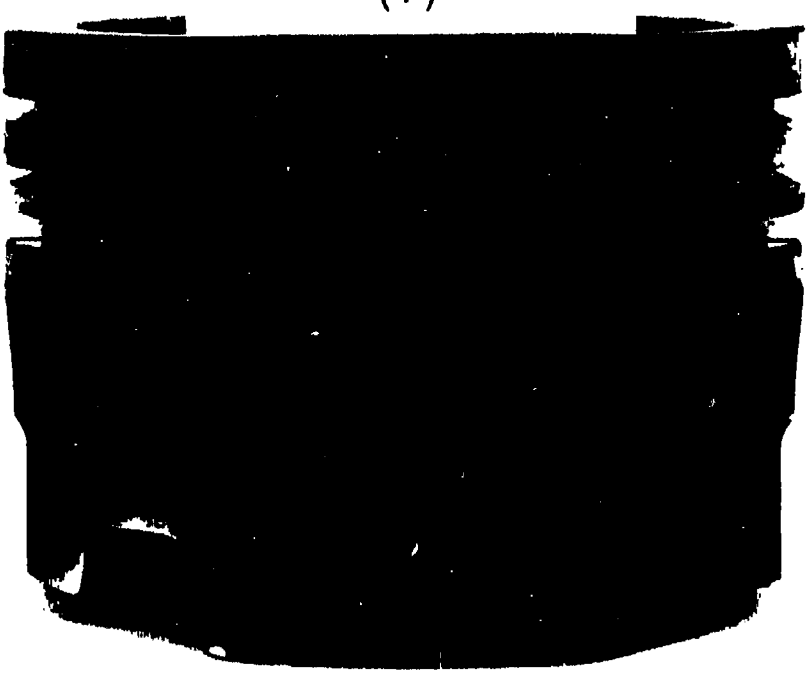
		GROOVES						LANDS						UPPER SKIRT		UNDER CROWN		PIN BORES			
		NO.1		NO.2		NO.3		NO.1		NO.2		NO.3						FRONT		REAR	
	dep factor	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM	A%	DEM
c a	hc-1.0	51	51.00	55	55.00			58	58.00	73	73.00	14	14.00								
r b	mc-0.5	4	2.00	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]								
o	lc-.25	45	11.25	45	11.25			42	10.50	7	1.75	86	21.50								
n	total	100	66.250	100	66.250			100	68.500	80	74.75[illegible]	100	35.500								
	8-9					80	7.200			12	1.000			45	4.050	100	9.000				
v	7-7.9					10	0.700							15	1.050			10	0.740	3	0.210
a	6-6.9																				
r	5-5.9									2	0.100										
n	4-4.9					5	0.225											10	0.420		
i	3-3.9																	10	0.300	22	0.660
s	2-2.9					5	0.135							5	0.125						
h	1-1.9									6	0.072							70	0.840	75	0.900
	0-0.9																				
	total					100	8.260			20	1.252			100	5.225	100	9.000	100	2.300	100	1.770
	rating	64.250		66.250		8.260		68.500		76.002		35.500		5.225		9.000		2.300		1.770	
	WDK loc fct	1.5		1.5		25		1		1		25		50		20		0		0	
	wt rating	96.375		99.375		206.500		68.500		76.002		887.500		261.250		180.000		0.000		0.000	

TGF%	INT GR FILL %	WDK	UN WEIGHTED DEP	T.L. HVY CRB %	T.L. FLAKED CRB %	ACC GR FILL %
57	76	1875.5	337.1	58	0	

SCE-903
AIPS-7 AL-19902-L
(AT)



SCE-903
AIPS-7 AL-19902-L
(T)



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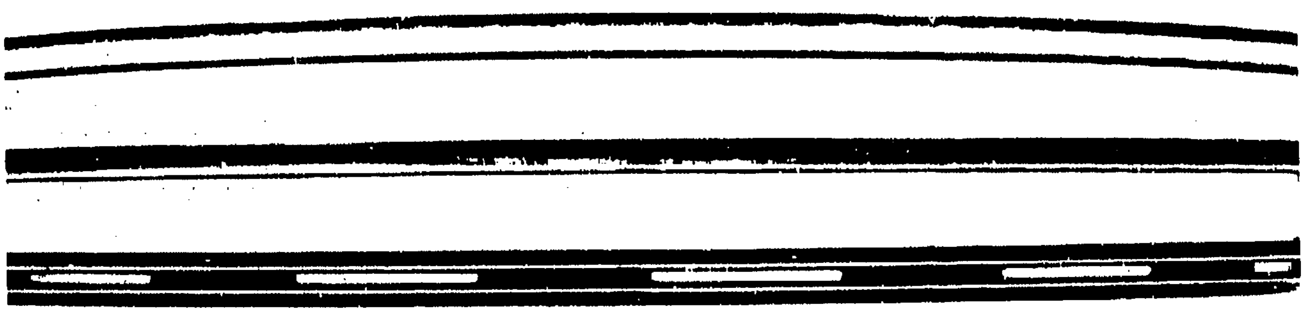
AIPS-7 AL-19902-L



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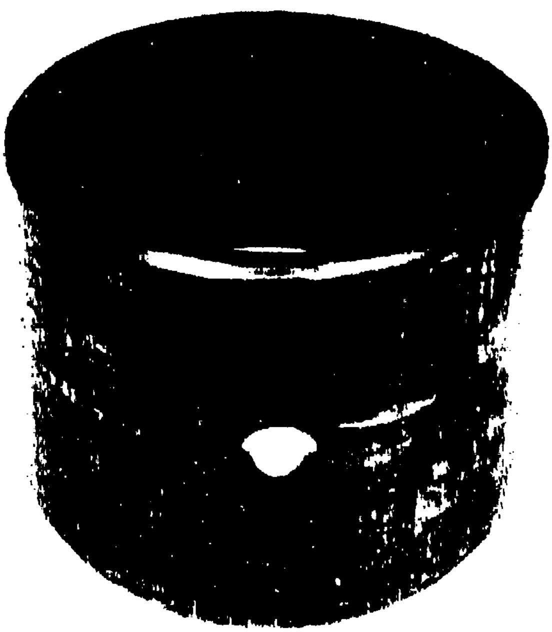
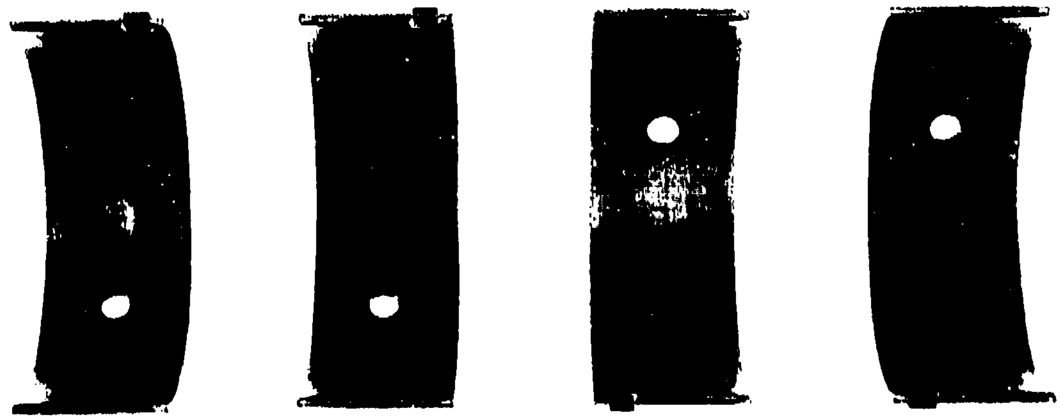
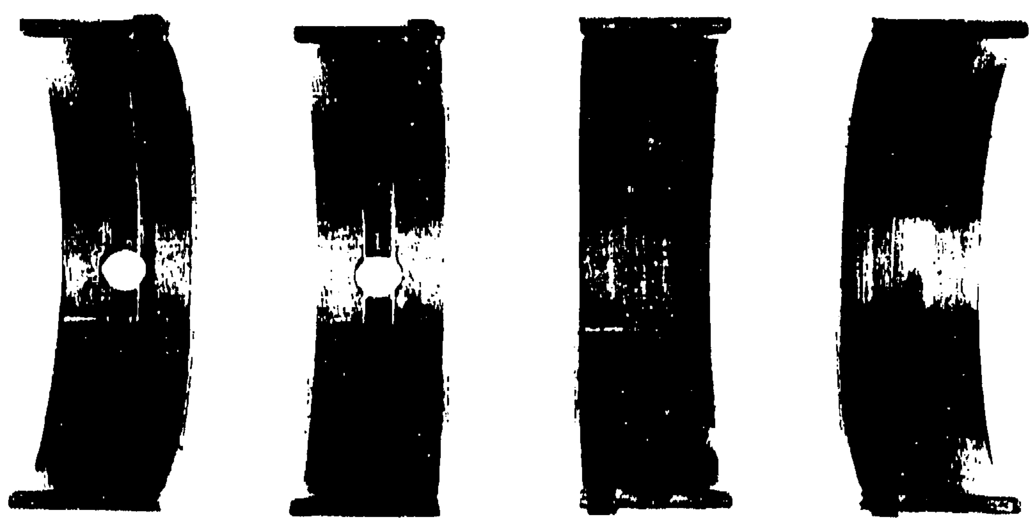
AIPS-7 AL-19902-L
BOTTOM/ROD BUSHING

SCE-903
AIPS-7 AL-19902-L
TOP/ROD BUSHING





SCE-903
AIPS-7 AL-19902-L
ROD BEARINGS



SCE-903
AIPS-7 AL-19902-L
MAIN BEARINGS

APPENDIX H

Dimensional Measurements on Worn Engine Components

Previously, full-scale engine tests were performed on a Cummins SCE-903 engine with each of the oils. The engine test parameters and conditions are detailed in TABLE H-1. The changes in dimension of various wear-prone engine components during the test are detailed in TABLE H-2. Only Oil D achieved the required 200-hour test duration. The tests with the remaining oils were terminated prior to the planned test duration due to viscosity increase or other technical problems. No test measurements are available for Test A-1 that was performed with Oil A. The engine test with Oil E was terminated after 100 hours due to severe journal bearing wear.

TABLE H-1. Main Characteristics of Cummins SCE-903 Test Engine

Bore, mm (in)	139.7 (5.5)
Stroke, mm (in)	120.7 (4.75)
Displacement, cc (in^3)	1,850 (112.9)
Compression Ratio	15.5 to 1
Piston Mass, kg (lb)	3.30 (7.29)
Connecting Rod Mass, kg (lb)	3.13 (6.9)
Speed, rpm	2,600
Power, Hp	68.8
Approximate Sump Temp., °C (°F)	166 (330)
TRR Temp., °C (°F)	234 (453)

TABLE H-2. Change in Dimension of Selected Engine Components (in)

	Test Number					
	A-2	A-3	A-4	A-5	A-6	A-7
Lubricant	Oil B	Oil C	Oil D	Oil E	Oil B	Oil F
Test Hours	40	90	200	100	49	75
Cylinder Liner						
ID Average	–0.0005	0.0002	0.0005	0.0002	0.0002	–0.0000
Taper	–0.0004	0.0004	–0.0006	0.0004	–0.0004	0.0000
Out-of-Round	–0.0002	0.0005	–0.0002	0.0004	–0.0001	0.0004
Piston Diameter						
Skirt	0.0006	0.0000	0.0000	0.0000	–0.0003	0.0000
Piston Liner						
Clearance	–0.0009	0.0002	0.0009	0.0005	0.0007	–0.0000
Piston Pin-Bore						
Clearance	0.0011	0.0010	0.0015	0.0012	0.0006	0.0007
Ring End-Gap						
Ring #1	0.0020	0.0020	–0.0010	0.0000	0.0020	–0.0010
Ring #2	0.0040	0.0030	0.0030	0.0000	0.0020	0.0000
Ring #3	0.0010	0.0030	0.0000	0.0010	0.0020	–0.0010
Bearing Journals						
Main #1	–0.0003	–0.0003	–0.0001	0.0000	0.0000	–0.0001
Main #2	0.0000	0.0000	–0.0001	0.0000	0.0000	–0.0002
Connecting Rod	0.0000	–0.0003	0.0000	0.0000	–0.0001	–0.0001
Bearing Shells						
Main #1	–0.0001	–0.0001	–0.0004	0.0006	–0.0001	–0.0002
Main #2	–0.0003	–0.0002	0.0001	0.0008	–0.0003	–0.0005
Connecting Rod	0.0002	0.0001	0.0009	0.0012	–0.0002	0.0008
Journal-Shell Clearance						
Main #1	0.0002	0.0002	–0.0003	0.0006	–0.0001	–0.0002
Main #2	–0.0003	–0.0002	0.0002	0.0008	–0.0003	–0.0003
Connecting Rod	0.0002	0.0004	0.0009	0.0012	–0.0001	0.0009
Bearing Weight Loss, grams						
Main #1, Upper	0.0221	0.0403	0.0363	1.0355	0.0279	0.0374
Main #1, Lower	0.0381	0.1432	0.1217	1.3185	0.0416	0.1350
Main #2, Upper	0.0128	0.0278	0.0212	0.9839	0.0185	0.0106
Main #2, Lower	0.0095	0.0163	0.0354	1.4297	0.0396	0.0746

TABLE H-2. Change in Dimension of Selected Engine Components (in) (Cont'd)

	Test Number					
	A-2	A-3	A-4	A-5	A-6	A-7
Connecting Rod, Upper	0.0549	0.1860	0.2858	0.9277	0.0632	0.3539
Connecting Rod, Lower	0.0093	0.0142	0.0530	0.8019	0.0132	0.0261
Valve Stem-to-Guide Clearance, average						
Intake	0.0004	0.0006	0.0002	0.0002	-0.0002	0.0006
Exhaust	0.0003	0.0005	0.0001	0.0010	0.0000	0.0003
Valve Recession, average						
Intake	-0.0044	-0.0007	-0.0026	-0.0041	-0.0013	-0.0045
Exhaust	-0.0015	-0.0005	-0.0053	-0.0076	-0.0035	-0.0046

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