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Full-Scale Engine Endurance Test of Swift Enterprises UL102 Fuel

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July 2010

Final Report

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16. Abstract

Researchers at the Federal Aviation Administration William J. Hughes Technical Center Aviation Fuel and Engine Test Facility (AFETF) entered a Cooperative Research and Development Agreement (CRDA) with Swift Enterprises. Swift has plans to produce a high-octane, nonoxygenated, binary fuel from biomass for spark ignition, piston aircraft engines. Due to the binary nature of the fuel and the use of heavy aromatics, the Swift fuel will require engine and airframe testing to determine the performance effects of noncompliance with the current aviation gasoline specification properties regarding distillation slope. This research was performed on a Swift binary blend, manufactured in a refinery and not in bio-process, to determine whether there were any initial major engine performance-related findings that would prevent further research into the use of a Swift binary blend of these components. It is noted that trace materials found in this Swift binary blend may differ from those that arise from manufacturing of the components from a biomass fermentation process and will probably differ depending on sugar source and bio-enzymes selected. Trace materials, even at the 100-ppm level, can impact engine performance.

A Lycoming IO540-K, six-cylinder, 300-horsepower, piston aircraft engine was tested using the Swift fuel for a total of 150 hours. The remanufactured engine was torn down and the critical, high-stress components were measured by Textron Lycoming and shipped to the AFETF. The engine was broken in and operated solely on the Swift binary blend at the AFETF. After of the endurance test was completed, the engine was sent back to Textron Lycoming for teardown, inspection, and remeasurement. The tests followed the Title 14 Code of Federal Regulation 33.49 endurance test block power setting procedures. The Swift binary blend weighed approximately 1 pound per gallon more than 100 low-lead (100LL) and contained 96.7% of the specific energy content, thus on a volumetric basis, the Swift fuel contained 13% more energy per gallon than 100LL. The Swift binary blend did not meet the current aviation gasoline specification ASTM D 910 at the 50%, 90%, or end distillation points. The endurance test results indicated that the engine experienced normal levels of engine wear during the 150-hour test, and combustion, oil, and fuel deposits were light. Marks in the secondary fuel pump diaphragm were discovered, and the fuel pump pressure remained within specification limits throughout the test. It was difficult to start the engine the mornings after the engine was left to sit overnight. When the engine was warm, it started immediately. The effects on aircraft structure or pilot operating handbooks from the additional fuel weight and fuel aging effects were beyond the scope of this research and were not addressed. Previous AFETF research addressed the detonation and power performance of the Swift binary blend. It is recommended that Swift perform additional engine, airframe, and fuel pump rig tests using a fuel made in their biomass process and perform the engine tests using a straight weight mineral oil.

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LIST OF ACRONYMS

100LL	100 low-lead
AFETF	Aviation Fuel and Engine Test Facility
CRDA	Cooperative Research and Development Agreement
CFR	Code of Federal Regulations
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FID	Flame ionization detection
GA	General aviation
GC	Gas chromatography
HP	Horsepower
inHg	Inches of mercury
MAP	Manifold absolute pressure
MON	Motor octane number per ASTM D 2700
NAAQS	National Ambient Air Quality Standard
ng/m^3	Nanograms per cubic meter
rpm	Revolutions per minute
RVP	Reid Vapor Pressure

EXECUTIVE SUMMARY

Researchers at the Federal Aviation Administration (FAA) William J. Hughes Technical Center Aviation Fuel and Engine Test Facility (AFETF) have considerable experience performing engine tests on unleaded aviation fuels. In 2008, the AFETF entered a Cooperative Research and Development Agreement with Swift Enterprises, Ltd. Swift has plans to produce a high-octane, nonoxygenated, binary fuel from biomass fermentation process for spark ignition, piston aircraft engines. Due to the binary nature of the fuel and the use of heavy aromatics, the Swift fuel requires further engine and airframe testing to determine the performance effects of noncompliance with the current aviation gasoline specification properties regarding distillation slope. This research was performed on a Swift binary blend, manufactured in a refinery, not in a bioprocess, to determine whether there were any initial major engine performance issues that would prevent further research into the use of a Swift binary blend of these components. It was noted that trace materials found in this Swift binary blend may differ from those that arise from manufacturing the components from a biomass fermentation process and may vary depending on sugar source and bio-enzymes selected. Trace materials, even at the 100-ppm level, can have an effect on engine performance and safety. This potential variation was not addressed by this research.

This work is a follow-on to the detonation and power performance tests that were performed at the AFETF on Swift's binary blend. The primary goal of these tests was to determine if using the suggested high-aromatic hydrocarbon component would result in excessive combustion chamber deposits, spark plug fouling, excessive valve seat wear, or materials compatibility issues.

Researchers at the AFETF completed a 150-hour endurance test on a Swift binary blend supplied by Swift Enterprises that was formulated in accordance with a proposed Swift binary blend ASTM specification and consisted of approximately 85% aromatic hydrocarbon (mesitylene or 1,3,5 trimethyl benzene) and 15% pentane isomerate added to achieve vapor pressure. Swift Enterprises supplied 4500 gallons of the Swift binary blend, which was stored in a tanker truck on-site during the tests.

The tests were performed in coordination with engineers at the Textron Lycoming Company, and a remanufactured six-cylinder, 300-horsepower, Lycoming IO540-K model engine was used. Lycoming researchers performed initial engine measurements and reassembled the engine for testing at the AFETF. The Lycoming engine was broken in on the supplied Swift binary blend, and all operations were performed with this fuel. At the completion of the tests, the engine was sent back to Lycoming to be dissembled, inspected, and remeasured.

There was no indication of excessive wear on any of the high-contact, high-stress parts of the engine, and the engine oil analyses showed minimal fuel dilution. There was no evidence of excess fuel nozzle deposits or fuel maldistribution. Cylinder combustion deposits, including spark plugs, valves, and piston face deposits, were light. Varnish and sludge buildup were light. The fuel pump secondary diaphragm showed stretch marks. The fuel pump outlet pressure slowly degraded but remained within specification at the end of the test. Starting difficulty was experienced in the mornings after the engine was left to sit overnight. It is recommended that

fuel pump diaphragm rig and soak tests be performed with a high-content mesitylene blend. Starting with a warm engine was immediate.

This research did not address fit-for-purpose testing that Swift will need to do on their binary blend made from biomass, nor did it address research requirements requested by voluntary consensus standards bodies for an industry-recognized specification. The FAA does not approve fuels, and this testing should not, in any way, be misinterpreted as FAA endorsement of a fuel. Further, this testing may not conform to Standard Practice for Evaluating the Compatibility of Proposed Fuel or Additives With Aviation Otto Cycle Fuels and Aircraft Fuel System Materials currently being developed by ASTM International.

It is recommended that further testing be done by Swift Enterprises on their blend made from their biomass process and conforming to an approved commercial ASTM fuel specification. It is also recommended that further testing be done in conformance to the aviation gasoline approval protocol currently being developed by the ASTM International voluntary consensus standards body.

1. INTRODUCTION.

1.1 PURPOSE.

The endurance performance of a high-octane, unleaded UL102 fuel was tested over a 150-hour period in a naturally aspirated, fuel-injected Lycoming IO540-K engine. The endurance test used the six-cylinder Lycoming IO540-K model engine, which had 300 horsepower, 8.7:1 compression ratio. (The IO in the engine model description refers to fuel injection and opposed cylinder and the numerical value refers to the cylinder displacement.) The purpose of this full-scale engine endurance test was to determine if there were any major engine performance issues that arose with the use of the particular aromatic hydrocarbon-content fuel that would prevent Swift from further pursuing their biomass fuel. Issues of oil dilution, nozzle and fuel system deposits, engine wear, oil system sludge buildup, combustion and valve deposits, materials compatibility, and start-ability were reviewed.

1.2 BACKGROUND.

Researchers at the Federal Aviation Administration (FAA) Aviation Fuel and Engine Test Facility (AFETF) at the FAA William J. Hughes Technical Center have been providing independent, full-scale engine test data on unleaded fuels to facilitate the development of a safe, high-octane, unleaded aviation gasoline for spark ignition, piston aircraft engines. The AFETF works closely with FAA certification officials, the Coordinating Research Council Unleaded Aviation Gasoline Committee, the ASTM International J0.2 subcommittee on aviation gasoline, and the General Aviation Stakeholders Coalition Future Aviation Gasoline Strategy and Transition Plan.

Federal Clean Air Act Amendments prohibit the sale of leaded fuels for on-road vehicles. As a result, the general aviation (GA) community is the largest domestic consumer of leaded fuels and, according to the Environmental Protection Agency (EPA), GA is responsible for 45% of the ambient air lead inventory. The Bluewater Network filed a petition with the EPA that called for either a complete ban on leaded aviation fuels or a commission to study of the effects of leaded aviation fuel on public health. This petition has significantly increased domestic environmental pressures against the use of leaded aviation fuels. An Advanced Notice of Proposed Rule Making was released on April 28, 2010 by the EPA in response to the Bluewater Network petition. In a related action, the EPA recently reduced the National Ambient Air Quality Standard (NAAQS) for lead by 90%, from 1500 nanograms per cubic meter of air (ng/m^3) to 150 ng/m^3. This significant reduction in the lead NAAQS resulted in the requirement for source-oriented monitoring by individual states to be operational by January 1, 2010.

Researchers at the AFETF entered into a Cooperative Research and Development Agreement (CRDA) with Swift Enterprises, Ltd. of Indiana. Under the CRDA, Swift Enterprises supplied 4500 gallons of a high-octane, Swift binary blend. The Swift binary blend was petroleum-based and not made in their biomass process. Swift Enterprises requested that the AFETF perform initial engine endurance tests on their Swift binary blend to determine whether there were any major engine performance-related findings that would prevent their continued pursuit of this endeavor.

The researchers at the AFETF have previously performed detonation and power performance tests on a Swift binary blend in both a turbocharged Lycoming TIO540-J2BD and a naturally aspirated Lycoming IO540-K engine. The results were published in an FAA report [1].

A 150-hour engine endurance test, following the Title 14 Code of Federal Regulations (CFR) 33.47 150-hour block test requirements, was performed. Testing was performed in coordination with engineers at Textron Lycoming. Lycoming supplied a remanufactured IO540-K engine and performed the initial teardown measurements. The engine was broken in and operated solely on the Swift-supplied fuel at the AFETF. The tests were performed to provide a cursory review of issues of wear, performance, materials compatibility, deposit formation, start-ability, and other issues. The majority of the tests were performed at full-rated power and engine speed under maximum cylinder head and oil temperatures.

1.3 RELATED DOCUMENTS.

- ASTM D 909, "Standard Test Method for Knock Characteristics of Motor and Aviation Fuels by the Supercharge Method."
- ASTM D 910, "Standard Specification for Aviation Gasoline."
- ASTM D 2700, "Standard Test Method for Knock Characteristics of Motor and Aviation Fuels by the Motor Method."
- ASTM D 6424, "Standard Practice for Octane Rating Naturally Aspirated Spark Ignition Aircraft Engines."
- ASTM D 445, "Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)."
- ASTM D 664, "Standard Test Method for Acid Number of Petroleum Products by Potentiometric Titration."
- ASTM D 3524, Standard Test Method for Diesel Fuel Diluent in Used Diesel Engine Oils by Gas Chromatography.
- FAA Advisory Circular 20-24B, "Qualification of Fuels, Lubricants, and Additives for Aircraft Engines."
- FAA Advisory Circular 33-49, "Endurance Testing in Reciprocating Aircraft Engines."
- FAA Report DOT/FAA/AR-04/25, "Full-Scale Engine Knock Tests of 30 Unleaded, High-Octane Blends," D. Atwood and A. Ivanov.
- FAA Report DOT/FAA/AR-99/70, "Evaluation of Reciprocating Aircraft Engines With Unleaded Fuels," D. Atwood and J. Canizales.

2. DISCUSSION.

Textron Lycoming provided a remanufactured Lycoming IO540-K engine and a series of measurements of the high-contact, high-stress engine components were taken. The engine was then shipped to the AFETF for testing (see figure 1).

Figure 1. IO540-K Engine Installation at the AFETF

Fuel samples were sent to an independent laboratory for comparison against the current ASTM D 910 leaded aviation gasoline specification, as shown in table 1. The first column lists the ASTM test method, and the last column on the right lists the current specification limits for the leaded aviation gasoline D 910 for 100 low-lead (100LL). The items in red indicate differences with the current ASTM D 910 specification. The Swift binary blend had a specific energy content that was 3.7% lower than the current 100LL specification. The potential consequences of reduced energy content are reduced range and increased fuel consumption. However, due to the much higher mass density of the fuel, the volumetric fuel consumption is lower. Therefore, in the Swift binary blend case, the 3.7% reduction in specific energy content may not be as significant. Effects of increased fuel weight, if any, on the structural integrity of the airframe and on potential revisions to pilot operating handbook performance curves were beyond the scope of this research.

Table 1. Swift Binary Blend Component Specification

ASTM Test	Description	Value	Current ASTM D 910 Specification for 100LL
D 2700	Motor octane number	102.2	99.6 minimum
	(BRE/30.1in/300F)		
D 909	ASTM Supercharge rating, mL TEL/gal	2.13	
	Performance number	139.6	130.0 minimum
D 5059	Lead, mL/L	<0.01	0.53 maximum
D 2392	Color	TBD	Blue
D 4052	Density, 15°C, kg/m^3	810.3	Reported
D 5191	Vapor pressure, 38°C, kPa	48.5	38.0-49.0
D 2386	Freezing point, °C	-64.5	-58 maximum
D 2622	Sulfur, mass %	<0.0001	0.05 maximum
D 4809	Net heat of combustion, MJ/kg	41.9 (3.7% from spec)	43.5 minimum
D 130	Copper corrosion, 2 hrs., 100°C	1b	1 maximum
D 873	Potential residue, 5 hrs., 100°C		
	Precipitate, mg/100 mL	<0.1	3 maximum
	Potential gum, mg/100 mL	2	6 maximum
D 1094	Water reaction		
	Interface rating	1	-
	Separation rating	1	-
	Volume change, mL	0	±2 maximum
D 86	Distillation, % evaporated, °C		
	IBP	28.0	Report
	10%	48.5	75 maximum
	40%	161.0	75 minimum
	50%	161.0	105 maximum
	90%	161.5	135 maximum
	End	175.0	170 maximum
	Sum of 10+50%	209.5	135 minimum
	Recovery	98.5	97 minimum
	Residue	0.5	1.5 maximum
	Loss	1.0	1.5 maximum

Note: Values in red deviate from current ASTM D 910 specification for 100LL.

MJ = Mega Joules
kg/m^3 = Kilogram per cubic meter
kPa = kilopascal
mL = milliliter
BRE = Bracketing equilibrium method
TEL = Tetraethyl lead

The fuel also did not match the distillation curve points at the T50, T90, and end point. A high-aromatic content unleaded fuel is not likely to meet the points at the high end of the distillation curve developed for a conventional 100LL. The aromatic, high-octane components are typically of high mass density and high boiling point. Previous FAA tests, in conjunction with the

Coordinating Research Council showed equivalent unleaded fuel detonation performance to the leaded 100LL was only attainable with an addition of 6% to 10% volume-to-volume aromatic amine in aviation alkylate or with a high-aromatic hydrocarbon-content fuel [2]. It is unlikely that such a fuel will meet the distillation curve parameters that have evolved for the current performance of an aviation alkylate with lead.

The purpose of this full-scale engine endurance test was to determine if there were any major engine performance issues that arose with the use of the particular aromatic hydrocarbon-content fuel that would prevent Swift from further pursuing their biomass fuel. Issues of oil dilution, nozzle and fuel system deposits, engine wear, oil system sludge buildup, combustion and valve deposits, materials compatibility, and start-ability were reviewed.

The potential effects of having a high 90% and end distillation point fuel includes excessive combustion chamber, valve, and spark plug deposits from incomplete combustion; excessive oil dilution; fuel maldistribution; fuel system deposits; heavy intake deposits; and cold starting difficulty. Swift has addressed some of these by using an aromatic hydrocarbon, mesitylene, which has strong solvent properties that may act to counter many of the above effects.

The Swift binary blend had an ASTM D 2700 motor octane number (MON) of 102.2 and an ASTM D 909 supercharge rich rating of 139.6, which were above the current specification minimums for 100LL. Further, the 102.2 MON was more than 2.5 MON higher than the 100LL minimum MON requirement to account for the differences in engine performance between leaded and unleaded fuels [3].

Table 2 shows the compositional analyses of the Swift binary blend by gas chromatography (GC) flame ionization detection (FID).

Table 2. Swift Binary Blend Component Composition by GC-FID

Component	Value
Mesitylene, (1,3,5-Trimethylbenzene)	82.50 mass %
Iso-pentane	16.59 mass %
Isobutane	112.3 ppm
Butane	131.6 ppm
Neopentane	376.0 ppm
Pentane	442.5 ppm
Isooctane	927.5 ppm
Toluene	238.2 ppm
p-Xylene	32.8 ppm
o-Xylene	451.6 ppm
Cumene	42.6 ppm
4-Ethyltoluene	1229.8 ppm

Table 2. Swift Binary Blend Component Composition by GC-FID (Continued)

Component	Value
2-Ethyltoluene	192.3 ppm
1,2,4-Trimethylbenzene	4352.6 ppm
1,2,3-Trimethylbenzene	14.0 ppm
Other	511.6 ppm

Note that the Swift binary blend consists of two main components, 82.5% by mass aromatic hydrocarbon and 16.6% by mass iso-pentane (volatility component), with approximately 0.9% being typical aviation gasoline component hydrocarbons.

Traditionally, engines and airframes were certified on available leaded fuels that met ASTM D 910. The actual unleaded fuel motor octane requirement for the portion of the fleet that consumes the majority of the aviation gasoline for unleaded fuels is more than 100 MON. The performance of unleaded fuels in spark ignition, piston aircraft engines can vary significantly from the performance of traditional leaded aviation gasoline [3].

Engine parameter data were recorded at a rate of one full channel scan every second. The engine was equipped with at least the following sensors:

- Cylinder head temperatures (1-6 cylinders)
- Exhaust gas temperatures (1-6 cylinders)
- Intake air temperature
- Intake air pressure
- Mass air flow rate
- Exhaust gas air-to-fuel ratio
- Manifold absolute pressure
- Engine speed (rpm)
- Engine shaft torque
- Brake horsepower (calculated)
- Fuel mass and volume flow rates
- Engine cowling air temperature and pressure
- Fuel temperatures
- Fuel mass density
- Metered fuel pressure
- Fuel pump pressure
- Oil temperature
- Oil pressure

All the sensors were installed at the manufacturer's recommended locations whenever possible. All sensors and thermocouple channels were calibrated through the data acquisition system prior to engine testing, and the calibrations were verified at the end of the test. The engine was also equipped with accelerometers to ensure engine detonation was not occurring.

All engine break-in and acceptance tests were performed with the Swift-supplied fuel. Prior to and after the completion of the 150-hour test, power baseline tests were performed. At the completion of all tests, the engine was sent back to Textron Lycoming, measured again, and compared to the original engine measurements taken after remanufacture. FAA researchers, Swift Enterprises representatives, and Lycoming engineers were present to witness and document the engine tear down.

A series of maintenance runs was performed to verify the engine system's integrity, proper fuel and oil pressures, and instrumentation accuracy. Following these test runs, a series of acceptance and oil consumption tests was completed. All the test runs were performed using Phillips Type M 20W-50 nondispersant mineral oil. Prior to any engine operation, the mixture cutoff, full-rich settings, and the throttle idle stop and throw positions were checked. All engine operations throughout this test were performed with the Swift binary blend; the engine was not operated on leaded fuel at any time during the test.

All engine operations following the break-in period were performed with Aeroshell 15W-50 multi-viscosity oil and any servicing of the engine with oil was recorded. It is likely that future endurance tests would be performed using a straight mineral oil without additives. However, details of a test protocol for alternative aviation gasoline approval are still being formulated at ASTM International. For the purpose of this test, data were available from other unleaded fuel endurance tests (performed at the AFETF) with this oil, which can be used for comparison.

The health of the engine was then verified. A dynamic engine power baseline test was performed by varying the manifold pressure from 20 inches of mercury (inHg) to full-throttle stop and by varying the revolutions per minute (rpm) from 2000 to 2700 rpm. The manifold absolute pressure (MAP) was varied by 2 inHg increments, whereas the rpm was varied by 100-rpm increments.

These power baselines encompass a combination of MAP settings and engine rpm settings over a practical operating envelope in set increments. The results from the baselines verify the health of the engine. A MAP setting is chosen, and the engine power data are collected for each subsequent engine rpm. The MAP is then changed and the process repeated until the engine power production data have been collected for all combinations of MAP and rpm.

The endurance block test was complied with 14 CFR 33.47 and immediately followed the power baseline test. The separate phases of the 150-hour endurance test are shown in table 3. It should be noted that total engine time (which includes start-up, warm-up, transition, and shutdown) is not the same as the engine point time (only the amount of time the engine is at the specified power setting).

Table 3. Phase Breakdown of Endurance Test

Phase	Horsepower Range	rpm Range	Point Time Duration Per Test (hr)	Number of Tests per Phase	Engine Point Time (hr)
1	291-309	2619-2781	1.0	15	15.0
	218-232	2383-2531	1.0	15	15.0
2	291-309	2619-2781	1.5	10	15.0
	218-232	2383-2531	0.5	10	5.0
3	291-309	2619-2781	1.5	10	15.0
	204-216	2331-2475	0.5	10	5.0
4	291-309	2619-2781	1.5	10	15.0
	189-201	2279-2419	0.5	10	5.0
5	291-309	2619-2781	1.5	10	15.0
	175-185	2214-2350	0.5	10	5.0
6	291-309	2619-2781	1.5	10	15.0
	146-155	2082-2211	0.5	10	5.0
7	291-309	2619-2781	2.5	4	10.0
	218-232	2377-2524	2.5	4	10.0
			Totals	138	150

The Lycoming IO540-K engine was equipped with a spin-on oil filter, allowing 50-hour maintenance intervals. After every 50 hours of engine operation, a scheduled inspection was performed. (This does not correspond to 50 hours of engine on-point test time.) These inspections included at least the following:

- A compression test was performed as soon as possible after the engine shutdown to ensure that the piston rings, cylinder walls, and other parts were well lubricated and at running tolerance. The test was performed using procedures and a differential pressure tester incorporating a master orifice device as described in Lycoming Service Instruction 1191a. Eighty psi of air pressure was applied to the cylinder while the pressure across the orifice device was measured with the piston at top-dead-center of the compression stroke.

- Oil sampling procedures followed those outlined in the Society of Automotive Engineers lubricating oil qualification test J1899. The oil system was drained and the oil pump filter screen was removed and inspected for metal particles and contamination. The screen was thoroughly cleaned, reinstalled with new gaskets, and safety wired. The system was serviced to the proper level with Aeroshell 15W-50 multi-viscosity oil.

- The oil samples were analyzed by an independent laboratory, as per ASTM D 445 for viscosity, ASTM D 664 for total acid number, ASTM D 3524 for fuel dilution, and ASTM D 5185 for metals content.

- After the engine cooled, a special inspection to monitor cylinder valve stem height was performed. The valve covers were removed and any valve cover gasket material were removed from the cylinder head. The rocker pin retaining bolts were removed, the pins pulled out, and the rocker arms removed. To ensure the valves were properly seated, a rubber mallet was used to carefully tap the valve stem heads. A special measurement plate was mounted to the cylinder head. Figure 2 shows the installation of a similar measurement plate on a Continental engine. With the measurement plate installed, the total valve train recession was obtained through the guide holes using a depth gauge, and the data were recorded as valve stem height.

- The fuel metering unit throttle and mixture control levers were inspected for freedom of movement. A beam-type torque wrench was used to measure the resistance to movement of the lever arms.

- The spark plugs were inspected for electrode wear, tested for spark strength, rotated, and reinstalled. They were not cleaned so the deposit buildup could be continuously monitored. A cylinder borescope was used to ensure that rings, valves, valve surfaces, piston crown, and cylinder walls were in visibly healthy condition.

- The fuel injection nozzles were removed from the engine, and rubber hoses were connected to the cylinder side of the injectors. These hoses were all of equal length and were run to graduated cylinders. The connections to the fuel manifold valve, fuel control unit, fuel pump, and fuel supply were left intact. The fuel tank boost pump was run, and the amount of fuel in each graduated cylinder was measured and recorded. The test was repeated three times, and the average of the tests was compared to previous values and to each other. The nozzles were also inspected using a mechanics light for visible deposit formation. The nozzles were reinstalled without cleaning.

- All fuel and oil lines were inspected for stiffness or excessive pliability. Hose fittings were also inspected for leaks or deposit buildup.

- The fuel inlet screen (finger screen) was removed, cleaned, reinstalled, and safety wired. The system was pressure checked for evidence of leaks at the sealing gasket.

- The engine cylinder assembly was inspected for evidence of overheating, leakage between exhaust ports and pipes, and warped exhaust port flanges. The baffling was inspected for condition and security. The fabricated sheet metal cowling was inspected for cracks, bowing, or other evidence of pressure-cycling fatigue.

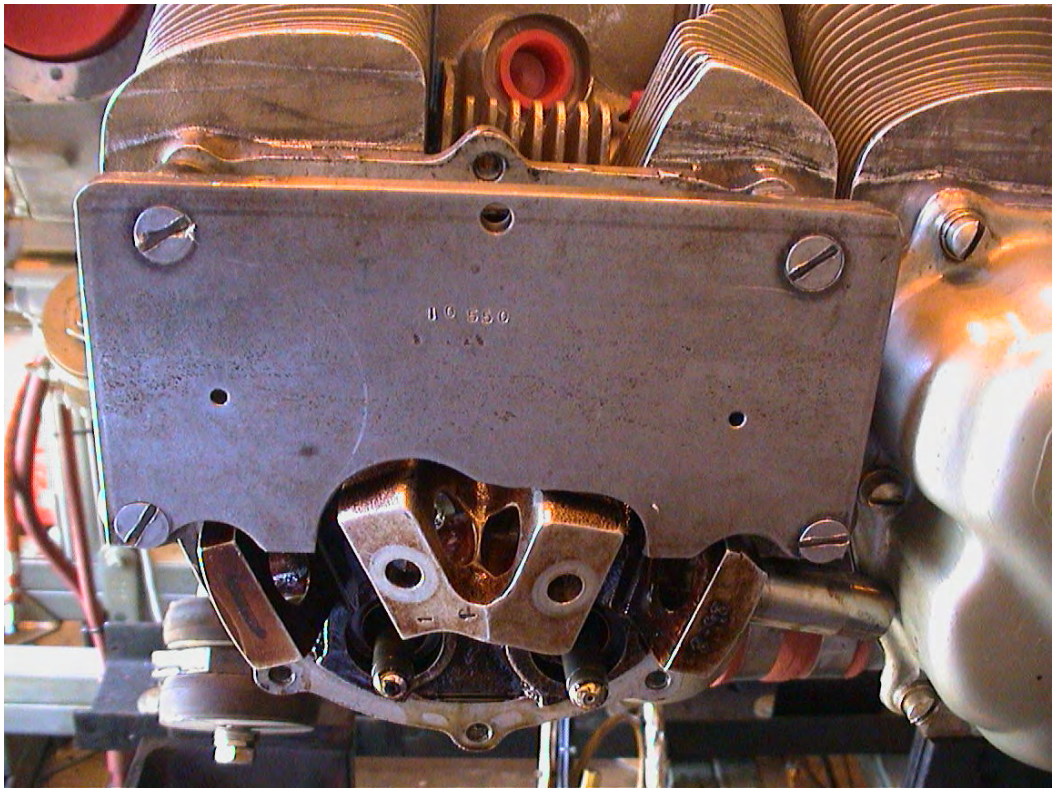


Figure 2. Valve Stem Height Measurement Tool (Typical)

Upon completion of the inspection, the engine was serviced with oil and inspected for evidence of oil and fuel leaks.

3. ANALYSES.

3.1 FUEL CHARACTERISTICS.

Figure 4 shows the Swift binary blend response of MON and Reid Vapor Pressure (RVP) versus mesitylene content. The mesitylene is a high-MON, low-RVP component, whereas the iso-pentane has a high RVP and lower MON. When the mesitylene content is higher, the MON is greater and the RVP of the Swift binary blend is lower. Conversely, when the iso-pentane component is higher, the MON is lower but the RVP of the Swift binary blend is higher.

The significance of this particular Swift binary blend is that the aging effects of the fuel are such that, as the iso-pentane of the Swift binary blend evaporates, the octane will increase and the vapor pressure will decrease. The boundaries of possible Swift binary blend composition will have to be fully evaluated, both at the high-octane, low-RVP and high-RVP, low-octane limits of the final fuel specification. Fuel that has been left in vented storage tanks over time may degrade start-ability and could make altitude relights or engine throttle response more difficult. The current specification for 100LL is ASTM D 910, which lists the allowable vapor pressure range as 5.5 to 7.0 psig. According to figure 3, this vapor pressure range would limit the mesitylene content between 80% and 85% of the Swift binary blend.

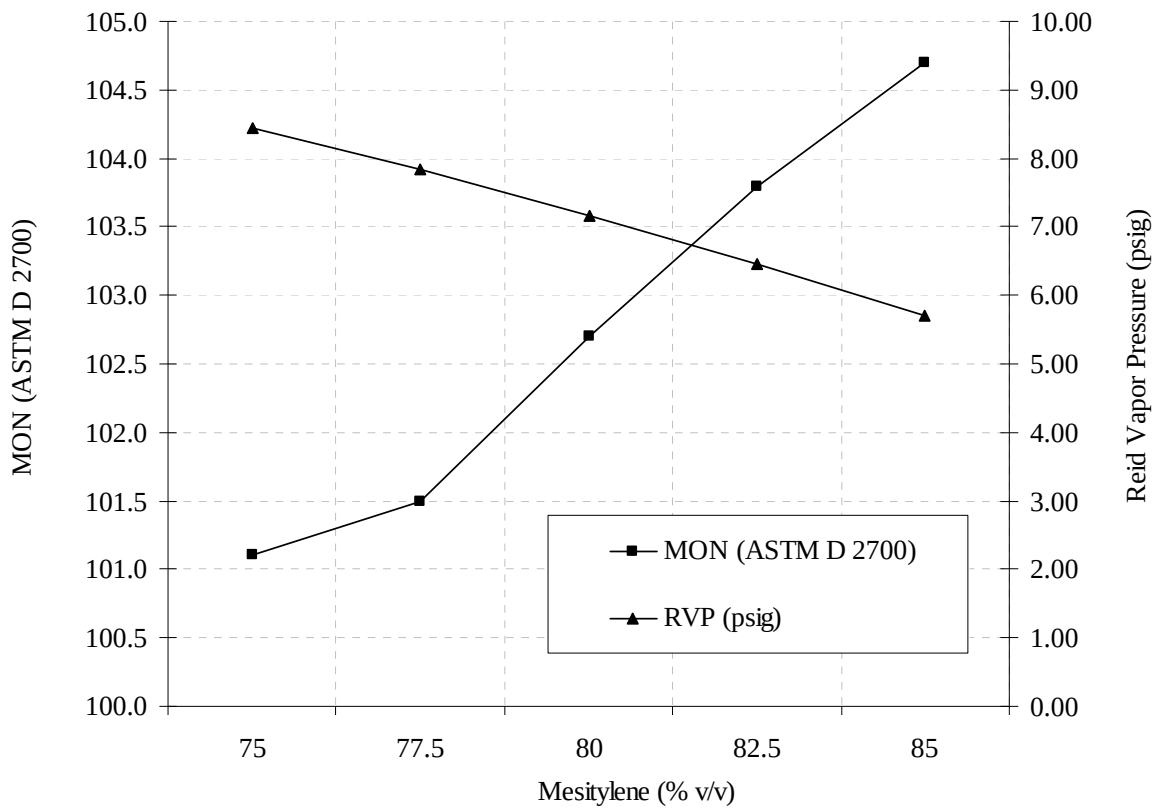


Figure 3. The MON and RVP for Swift Binary Blend

Figure 4 shows the distillation slope of the Swift binary blend fuel compared to a locally purchased 100LL fuel. Also included on the graph (in red) are the current ASTM D 910 distillation specification limits for a leaded, hydrocarbon-based, crude-derived aviation gasoline. These limits evolved by industry consensus from extensive experience with traditional leaded hydrocarbon fuels and their effect on aircraft and aircraft engine performance. Deviations from this known slope will require testing to address effects on start-ability, vapor lock, hot fuel, engine combustion deposits, gum formation, varnish buildup, oil dilution, valve sticking, fuel atomization, fuel mal-distribution, throttle and mixture response, cold-weather operation, and altitude relight. Another effect of the high distillation temperatures is that the oil temperatures are not high enough to boil off the fuel that migrates into the oil; thus, the majority of the fuel that ends up in the oil will remain, which diminishes the lubricating effects of the oil, until the next oil change. In this research, the oil dilution remained less than 1%.

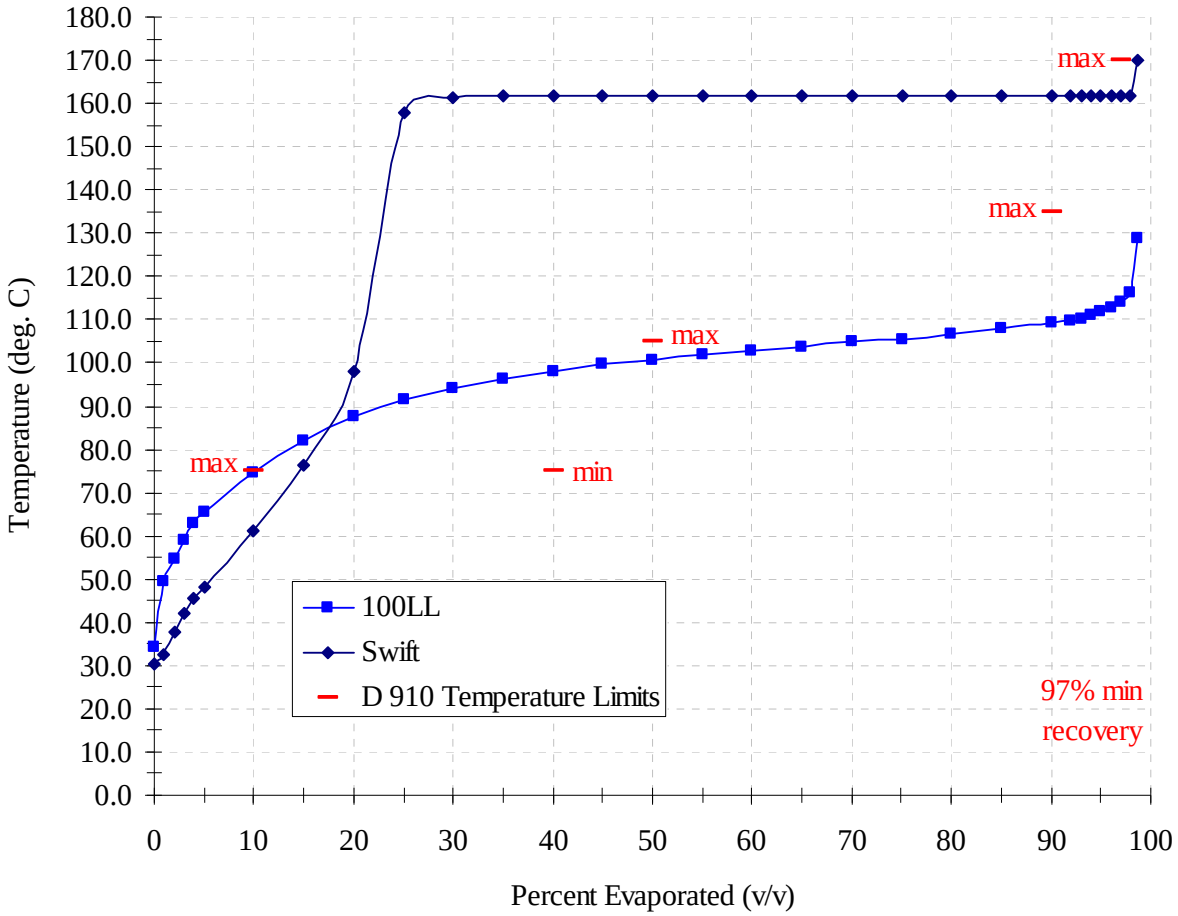


Figure 4. Distillation Curves for Swift Binary Blend and 100LL

3.2 ENGINE WEAR.

Table 4 contains the lubricating engine oil analyses at 50 engine-hour intervals. The trace metal content of iron, silicon, lead, copper, nickel, and tin showed levels higher than typically observed in past experience for this type of test. It was noted during teardown that the valve tappet faces in four of the cylinders showed excessive wear (see figure 5). This was not attributed to the fuel as accelerated wear had been found on this type of tappet material and design, which is no longer used by Lycoming. This could account for the elevated iron and silicon levels. The lead, nickel, and tin are typically found in the crankshaft bearings, all of which showed normal wear. The elevated copper levels could have been from the wearing of the crankshaft bearing coatings and exposure of the copper and also from the edges of the components with copper plating, including the crankshaft, camshaft, and some gears. All the metal trace levels peaked at the 150 engine-hour mark and proceeded to decrease to the 180 engine-hour mark, which is a typical wear trend pattern. The acid number of the oil also followed this trend.

Table 4. Engine Lubricating Oil Analyses

ASTM	Date		6/9/09	6/18/09	7/1/09	7/14/09	7/15/09
	Engine hours	0	50	98.6	148.5	176.8	179.2
D 445	Viscosity, mm^2/s						
	40°C	142.4	207.7	230.7	225.9	186.4	126.6
	100°C	19.66	25.21	27.22	26.72	23.41	18.03
D 664	Acid number, mg KOH/g	0.6	1.0	1.3	1.2	1.0	0.6
D 3525	Gasoline fuel, mass %	0.06	0.92	0.84	0.90	0.98	1.83
D 5185	Trace metal content, mg/kg						
	Silver	0.19	<0.01	<0.01	< 0.01	0.21	0.04
	Aluminum	0.07	45	27	27	15	4.8
	Chromium	<0.01	2.0	2.2	2.7	1.9	0.42
	Copper	<0.01	96	59	52	34	5.5
	Iron	<0.01	78	110	160	120	25
	Magnesium	<0.01	3.90	2.22	1.68	1.52	0.26
	Molybdenum	<0.01	0.28	0.34	0.29	0.19	<0.01
	Nickel	0.05	1.2	1.0	1.4	0.93	0.36
	Lead	<0.01	34	34	37	30	4.7
	Silicon	3.4	29	21	17	9.8	4.1
	Tin	<0.01	8.2	7.3	6.3	3.7	0.52
	Titanium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Zinc	0.78	21.4	20.8	19.0	13.6	2.34

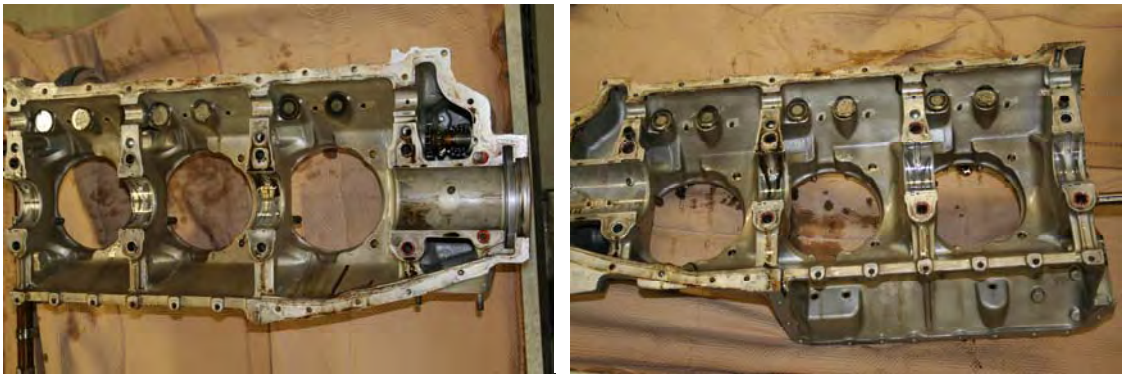


Figure 5. Left and Right Crankcase Halves With Tappets Installed

Table 5 shows the main bearing measurements, and figure 6 shows the measurement locations. The largest bearing thickness change was 1.8 thousandths of an inch in the #1 bottom B location. All the other measurements were less than a thousandth of an inch change, which are normal wear levels.

Table 5. Main Bearing Thickness Measurements for Numbers 1 and 2

Bearing No.	Location	Top			Bottom		
		Before	After Test	Change	Before	After Test	Change
1	A	0.0947	0.0946	-0.0001	0.0949	0.0945	-0.0004
	B	0.0949	0.0945	-0.0004	0.0945	0.0947	0.0002
	C	0.0947			0.0917	0.0920	0.0003
	D	0.0919	0.0920	0.0001	0.0953		
	E	0.0950	0.0948	-0.0002	0.0949	0.0950	0.0001
	F	0.0951	0.0948	-0.0003	0.0949	0.0947	-0.0002
2	A	0.0952	0.0947	-0.0005	0.0949	0.0946	-0.0003
	B	0.0946	0.0946	0.0000	0.0947	0.0943	-0.0004
	C	0.0921	0.0920	-0.0001	0.0950		
	D	0.0948			0.0927	0.0921	-0.0006
	E	0.0951	0.0942	-0.0009	0.0947	0.0946	-0.0001
	F	0.0950	0.0948	-0.0002	0.0947	0.0947	0.0000

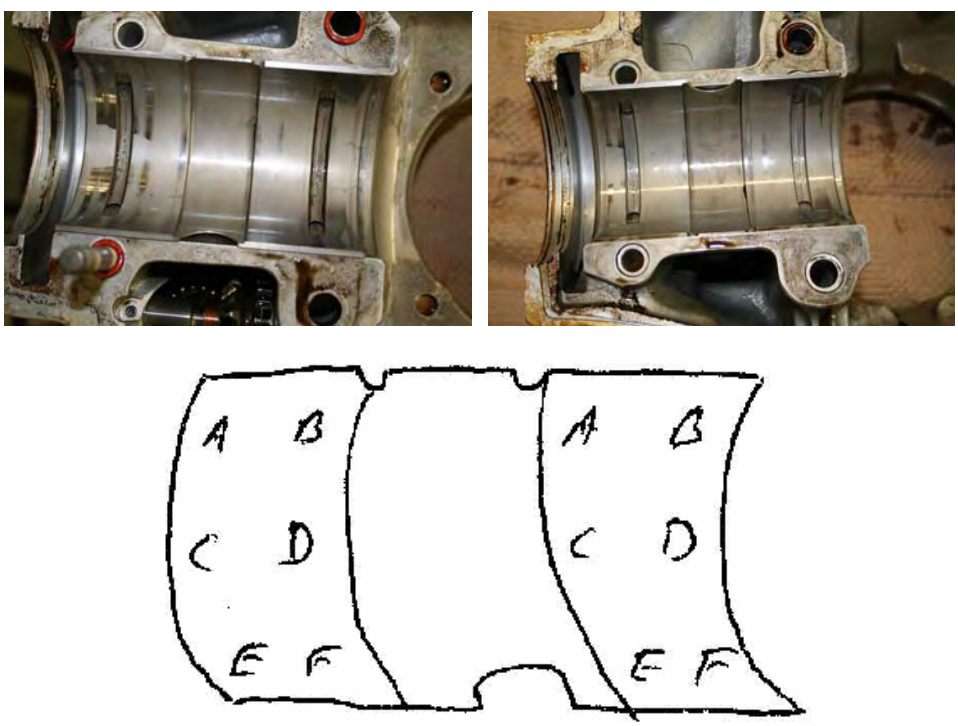


Figure 6. Front Main Crankshaft Bearings With Associated Drawing Showing Measurement Locations

Table 6 shows the main crankshaft bearing measurements for numbers 3, 4, and 5, and figure 7 shows the main crankshaft measurement locations for numbers 3, 4 and 5. This table shows

normal bearing wear with less than a thousandth of an inch change in thickness and normal wear modes.

Table 6. Main Crankshaft Bearing Thickness Measurements for Numbers 3, 4, and 5

Bearing No.	Location	Even (in.)			Odd (in.)		
		Before	After Test	Change	Before	After Test	Change
3	A	0.0949	0.0948	-0.0001	0.0950	0.0947	-0.0003
	B	0.0948	0.0950	0.0002	0.0949	0.0949	0.0000
	C	0.0951	0.0944	-0.0007	0.0953	0.0946	-0.0007
	D	0.0948	0.0948	0.0000	0.0952	0.0947	-0.0005
	E	0.0950	0.0944	-0.0006	0.0949	0.0943	-0.0006
	F	0.0948	0.0948	0.0000	0.0949	0.0946	-0.0003
4	A	0.0951	0.0947	-0.0004	0.0951	0.0949	-0.0002
	B	0.0948	0.0951	0.0003	0.0950	0.0950	0.0000
	C	0.0951	0.0947	-0.0004	0.0952	0.0945	-0.0007
	D	0.0951	0.0951	0.0000	0.0951	0.0948	-0.0003
	E	0.0947	0.0944	-0.0003	0.0948	0.0946	-0.0002
	F	0.0949	0.0955	0.0006	0.0950	0.0947	-0.0003
5	A	0.0949	0.0947	-0.0002	0.0952	0.0951	-0.0001
	B	0.0947	0.0948	0.0001	0.0948	0.0948	0.0000
	C	0.0949	0.0945	-0.0004	0.0951	0.0944	-0.0007
	D	0.0951	0.0948	-0.0003	0.0951	0.0948	-0.0003
	E	0.0946	0.0944	-0.0002	0.0949	0.0945	-0.0004
	F	0.0947	0.0947	0.0000	0.0950	0.0947	-0.0003

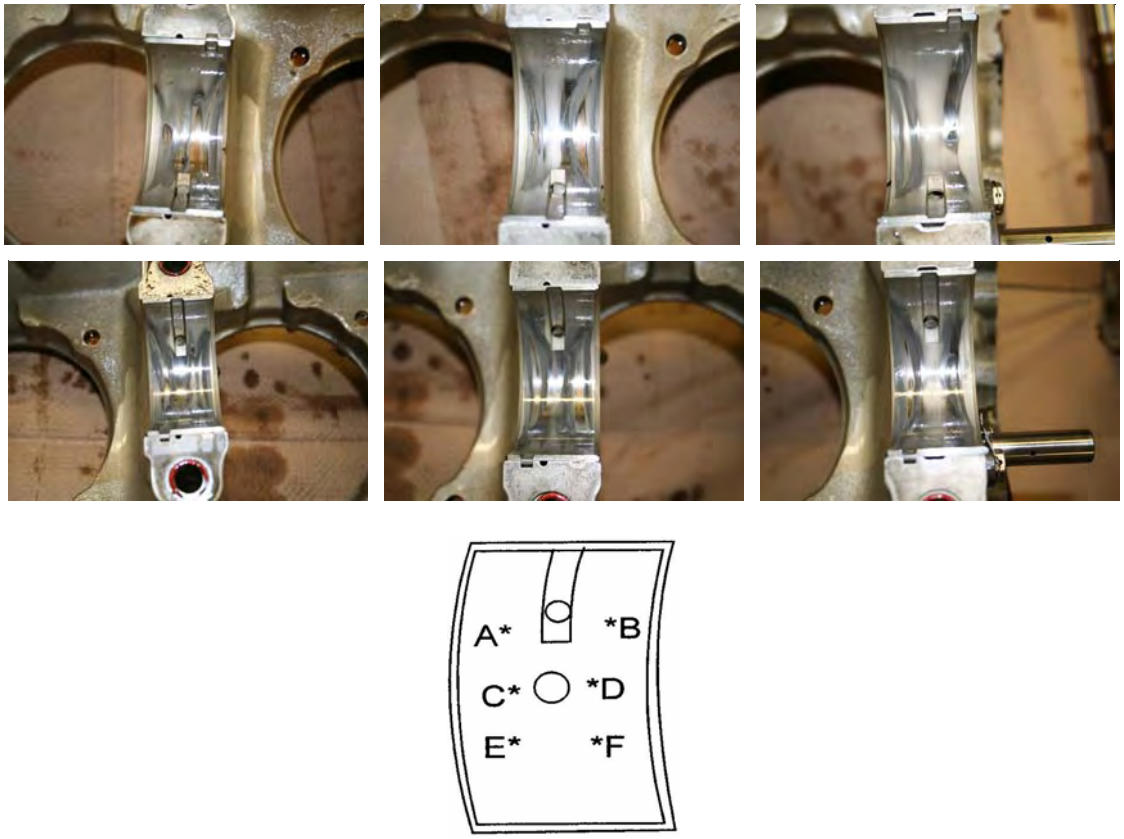


Figure 7. Main Crankshaft Bearings for Numbers 3, 4, and 5 With Associated Drawing Showing Measurement Locations

Table 7 shows the main crankshaft journal wear, and figure 8 shows the measurement locations. This table shows that there was no measurable wear in the journals.

Table 7. Main Crankshaft Journal Measurements

Cylinder No.	Location	Dimensions		Wear
		Before	After	
1	A	2.6250	2.6250	0.0000
	A'	2.6250	2.6250	0.0000
	B	2.6250	2.6250	0.0000
	B'	2.6246	2.6246	0.0000
2	A	2.6252	2.6252	0.0000
	A'	2.6250	2.6250	0.0000
	B	2.6249	2.6249	0.0000
	B'	2.6250	2.6250	0.0000

Table 7. Main Crankshaft Journal Measurements (Continued)

Cylinder No.	Location	Dimensions		Wear
		Before	After	
3	A	2.6249	2.6249	0.0000
	A'	2.6249	2.6249	0.0000
	B	2.6252	2.6252	0.0000
	B'	2.6250	2.6250	0.0000
4	A	2.6249	2.6249	0.0000
	A'	2.6249	2.6249	0.0000
	B	2.6250	2.6250	0.0000
	B'	2.6250	2.6250	0.0000
5	A	2.6245	2.6245	0.0000
	A'	2.6245	2.6245	0.0000
	B	2.6246	2.6246	0.0000
	B'	2.6246	2.6246	0.0000

All dimensions are in inches.

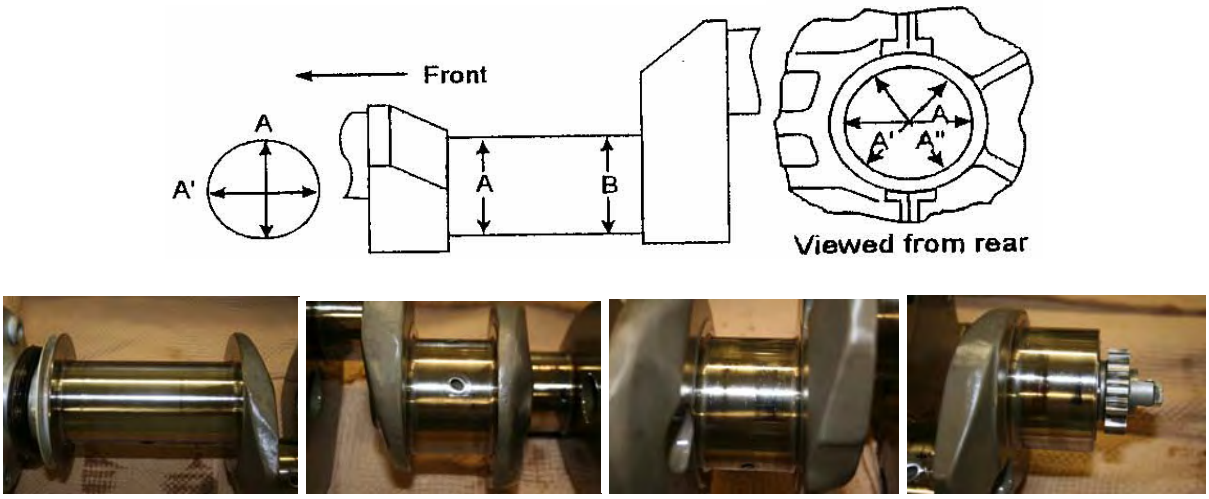


Figure 8. Main Crankshaft Journal Photos With Associated Drawing Showing Measurement Locations

As shown in table 4, oil dilution levels from fuel were typically less than 1%. Table 8 shows viscosity data for varying fuel dilution levels in oil for both 100LL and Swift binary blend. The data show that the effect on the oil viscosity was relatively the same regardless of whether the dilution occurred from the Swift binary blend or the 100LL, and at 1% dilution levels, the viscosity change was minimal. However, as previously shown by the distillation data in figure 4, the majority of the Swift binary blend (approximately 80%) boils at 162°C (324°F), which is

higher than the oil temperatures reach during normal operation. Therefore, the majority of the Swift binary blend dilution that occurs does not evaporate out of the crankcase breather but remains in the oil until the oil is replaced. Conversely, more than 50% of the 100LL fuel boils at a temperature less than 100°C (212°F). If a condition were to develop that resulted in elevated Swift binary blend oil dilution, the oil lubricity properties could be compromised to a greater extent than would occur with 100LL.

Table 8. Kinematic Viscosity of Base Oil With Varying Dilution Levels of 100LL and Swift Binary Blend Fuel

Kinematic Viscosity at 100°C, cSt					
Fuel	100% Oil	99.5% Oil	99% Oil	97% Oil	95% Oil
100LL	19.99	19.32	18.68	16.44	14.40
Swift binary blend	19.99	19.27	18.59	16.40	14.52

cSt = Centistokes

Valve stem height measurements taken every 50 engine hours during testing show that valve seat recession was minimal (see tables 9 and 10 and figures 9 and 10). Total valve recession for both the intake and exhaust valves for any cylinder was less than 3 thousandths of an inch at the end of the test. One of the reasons this value has been so low is due to the lack of wear grooves on the exhaust valve faces.

Table 9. Intake Valve Stem Height by Engine Hours

Engine Hours	Change in Valve Stem Height From Start of Test (thousandths of an inch)					
	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4	Cylinder 5	Cylinder 6
0	0	0	0	0	0	0
50	0.6	1.2	1	0.1	1.7	-0.5
98.6	0.2	0.2	1.1	1	2.2	-1
148.5	1.3	0	0.4	-1	2.7	-0.5
179.2	0.8	0.9	2.2	-0.2	1.7	-0.2

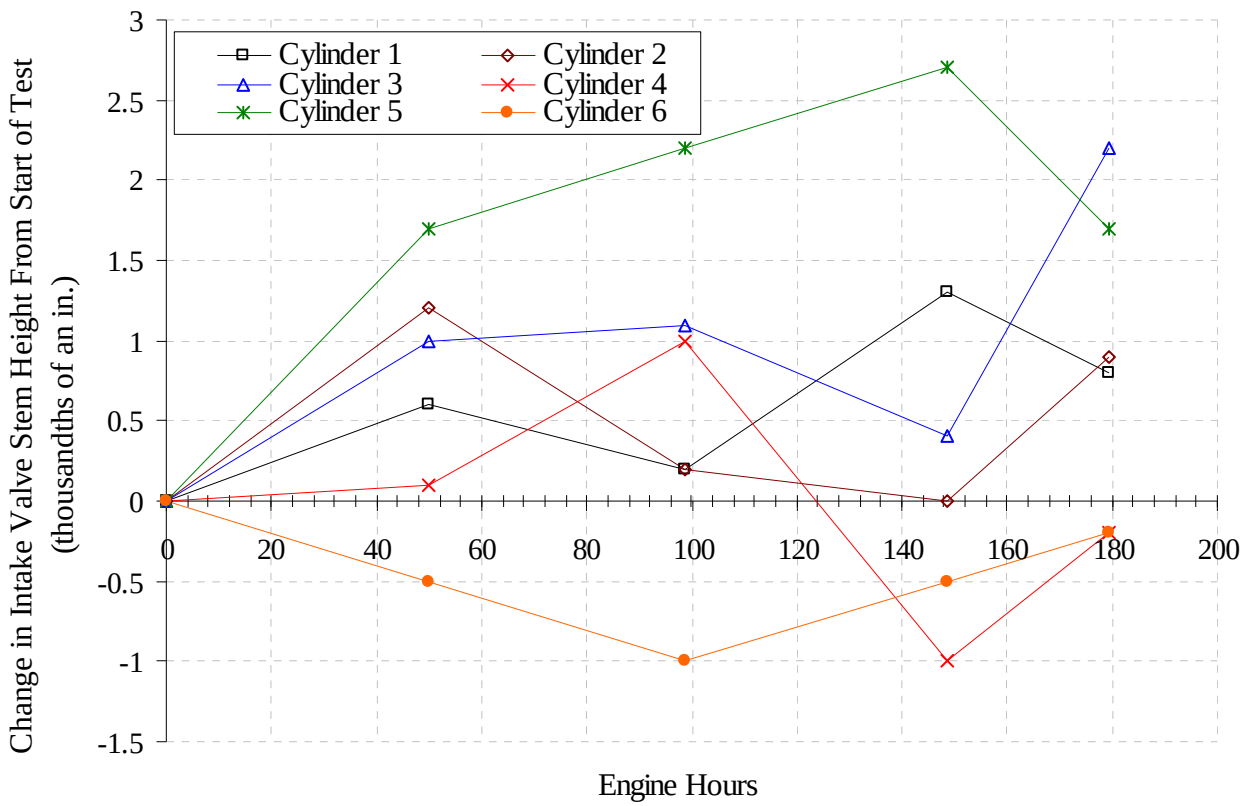


Figure 9. Intake Valve Stem Height Measurements

Table 10. Exhaust Valve Stem Height by Engine Hours

Engine Hours	Change in Valve Stem Height From Start of Test (thousandths of an inch)					
	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4	Cylinder 5	Cylinder 6
0	0	0	0	0	0	0
50	2	0.5	1.4	1	1.3	0.2
98.6	0.17	0	1.1	1.2	0.3	0.4
148.5	0.29	0.3	0.6	2	0.1	0.4
179.2	0.3	1	0.6	1.5	0.1	0.1

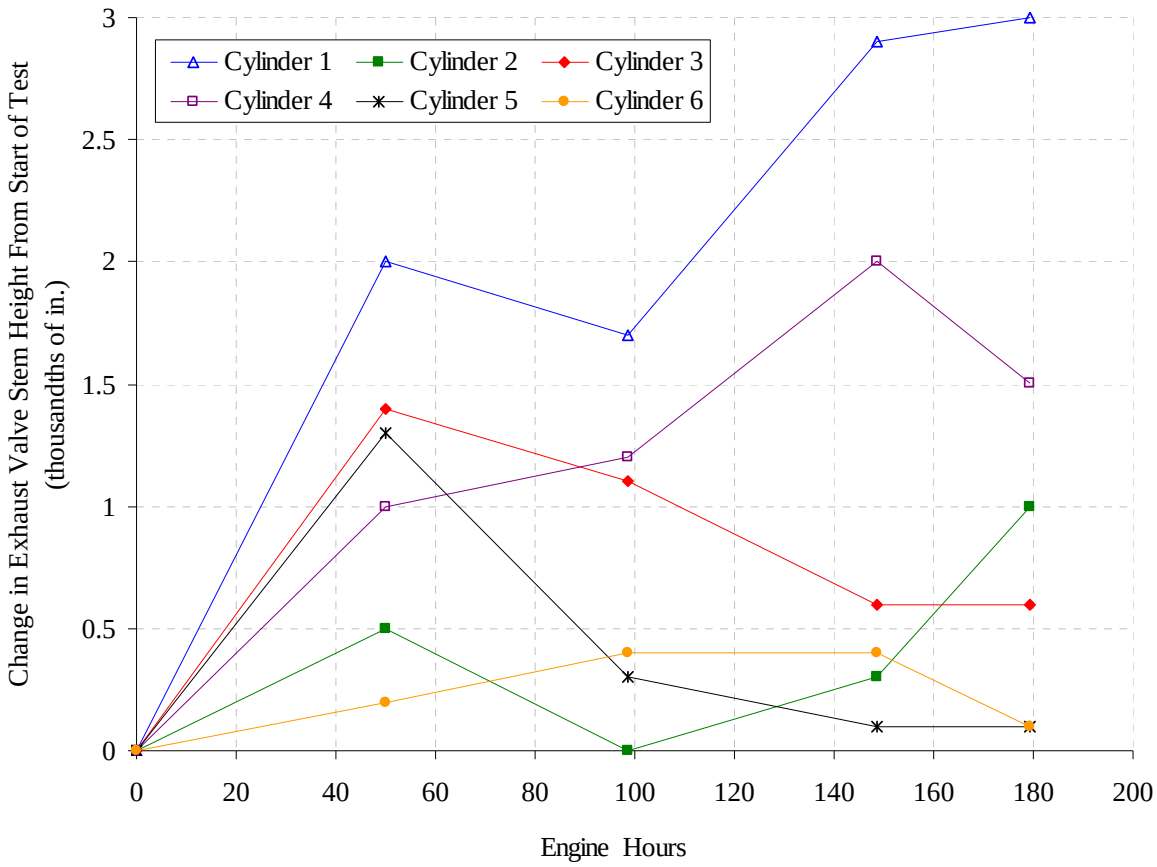
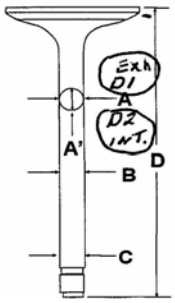


Figure 10. Exhaust Valve Stem Height Measurements

Table 11 shows the posttest valve measurements. The measurement locations are shown graphically in the far right column of the table. As shown in the table, the largest change in valve length was the intake valve of cylinder 2. This value was still within the manufacturer's new limit specifications of 4.580 ±0.007 inches. All other measurements were within the manufacturer's new limits, except for the exhaust valve in cylinder 5, which started at the minimum-allowable diameter and wore 0.0001 inch.

Table 12 shows the valve seat and face run-out measurements, and figure 11 shows the measurement locations. All the seat run-out measurement changes were less than 0.0013 inch, except for the exhaust valve in cylinder 1, which showed a 4 thousandths of an inch change. All the valve face run-out measurements were less than the maximum-allowable level of 0.0015 inch.

Table 11. Valve Measurements

Cylinder No.	Intake Valves				Exhaust Valves				Measurement Locations
	Location	Dimensions Before	Dimensions After	Wear	Location	Dimensions Before	Dimensions After	Wear	
1	A	0.4028	0.4028	0.0000	A	0.4962	0.4962	0.0000	
	A'	0.4028	0.4028	0.0000	A'	0.4962	0.4962	0.0000	
	B	0.4028	0.4027	-0.0001	B	0.4961	0.4961	0.0000	
	B'	0.4028	0.4027	-0.0001	B'	0.4961	0.4960	-0.0001	
	C	0.4027	0.4027	0.0000	C	0.4960	0.4960	0.0000	
	C'	0.4027	0.4027	0.0000	C'	0.4960	0.4960	0.0000	
	D	4.580	4.580	0.0000	D	4.526	4.526	0.0000	
2	A	0.4029	0.4028	-0.0001	A	0.4960	0.4960	0.0000	
	A'	0.4029	0.4028	-0.0001	A'	0.4960	0.4961	0.0001	
	B	0.4027	0.4027	0.0000	B	0.4958	0.4958	0.0000	
	B'	0.4027	0.4027	0.0000	B'	0.4958	0.4958	0.0000	
	C	0.4027	0.4027	0.0000	C	0.4958	0.4958	0.0000	
	C'	0.4027	0.4027	0.0000	C'	0.4958	0.4958	0.0000	
	D	4.582	4.579	-0.0030	D	4.526	4.526	0.0000	
3	A	0.4028	0.4028	0.0000	A	0.4960	0.4961	0.0001	
	A'	0.4028	0.4028	0.0000	A'	0.4960	0.4960	0.0000	
	B	0.4027	0.4027	0.0000	B	0.4960	0.4960	0.0000	
	B'	0.4027	0.4027	0.0000	B'	0.4960	0.4960	0.0000	
	C	0.4026	0.4026	0.0000	C	0.4961	0.4961	0.0000	
	C'	0.4026	0.4026	0.0000	C'	0.4961	0.4960	-0.0001	
	D	4.580	4.580	0.0000	D	4.525	4.524	-0.0010	
4	A	0.4028	0.4029	0.0001	A	0.4960	0.4960	0.0000	
	A'	0.4028	0.4028	0.0000	A'	0.4960	0.4960	0.0000	
	B	0.4027	0.4027	0.0000	B	0.4959	0.4958	-0.0001	
	B'	0.4027	0.4027	0.0000	B'	0.4959	0.4958	-0.0001	
	C	0.4027	0.4027	0.0000	C	0.4959	0.4959	0.0000	
	C'	0.4027	0.4027	0.0000	C'	0.4959	0.4959	0.0000	
	D	4.580	4.580	0.0000	D	4.525	4.526	0.0010	
5	A	0.4028	0.4028	0.0000	A	0.4958	0.4957	-0.0001	
	A'	0.4028	0.4028	0.0000	A'	0.4958	0.4957	-0.0001	
	B	0.4027	0.4027	0.0000	B	0.4957	0.4957	0.0000	
	B'	0.4027	0.4027	0.0000	B'	0.4957	0.4956	-0.0001	
	C	0.4026	0.4026	0.0000	C	0.4956	0.4956	0.0000	
	C'	0.4026	0.4026	0.0000	C'	0.4956	0.4956	0.0000	
	D	4.579	4.580	0.0010	D	4.526	4.524	-0.0020	
6	A	0.4029	0.4029	0.0000	A	0.4960	0.4961	0.0001	
	A'	0.4029	0.4028	-0.0001	A'	0.4959	0.4960	0.0001	
	B	0.4029	0.4029	0.0000	B	0.4959	0.4958	-0.0001	
	B'	0.4029	0.4029	0.0000	B'	0.4959	0.4958	-0.0001	
	C	0.4028	0.4028	0.0000	C	0.4959	0.4959	0.0000	
	C'	0.4028	0.4028	0.0000	C'	0.4959	0.4959	0.0000	
	D	4.580	4.580	0.0000	D	4.527	4.527	0.0000	

All dimensions are in inches.

Table 12. Valve Seat and Face Run-Out Measurements

Seat					Face				
Cylinder No.	Location	Before Test	After Test	Change	Cylinder No.	Location	Before Test	After Test	Change
1	Intake	0.0011	0.0011	0.0000	1	Intake	0.0000	0.0000	0.0000
	Exhaust	0.0017	0.0057	0.0040		Exhaust	0.0000	0.0005	0.0005
2	Intake	0.0011	0.0022	0.0011	2	Intake	0.0000	0.0000	0.0000
	Exhaust	0.0027	0.0038	0.0011		Exhaust	0.0000	0.0005	0.0005
3	Intake	0.0017	0.0023	0.0006	3	Intake	0.0000	0.0000	0.0000
	Exhaust	0.0026	0.0027	0.0001		Exhaust	0.0005	0.0005	0.0000
4	Intake	0.0005	0.0015	0.0010	4	Intake	0.0000	0.0000	0.0000
	Exhaust	0.0010	0.0013	0.0003		Exhaust	0.0000	0.0010	0.0010
5	Intake	0.0015	0.0022	0.0007	5	Intake	0.0000	0.0000	0.0000
	Exhaust	0.0021	0.0018	-0.0003		Exhaust	0.0005	0.0005	0.0000
6	Intake	0.0007	0.0013	0.0006	6	Intake	0.0000	0.0000	0.0000
	Exhaust	0.0021	0.0034	0.0013		Exhaust	0.0000	0.0005	0.0005

All dimensions are in inches.

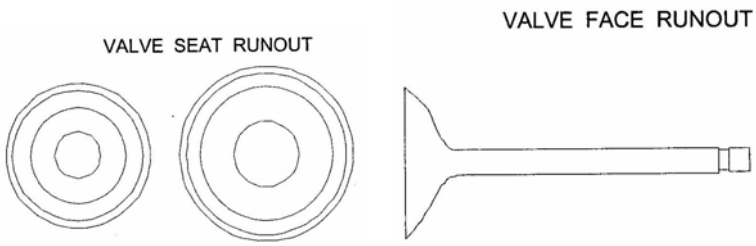


Figure 11. Valve Seat and Face Run-Out Measurement Locations

Table 13 shows the valve guide measurements, and figure 12 shows the measurement locations. All the intake guides fell out of the manufacturer's specification range at the A measurement location. However, these parts are automatically replaced at overhaul, as they are part of the cylinder assembly. The largest intake valve guide wear was in cylinder 1 with 1.8 thousandths of an inch, and the largest exhaust valve guide wear was in cylinder 5 with 2.3 thousandths of an inch. All the other intake valve guides showed wear less than 0.0006 inch and the exhaust valve guides showed wear less than 1.4 thousandths of an inch. All the clearance measurements for valve-to-valve guides fell out of specification for at least one measurement location for the exhaust valves and all the intake valve-to-valve guide clearances were still within new specification, except for the A location in cylinder 1. All intake clearances were within serviceable limits of 0.006 inch.

Table 13. Valve Guide Measurements

Intake					Exhaust				
Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
1	A	0.4048	0.4066	0.0018	1	A	0.5003	0.5002	-0.0001
	A'	0.4049	0.4063	0.0014		A'	0.5000	0.5004	0.0004
	B	0.4048	0.4049	0.0001		B	0.5003	0.5002	-0.0001
	B'	0.4048	0.4050	0.0002		B'	0.5003	0.5002	-0.0001
	C	0.4047	0.4048	0.0001		C	0.5002	0.5011	0.0009
	C'	0.4047	0.4048	0.0001		C'	0.5003	0.5006	0.0003
2	A	0.4046	0.4052	0.0006	2	A	0.5001	0.5000	-0.0001
	A'	0.4051	0.4055	0.0004		A'	0.5001	0.5003	0.0002
	B	0.4048	0.4049	0.0001		B	0.5003	0.5005	0.0002
	B'	0.4048	0.4050	0.0002		B'	0.5003	0.5003	0.0000
	C	0.4047	0.4048	0.0001		C	0.5001	0.5014	0.0013
	C'	0.4047	0.4048	0.0001		C'	0.5001	0.5001	-0.0000
3	A	0.4047	0.4051	0.0004	3	A	0.5002	0.5001	-0.0001
	A'	0.4049	0.4051	0.0002		A'	0.5002	0.4997	-0.0005
	B	0.4048	0.4049	0.0001		B	0.5003	0.4999	-0.0004
	B'	0.4048	0.4049	0.0001		B'	0.5003	0.5000	-0.0003
	C	0.4047	0.4047	0.0000		C	0.5002	0.5021	0.0019
	C'	0.4047	0.4048	0.0001		C'	0.5002	0.5007	0.0005
4	A	0.4047	0.4052	0.0005	4	A	0.5006	0.5012	0.0006
	A'	0.4050	0.4055	0.0005		A'	0.5004	0.5009	0.0005
	B	0.4048	0.4049	0.0001		B	0.5006	0.5004	-0.0002
	B'	0.4048	0.4049	0.0001		B'	0.5005	0.5005	0.0000
	C	0.4046	0.4047	0.0001		C	0.5004	0.5015	0.0011
	C'	0.4046	0.4047	0.0001		C'	0.5004	0.5009	0.0005
5	A	0.4048	0.4052	0.0004	5	A	0.5004	0.5003	-0.0001
	A'	0.4049	0.4052	0.0003		A'	0.5002	0.4996	-0.0006
	B	0.4048	0.4049	0.0001		B	0.5003	0.5004	0.0001
	B'	0.4049	0.4050	0.0001		B'	0.5003	0.5005	0.0002
	C	0.4047	0.4048	0.0001		C	0.5002	0.5025	0.0023
	C'	0.4047	0.4047	0.0000		C'	0.5002	0.5007	0.0005
6	A	0.4048	0.4052	0.0004	6	A	0.5004	0.5003	-0.0001
	A'	0.4049	0.4051	0.0002		A'	0.5000	0.5003	0.0003
	B	0.4049	0.4049	0.0000		B	0.5002	0.5006	0.0004
	B'	0.4049	0.4049	0.0000		B'	0.5002	0.5003	0.0001
	C	0.4046	0.4047	0.0001		C	0.5001	0.5015	0.0014
	C'	0.4046	0.4047	0.0001		C'	0.5001	0.5006	0.0005

All dimensions are in inches.

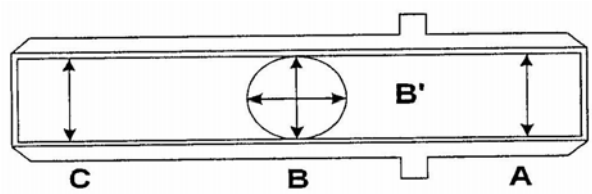


Figure 12. Valve Guide Measurement Locations

The valve tappet bore measurements are shown in table 14, and measurement locations are shown in figure 13. New and service limits specifications were not shown in the overhaul manual for this particular engine. The table shows that there was minimal wear in the exhaust and intake tappet bores.

Table 14. Valve Tappet Bore Measurements

Intake					Exhaust				
Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
1	A	0.7228	0.7228	0.0000	1	A	0.7215	0.7215	0.0000
	A'	0.7227	0.7227	0.0000		A'	0.7217	0.7217	0.0000
	B	0.7215	0.7215	0.0000		B	0.7212	0.7211	-0.0001
	B'	0.7214	0.7214	0.0000		B'	0.7213	0.7213	0.0000
2	A	0.7207	0.7209	0.0002	2	A	0.7207	0.7209	0.0002
	A'	0.7207	0.7209	0.0002		A'	0.7206	0.7206	0.0000
	B	0.7209	0.7207	-0.0002		B	0.7204	0.7204	0.0000
	B'	0.7209	0.7207	-0.0002		B'	0.7207	0.7205	-0.0002
3	A	0.7212	0.7213	0.0001	3	A	0.7217	0.7217	0.0000
	A'	0.7215	0.7217	0.0002		A'	0.7221	0.7222	0.0001
	B	0.7202	0.7204	0.0002		B	0.7213	0.7210	-0.0003
	B'	0.7199	0.7202	0.0003		B'	0.7212	0.7214	0.0002
4	A	0.7203	0.7204	0.0001	4	A	0.7197	0.7196	-0.0001
	A'	0.7202	0.7206	0.0004		A'	0.7196	0.7196	0.0000
	B	0.7212	0.7216	0.0004		B	0.7208	0.7210	0.0002
	B'	0.7211	0.7214	0.0003		B'	0.7206	0.7208	0.0002
5	A	0.7195	0.7192	-0.0003	5	A	0.7221	0.7221	0.0000
	A'	0.7190	0.7189	-0.0001		A'	0.7224	0.7224	0.0000
	B	0.7192	0.7193	0.0001		B	0.7215	0.7214	-0.0001
	B'	0.7189	0.7186	-0.0003		B'	0.7216	0.7213	-0.0003
6	A	0.7215	0.7214	-0.0001	6	A	0.7211	0.7212	0.0001
	A'	0.7207	0.7206	-0.0001		A'	0.7207	0.7210	0.0003
	B	0.7215	0.7215	0.0000		B	0.7206	0.7209	0.0003
	B'	0.7215	0.7215	0.0000		B'	0.7204	0.7206	0.0002

All dimensions are in inches.

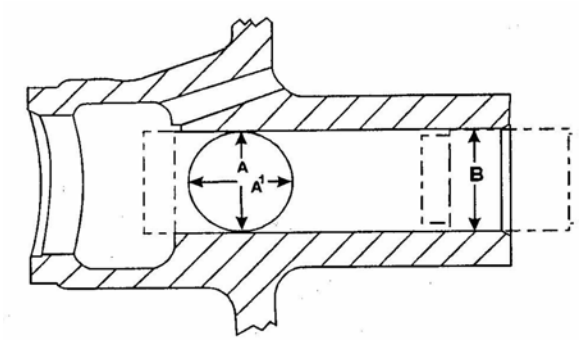


Figure 13. Valve Tappet Bore Measurement Locations

Table 15 shows the valve tappet measurements, and figure 14 shows the measurement locations. The C length measurement showed extensive wear in some of the tappets. This was previously discussed section 3.2.

Table 15. Valve Tappet Measurements

Intake					Exhaust				
Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
1	A	0.7174	0.7175	0.0001	1	A	0.7174	0.7175	0.0001
	A'	0.7174	0.7175	0.0001		A'	0.7174	0.7175	0.0001
	B	0.7174	0.7176	0.0002		B	0.7175	0.7175	0.0000
	B'	0.7174	0.7176	0.0002		B'	0.7175	0.7175	0.0000
	C	1.3720	1.3700	-0.002		C	1.3720	1.3720	0.0000
2	A	0.7172	0.7173	0.0001	2	A	0.7172	0.7173	0.0001
	A'	0.7172	0.7175	0.0003		A'	0.7172	0.7173	0.0001
	B	0.7172	0.7174	0.0002		B	0.7173	0.7174	0.0001
	B'	0.7172	0.7175	0.0003		B'	0.7173	0.7175	0.0002
	C	1.3720	1.3685	-0.0035		C	1.3750	1.3685	-0.0065
3	A	0.7175	0.7176	0.0001	3	A	0.7173	0.7174	0.0001
	A'	0.7175	0.7175	0.0000		A'	0.7173	0.7174	0.0001
	B	0.7174	0.7177	0.0003		B	0.7172	0.7174	0.0002
	B'	0.7174	0.7175	0.0001		B'	0.7172	0.7174	0.0002
	C	1.3720	1.3670	-0.0050		C	1.3750	1.3670	-0.0020
4	A	0.7173	0.7174	0.0001	4	A	0.7174	0.7175	0.0001
	A'	0.7174	0.7174	0.0000		A'	0.7173	0.7174	0.0001
	B	0.7174	0.7174	0.0000		B	0.7175	0.7175	0.0000
	B'	0.7174	0.7174	0.0000		B'	0.7175	0.7175	0.0000
	C	1.3720	1.3630	-0.0090		C	1.3730	1.3620	-0.0110

Table 15. Valve Tappet Measurements (Continued)

Intake					Exhaust				
Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
5	A	0.7173	0.7174	0.0001	5	A	0.7173	0.7174	0.0001
	A'	0.7174	0.7174	0.0000		A'	0.7174	0.7174	0.0001
	B	0.7174	0.7175	0.0001		B	0.7174	0.7174	0.0000
	B'	0.7174	0.7175	0.0001		B'	0.7174	0.7174	0.0000
	C	1.3740	1.3720	-0.0020		C	1.3740	1.3705	-0.0035
6	A	0.7173	0.7174	0.0001	6	A	0.7174	0.7174	0.0000
	A'	0.7173	0.7174	0.0001		A'	0.7173	0.7174	0.0001
	B	0.7174	0.7173	-0.0001		B	0.7173	0.7174	0.0001
	B'	0.7174	0.7173	-0.0001		B'	0.7173	0.7174	0.0001
	C	1.3720	1.3690	-0.0030		C	1.3730	1.3680	-0.0050

All dimensions are in inches.

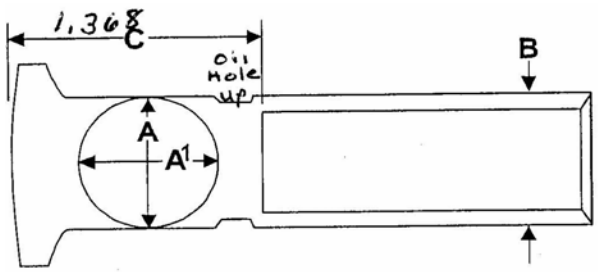


Figure 14. Valve Tappet Measurement Locations

The maximum serviceable clearance between tappet body and tappet bore is 0.004 inch. The intake clearances in cylinders 1, 3, 4, and 6 and the exhaust clearances in cylinders 1, 3, and 5 were out of serviceable maximum limits.

Table 16 shows the valve spring tension measurements. The open valve position specifications for the inner and outer springs are 73-83 lb at 1.330 inches and 114-124 lb at 1.430 inches, respectively. The closed valve position specifications for the inner and outer springs are 40-44 lb at 1.800 inches and 53-59 lb at 1.930 inches, respectively. All the spring tensions were within specification limits in the valve open position. The cylinder 4 intake valve outer spring for the closed valve position was out of specification limits, all the exhaust valves for the valve closed position were out of specification limits, and the intake valve inner spring in cylinders 2 and 4 were out of specification limits. These out of specification limits were not fuel related. The valve springs are routinely replaced at overhaul.

Table 16. Valve Spring Tension Measurements

Valve		Valve Open Position						Valve Closed Position					
		Inner Spring			Outer Spring			Inner Spring			Outer Spring		
Cylinder No.	Location	Before	After	Loss	Before	After	Loss	Before	After	Loss	Before	After	Loss
1	Intake	79.1	77.1	-2.0	123.4	122.5	-0.9	42.9	40.0	-2.9	57.9	54.2	-3.7
	Exhaust	79.2	75.6	-3.6	121.2	121.9	0.7	42.6	38.9	-3.7	57.1	56.2	-0.9
2	Intake	78.6	74.9	-3.7	124.1	120.5	-3.6	42.5	38.5	-4.0	58.2	55.9	-2.3
	Exhaust	79.3	76.7	-2.6	121.0	117.7	-3.3	42.9	39.1	-3.8	56.3	55.5	-0.8
3	Intake	80.4	77.4	-3.0	122.4	119.2	-3.2	43.1	40.6	-2.5	57.2	55.4	-1.8
	Exhaust	79.3	76.9	-2.4	121.7	122.2	0.5	42.7	38.9	-3.8	56.8	56.4	-0.4
4	Intake	78.7	74.1	-4.6	118.6	122.2	3.6	42.1	36.6	-5.5	55.9	52.7	-3.2
	Exhaust	79.0	76.3	-2.7	120.8	122.5	1.7	42.7	39.9	-2.8	56.1	54.7	-1.4
5	Intake	79.6	77.5	-2.1	120.8	117.3	-3.5	42.8	40.3	-2.5	56.4	54.1	-2.3
	Exhaust	79.1	76.1	-3.0	120.4	120.4	0.0	42.5	38.6	-3.9	56.2	54.9	-1.3
6	Intake	80.4	77.7	-2.7	121.6	121.0	-0.6	43.6	40.6	-3.0	57.2	54.6	-2.6
	Exhaust	78.9	77.0	-1.9	122.0	122.4	0.4	42.7	40.3	-2.4	57.2	56.3	-0.9

All dimensions are in in-lb.

The camshaft journal measurements are shown in table 17. The measurement locations are shown in figure 15. The camshaft journals showed negligible wear.

Table 18 shows the crankshaft pin measurements, and figure 16 shows the crankshaft pins and of the measurement locations. As shown in the table, no measurable wear had occurred in the crankshaft pins.

Table 17. Camshaft Journal Measurements

Cylinder No.	Location	Dimensions		Wear
		Before	After	
1	A	1.0275	1.0275	0.0000
	A'	1.0275	1.0275	0.0000
	B	1.0274	1.0274	0.0000
	B'	1.0274	1.0274	0.0000
2	A	1.0272	1.0272	0.0000
	A'	1.0273	1.0273	0.0000
	B	1.0274	1.0274	0.0000
	B'	1.0274	1.0274	0.0000
3	A	1.0273	1.0273	0.0000
	A'	1.0273	1.0273	0.0000
	B	1.0274	1.0274	0.0000
	B'	1.0274	1.0274	0.0000
4	A	1.0278	1.0276	-0.0002
	A'	1.0276	1.0276	0.0000
	B	1.0273	1.0273	0.0000
	B'	1.0274	1.0273	-0.0001

All dimensions are in inches.

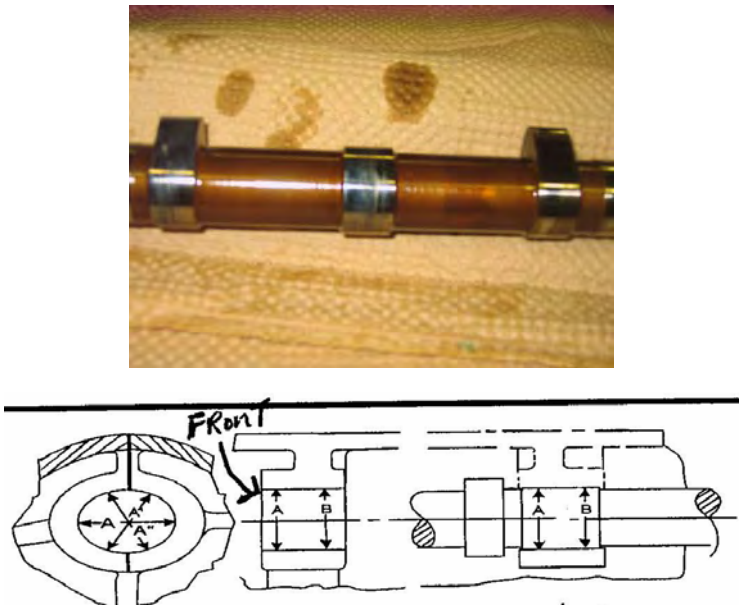


Figure 15. Main Camshaft Journal (typical) With Associated Measurement Locations

Table 18. Crankshaft Pin Measurements

Cylinder No.	Location	Dimensions		Wear
		Before	After	
1	A	2.2497	2.2497	0.0000
	A'	2.2500	2.2500	0.0000
	B	2.2497	2.2497	0.0000
	B'	2.2497	2.2497	0.0000
2	A	2.2494	2.2494	0.0000
	A'	2.2494	2.2494	0.0000
	B	2.2494	2.2494	0.0000
	B'	2.2494	2.2494	0.0000
3	A	2.2494	2.2494	0.0000
	A'	2.2497	2.2497	0.0000
	B	2.2494	2.2494	0.0000
	B'	2.2497	2.2497	0.0000
4	A	2.2498	2.2497	-0.0001
	A'	2.2497	2.2497	0.0000
	B	2.2497	2.2497	0.0000
	B'	2.2497	2.2497	0.0000
5	A	2.2497	2.2497	0.0000
	A'	2.2497	2.2497	0.0000
	B	2.2497	2.2497	0.0000
	B'	2.2495	2.2495	0.0000
6	A	2.2495	2.2495	0.0000
	A'	2.2499	2.2499	0.0000
	B	2.2495	2.2495	0.0000
	B'	2.2499	2.2499	0.0000

All dimensions are in inches.

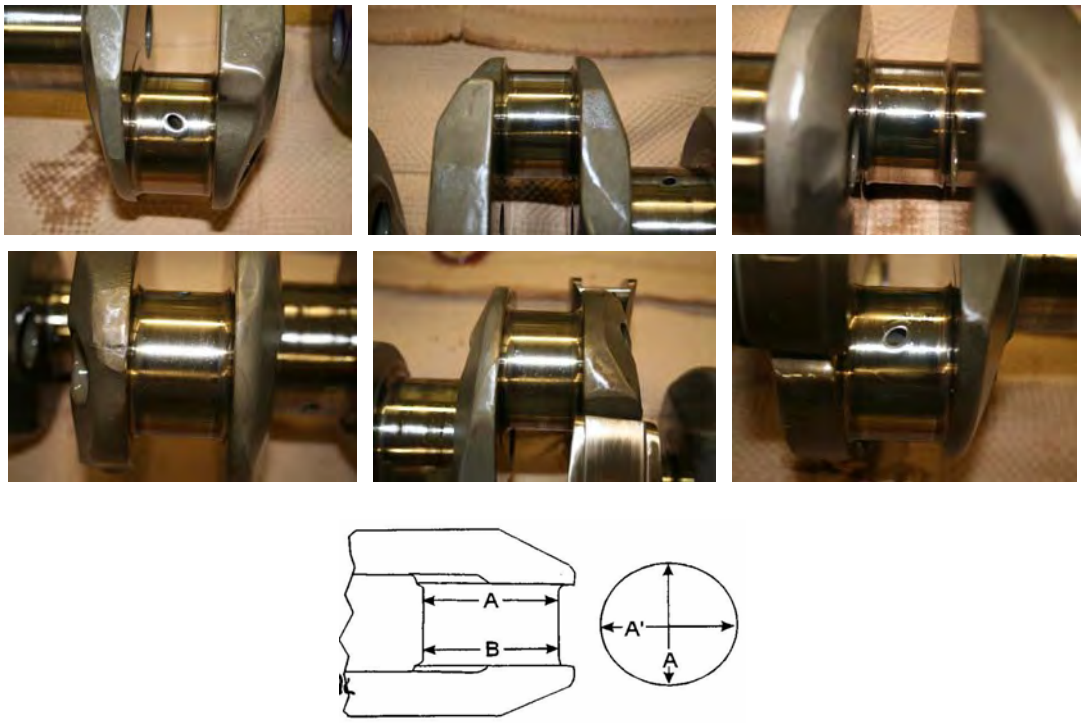


Figure 16. Crankshaft Pin and Measurement Locations

Cylinder barrel measurements for cylinders 1 and 2, 3 and 4, and 5 and 6 are shown in tables 19 through 21, respectively. Figure 17 shows the typical posttest cylinder and the measurement locations. All the cylinder measurements showed minimal wear and were less than the maximum-allowable cylinder diameter of 5.1305 in. Cylinder crosshatching was still visible. The maximum wear measurement in cylinders 1 and 2 was 1.5 thousandths of an inch. For cylinders 3 and 4, all the measurements were less than 1 thousandth of an inch. Cylinder 5 had a maximum wear measurement of 1.5 thousandths of an inch. Cylinder 6 had the most wear with one measurement reading 3.3 thousandths of an inch.

Table 19. Cylinder Barrels 1 and 2 Measurements

Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
1	A	5.1194	5.1209	0.0015	2	A	5.1204	5.1210	0.0006
	A1	5.1176	5.1179	0.0003		A1	5.1188	5.1195	0.0007
	A2	5.1172	5.1168	-0.0004		A2	5.1191	5.1188	-0.0003
	A3	5.1175	5.1183	0.0008		A3	5.1190	5.1190	0.0000
	B	5.1237	5.1234	-0.0003		B	5.1247	5.1246	-0.0001
	B1	5.1213	5.1216	0.0003		B1	5.1217	5.1232	0.0015
	B2	5.1213	5.1210	-0.0003		B2	5.1233	5.1230	-0.0003
	B3	5.1217	5.1223	0.0006		B3	5.1232	5.1227	-0.0005
	C	5.1252	5.1252	0.0000		C	5.1261	5.1263	0.0002
	C1	5.1237	5.1240	0.0003		C1	5.1252	5.1252	0.0000
	C2	5.1231	5.1235	0.0004		C2	5.1246	5.1253	0.0007

Table 19. Cylinder Barrels 1 and 2 Measurements (Continued)

Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
1	C3	5.1234	5.1245	0.0011	2	C3	5.1251	5.1253	0.0002
	D	5.1260	5.1260	0.0000		D	5.1270	5.1272	0.0002
	D1	5.1248	5.1250	0.0002		D1	5.1261	5.1262	0.0001
	D2	5.1243	5.1247	0.0004		D2	5.1261	5.1265	0.0004
	D3	5.1245	5.1253	0.0008		D3	5.1263	5.1263	0.0000
	E	5.1261	5.1260	-0.0001		E	5.1273	5.1273	0.0000
	E1	5.1251	5.1252	0.0001		E1	5.1266	5.1266	0.0000
	E2	5.1247	5.1250	0.0003		E2	5.1265	5.1265	0.0000
	E3	5.1248	5.1256	0.0008		E3	5.1266	5.1264	-0.0002
	F	5.1257	5.1253	-0.0004		F	5.1274	5.1273	-0.0001
	F1	5.1245	5.1252	0.0007		F1	5.1261	5.1266	0.0005
	F2	5.1247	5.1250	0.0003		F2	5.1266	5.1266	0.0000
	F3	5.1248	5.1254	0.0006		F3	5.1264	5.1265	0.0001
	G	5.1266	5.1260	-0.0006		G	5.1286	5.1283	-0.0003
	G1	5.1256	5.1260	0.0004		G1	5.1274	5.1276	0.0002
	G2	5.1255	5.1260	0.0005		G2	5.1277	5.1277	0.0000
	G3	5.1259	5.1260	0.0001		G3	5.1274	5.1276	0.0002

All dimensions are in inches.

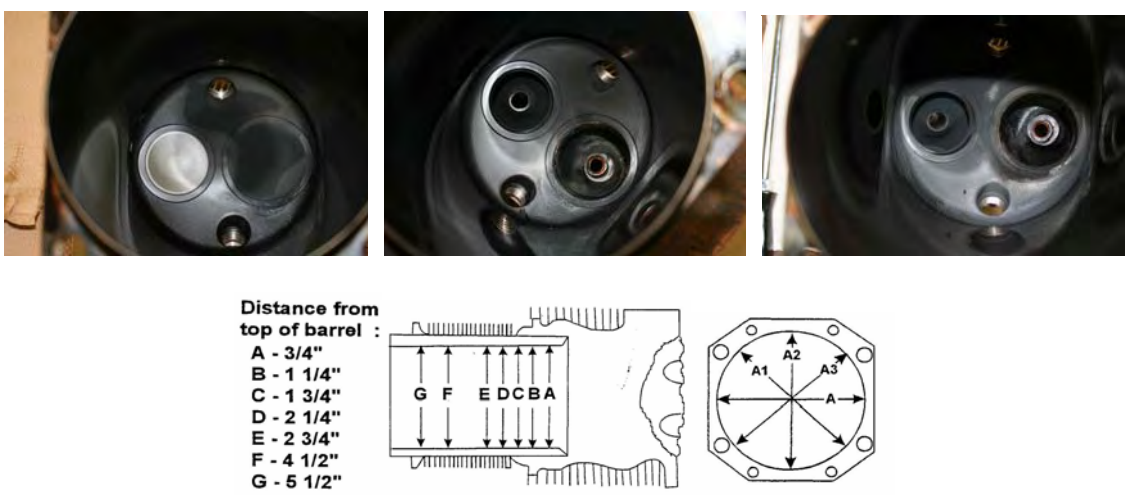


Figure 17. Combustion Chamber (typical) and Measurement Locations

Table 20. Cylinder Barrels 3 and 4 Measurements

Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
3	A	5.1191	5.1197	0.0006	4	A	5.1193	5.1202	0.0009
	A1	5.1171	5.1172	0.0001		A1	5.1178	5.1177	-0.0001
	A2	5.1172	5.1172	0.0000		A2	5.1176	5.1181	0.0005
	A3	5.1172	5.1174	0.0002		A3	5.1183	5.1178	-0.0005
	B	5.1234	5.1232	-0.0002		B	5.1238	5.1236	-0.0002
	B1	5.1215	5.1212	-0.0003		B1	5.1225	5.1218	-0.0007
	B2	5.1217	5.1215	-0.0002		B2	5.1222	5.1225	0.0003
	B3	5.1218	5.1214	-0.0004		B3	5.1226	5.1219	-0.0007
	C	5.1248	5.1250	0.0002		C	5.1254	5.1257	0.0003
	C1	5.1238	5.1236	-0.0002		C1	5.1247	5.1244	-0.0003
	C2	5.1235	5.1238	0.0003		C2	5.1243	5.1248	0.0005
	C3	5.1234	5.1237	0.0003		C3	5.1246	5.1245	-0.0001
	D	5.1258	5.1260	0.0002		D	5.1262	5.1266	0.0004
	D1	5.1250	5.1250	0.0000		D1	5.1256	5.1251	-0.0005
	D2	5.1248	5.1250	0.0002		D2	5.1255	5.1258	0.0003
	D3	5.1247	5.1249	0.0002		D3	5.1257	5.1256	-0.0001
	E	5.1260	5.1261	0.0001		E	5.1265	5.1266	0.0001
	E1	5.1254	5.1252	-0.0002		E1	5.1262	5.1257	-0.0005
	E2	5.1252	5.1253	0.0001		E2	5.1258	5.1259	0.0001
	E3	5.1251	5.1252	0.0001		E3	5.1259	5.1259	0.0000
	F	5.1260	5.1257	-0.0003		F	5.1262	5.1263	0.0001
	F1	5.1250	5.1252	0.0002		F1	5.1264	5.1256	-0.0008
	F2	5.1252	5.1253	0.0001		F2	5.1256	5.1258	0.0002
	F3	5.1250	5.1252	0.0002		F3	5.1258	5.1258	0.0000
	G	5.1267	5.1265	-0.0002		G	5.1272	5.1272	0.0000
	G1	5.1260	5.1262	0.0002		G1	5.1275	5.1266	-0.0009
	G2	5.1264	5.1263	-0.0001		G2	5.1265	5.1268	0.0003
	G3	5.1262	5.1262	0.0000		G3	5.1269	5.1266	-0.0003

All dimensions are in inches.

Table 21. Cylinder Barrels 5 and 6 Measurements

Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
5	A	5.1190	5.1203	0.0013	6	A	5.1192	5.1203	0.0011
	A1	5.1173	5.1184	0.0011		A1	5.1167	5.1175	0.0008
	A2	5.1170	5.1163	-0.0007		A2	5.1180	5.1172	-0.0008
	A3	5.1172	5.1175	0.0003		A3	5.1173	5.1185	0.0012
	B	5.1235	5.1235	0.0000		B	5.1237	5.1240	-0.0033
	B1	5.1218	5.1220	0.0002		B1	5.1208	5.1217	0.0009
	B2	5.1216	5.1217	0.0001		B2	5.1224	5.1216	-0.0008
	B3	5.1217	5.1214	-0.0003		B3	5.1218	5.1223	0.0005
	C	5.1251	5.1255	0.0004		C	5.1253	5.1257	0.0004
	C1	5.1237	5.1244	0.0007		C1	5.1238	5.1244	0.0006
	C2	5.1239	5.1241	0.0002		C2	5.1244	5.1244	0.0000
	C3	5.1238	5.1239	0.0001		C3	5.1241	5.1246	0.0005
	D	5.1260	5.1262	0.0002		D	5.1262	5.1265	0.0003
	D1	5.1239	5.1254	0.0015		D1	5.1253	5.1255	0.0002
	D2	5.1251	5.1251	0.0000		D2	5.1255	5.1254	-0.0001
	D3	5.1249	5.1250	0.0001		D3	5.1253	5.1256	0.0003
	E	5.1261	5.1262	0.0001		E	5.1263	5.1265	0.0002
	E1	5.1251	5.1255	0.0004		E1	5.1252	5.1256	0.0004
	E2	5.1253	5.1251	-0.0002		E2	5.1257	5.1255	-0.0002
	E3	5.1251	5.1252	0.0001		E3	5.1255	5.1257	0.0002
	F	5.1260	5.1260	0.0000		F	5.1260	5.1260	0.0000
	F1	5.1248	5.1252	0.0004		F1	5.1254	5.1255	0.0001
	F2	5.1253	5.1248	-0.0005		F2	5.1255	5.1254	-0.0001
	F3	5.1248	5.1253	0.0005		F3	5.1254	5.1255	0.0001
	G	5.1272	5.1270	-0.0002		G	5.1270	5.1270	0.0000
	G1	5.1254	5.1252	-0.0002		G1	5.1266	5.1266	0.0000
	G2	5.1262	5.1256	-0.0006		G2	5.1266	5.1264	-0.0002
	G3	5.1256	5.1257	0.0004		G3	5.1265	5.1265	0.0000

All dimensions are in inches.

Piston measurements for cylinders 1 and 2, 3 and 4, and 5 and 6 are shown in tables 22 through 24, respectively. Figures 18 through 20 show the posttest pistons and the measurement locations. All the clearance measurements for the piston skirt to the cylinder barrel were within maximum allowable new clearance limit specifications of 18 thousandths of an inch, except for one direction in cylinder 1 and two directions in cylinder 2. Those clearances were approximately 1 thousandth of an inch greater than the new clearance limit. Again, these tables indicate normal wear, and the photographs show typical light scuffing on the piston crowns. The piston boss measurements showed normal wear.

Table 22. Piston Land, Skirt, and Boss Measurements for Cylinders 1 and 2

Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
1	A	5.0840	5.0864	0.0024	2	A	5.0836	5.0875	0.0039
	A1	5.0841	5.0862	0.0021		A1	5.0829	5.0858	0.0029
	A2	5.0841	5.0860	0.0019		A2	5.0834	5.0848	0.0014
	A3	5.0840	5.0852	0.0012		A3	5.0830	5.0851	0.0021
	B	5.0842	5.0872	0.0030		B	5.0840	5.0902	0.0062
	B1	5.0841	5.0878	0.0037		B1	5.0841	5.0915	0.0074
	B2	5.0840	5.0878	0.0038		B2	5.0844	5.0921	0.0077
	B3	5.0842	5.0891	0.0049		B3	5.0840	5.0889	0.0049
	C	5.0841	5.0868	0.0027		C	5.0840	5.0872	0.0032
	C1	5.0840	5.0868	0.0028		C1	5.0839	5.0869	0.0030
	C2	5.0840	5.0861	0.0021		C2	5.0842	5.0862	0.0020
	C3	5.0840	5.0865	0.0025		C3	5.0839	5.0868	0.0029
	D	5.0987	5.1010	0.0023		D	5.0990	5.1030	0.0040
	D1	5.1007	5.1011	0.0004		D1	5.1008	5.1035	0.0027
	D2	5.1098	5.1088	-0.0010		D2	5.1098	5.1085	-0.0013
	D3	5.1006	5.1030	0.0024		D3	5.1038	5.1028	-0.0010
	E	5.1035	5.1078	0.0043		E	5.1036	5.1091	0.0055
	E1	5.1066	5.1092	0.0026		E1	5.1064	5.1092	0.0028
	E2	5.1150	5.1135	-0.0015		E2	5.1141	5.1130	-0.0011
	E3	5.1070	5.1098	0.0028		E3	5.1091	5.1122	0.0031
	F	1.1252	1.1253	0.0001		F	1.1252	1.1253	0.0001
	F1	1.1252	1.1259	0.0007		F1	1.1252	1.1259	0.0007
	G	1.1253	1.1257	0.0004		G	1.1253	1.1260	0.0007
	G1	1.1253	1.1257	0.0004		G1	1.1252	1.1257	0.0005
	H	1.1253	1.1254	0.0001		H	1.1252	1.1255	0.0003
	H1	1.1252	1.1260	0.0008		H1	1.1253	1.1258	0.0005
	I	1.1253	1.1257	0.0004		I	1.1253	1.1255	0.0002
	I1	1.1254	1.1257	0.0003		I1	1.1253	1.1259	0.0006

All dimensions are in inches.

Figure 18. Pistons 1 and 2 and Measurement Locations

Table 23. Piston Land, Skirt, and Boss Measurements for Cylinders 3 and 4

Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
3	A	5.0840	5.0865	0.0025	4	A	5.0838	5.0868	0.0030
	A1	5.0842	5.0859	0.0017		A1	5.0838	5.0860	0.0022
	A2	5.0841	5.0848	0.0007		A2	5.0835	5.0849	0.0014
	A3	5.0838	5.0852	0.0014		A3	5.0833	5.0861	0.0028
	B	5.0848	5.0908	0.0060		B	5.0837	5.0917	0.0080
	B1	5.0843	5.0900	0.0057		B1	5.0844	5.0925	0.0081
	B2	5.0842	5.0882	0.0040		B2	5.0842	5.0911	0.0069
	B3	5.0840	5.0890	0.0050		B3	5.0846	5.0932	0.0086
	C	5.0842	5.0881	0.0039		C	5.0835	5.0882	0.0047
	C1	5.0840	5.0875	0.0035		C1	5.0839	5.0878	0.0039
	C2	5.0841	5.0855	0.0014		C2	5.0838	5.0855	0.0017
	C3	5.0840	5.0871	0.0031		C3	5.0836	5.0875	0.0039
	D	5.0987	5.1022	0.0035		D	5.0987	5.1021	0.0034
	D1	5.1005	5.1020	0.0015		D1	5.0995	5.1033	0.0038
	D2	5.1096	5.1078	-0.0018		D2	5.1100	5.1072	-0.0028
	D3	5.1025	5.1030	0.0005		D3	5.1023	5.1063	0.0040
	E	5.1032	5.1098	0.0066		E	5.1038	5.1100	0.0062
	E1	5.1058	5.1131	0.0073		E1	5.1045	5.1105	0.0060
	E2	5.1143	5.1139	-0.0004		E2	5.1150	5.1118	-0.0032
	E3	5.1060	5.1142	0.0082		E3	5.1085	5.1128	0.0043
	F	1.1253	1.1255	0.0002		F	1.1253	1.1256	0.0003
	F1	1.1252	1.1255	0.0003		F1	1.1252	1.1265	0.0013
	G	1.1253	1.1272	0.0019		G	1.1254	1.1285	0.0031
	G1	1.1252	1.1262	0.0010		G1	1.1253	1.1272	0.0019
	H	1.1253	1.1258	0.0005		H	1.1253	1.1254	0.0001
	H1	1.1252	1.1262	0.0010		H1	1.1253	1.1262	0.0009
	I	1.1253	1.1253	0.0000		I	1.1253	1.1255	0.0002
	I1	1.1252	1.1261	0.0009		I1	1.1253	1.1260	0.0007

All dimensions are in inches.

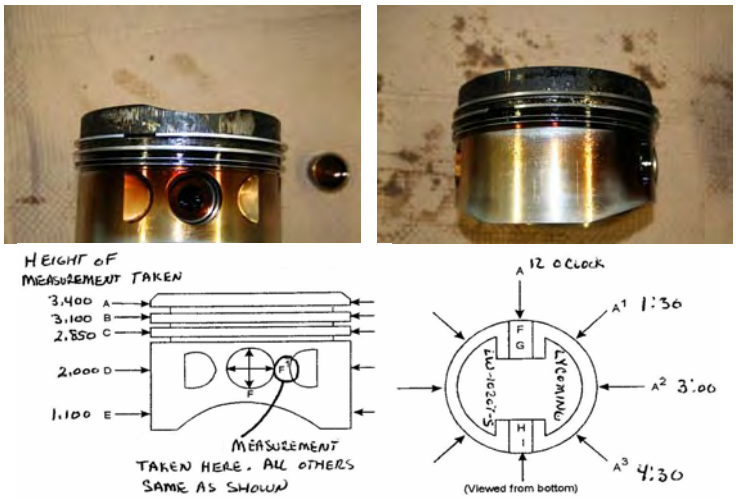


Figure 19. Pistons 3 and 4 and Measurement Locations

Table 24. Piston Land, Skirt, and Boss Measurements for Cylinders 5 and 6

Cylinder No.	Location	Dimensions		Wear	Cylinder No.	Location	Dimensions		Wear
		Before	After				Before	After	
5	A	5.0828	5.0847	0.0019	6	A	5.0823	5.0845	0.0022
	A1	5.0828	5.0854	0.0026		A1	5.0827	5.0847	0.0020
	A2	5.0830	5.0854	0.0024		A2	5.0823	5.0847	0.0024
	A3	5.0829	5.0851	0.0022		A3	5.0825	5.0850	0.0025
	B	5.0837	5.0884	0.0047		B	5.0837	5.0873	0.0036
	B1	5.0837	5.0928	0.0091		B1	5.0842	5.0897	0.0055
	B2	5.0840	5.0935	0.0095		B2	5.0837	5.0933	0.0096
	B3	5.0834	5.0898	0.0064		B3	5.0839	5.0922	0.0083
	C	5.0838	5.0855	0.0017		C	5.0830	5.0857	0.0027
	C1	5.0835	5.0865	0.0030		C1	5.0839	5.0864	0.0025
	C2	5.0835	5.0870	0.0035		C2	5.0833	5.0884	0.0051
	C3	5.0835	5.0861	0.0026		C3	5.0830	5.0886	0.0056
	D	5.0987	5.1091	0.0104		D	5.0989	5.1081	0.0092
	D1	5.0995	5.1050	0.0055		D1	5.1000	5.1028	0.0028
	D2	5.1106	5.1062	-0.0044		D2	5.1100	5.1058	-0.0042
	D3	5.0995	5.1059	0.0064		D3	5.0998	5.1010	0.0012
	E	5.1034	5.1122	0.0088		E	5.1041	5.1093	0.0052
	E1	5.1053	5.1098	0.0045		E1	5.1050	5.1101	0.0051
	E2	5.1148	5.1115	-0.0033		E2	5.1157	5.1123	-0.0034
	E3	5.1060	5.1100	0.0040		E3	5.1060	5.1098	0.0038
	F	1.1252	1.1254	0.0002		F	1.1253	1.1254	0.0001
	F1	1.1251	1.1261	0.0010		F1	1.1252	1.1261	0.0009
	G	1.1252	1.1260	0.0008		G	1.1252	1.1259	0.0007
	G1	1.1252	1.1263	0.0011		G1	1.1252	1.1262	0.0010
	H	1.1252	1.1259	0.0007		H	1.1253	1.1258	0.0005
	H1	1.1252	1.1263	0.0011		H1	1.1252	1.1262	0.0010
	I	1.1253	1.1254	0.0001		I	1.1253	1.1255	0.0002
	I1	1.1252	1.1261	0.0009		I1	1.1253	1.1260	0.0007

All dimensions are in inches.

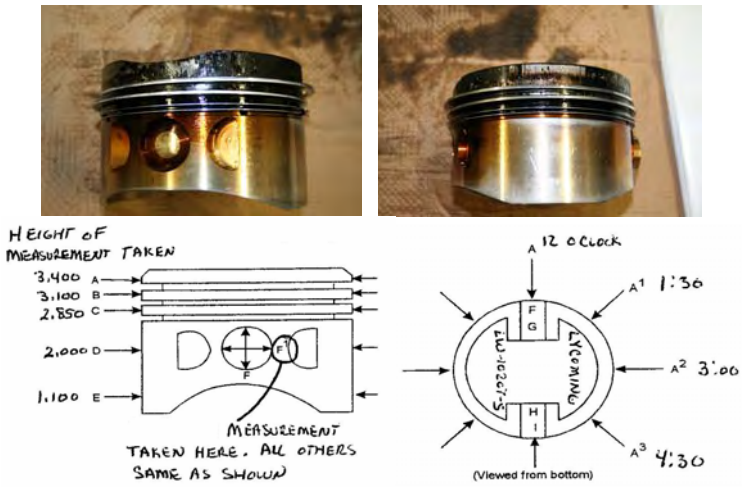


Figure 20. Pistons 5 and 6 and Measurement Locations

Table 25 shows the connecting rod bushing measurements and the measurement locations. As shown in the table, the wear was much less than the permissible wear of 0.0015 in. All the after measurements remained within new limit specifications, except for the A direction of rod 1, which was 1 ten thousandth of an inch outside the limit. There was no visible scoring of the bearings.

Table 25. Connecting Rod Bushing Measurements

Cylinder No.	Location	Dimensions		Wear	Connecting Rod Bushing (typical) and Measurement Locations
		Before	After		
1	A	1.1262	1.1263	0.0001	
	A'	1.1257	1.1257	0.0000	
	B	1.1262	1.1262	0.0000	
	B'	1.1258	1.1253	-0.0005	
2	A	1.1260	1.1261	0.0001	
	A'	1.1255	1.1258	0.0003	
	B	1.1259	1.1261	0.0002	
	B'	1.1256	1.1253	-0.0003	
3	A	1.1257	1.1258	0.0001	
	A'	1.1256	1.1254	-0.0002	
	B	1.1257	1.1260	0.0003	
	B'	1.1257	1.1252	-0.0005	
4	A	1.1256	1.1258	0.0002	
	A'	1.1257	1.1257	0.0000	
	B	1.1256	1.1256	0.0000	
	B'	1.1256	1.1256	0.0000	
5	A	1.1255	1.1257	0.0002	
	A'	1.1257	1.1253	-0.0004	
	B	1.1255	1.1256	0.0001	
	B'	1.1256	1.1254	-0.0002	

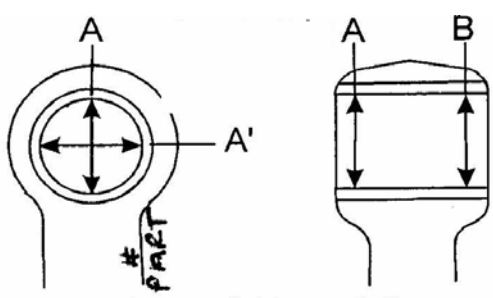


Table 25. Connecting Rod Bushing Measurements (Continued)

Cylinder No.	Location	Dimensions		Wear
		Before	After	
6	A	1.1253	1.1254	0.0001
	A'	1.1253	1.1250	-0.0003
	B	1.1254	1.1254	0.0000
	B'	1.1253	1.1250	-0.0003

All dimensions are in inches.

Table 26 shows the piston pins and the measurement locations. As shown in the table, there was negligible wear in the piston pins. All the piston pin-to-piston hole clearances were within maximum service limits, except for one of the eight directions in cylinder 3 and one of the eight directions in cylinder 4. All the piston pin-to-connecting rod bushing clearance measurements remained within the new limit specifications.

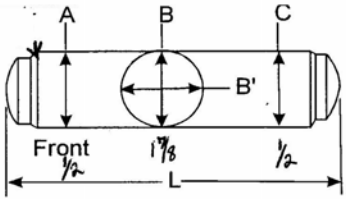
Table 26. Piston Pin Measurements

Cylinder No.	Location	Dimensions		Wear	Piston Pins and Measurement Location
		Before	After		
1	A	1.1245	1.1245	0.0000	
	A'	1.1245	1.1245	0.0000	
	B	1.1245	1.1245	0.0000	
	B'	1.1245	1.1245	0.0000	
	C	1.1245	1.1245	0.0000	
	C'	1.1245	1.1245	0.0000	
	L	3.746	3.746	0.0000	
2	A	1.1245	1.1245	0.0000	
	A'	1.1245	1.1245	0.0000	
	B	1.1245	1.1245	0.0000	
	B'	1.1245	1.1245	0.0000	
	C	1.1245	1.1245	0.0000	
	C'	1.1245	1.1245	0.0000	
	L	3.744	3.744	0.0000	
3	A	1.1245	1.1245	0.0000	
	A'	1.1245	1.1245	0.0000	
	B	1.1245	1.1245	0.0000	
	B'	1.1245	1.1245	0.0000	
	C	1.1245	1.1245	0.0000	
	C'	1.1245	1.1245	0.0000	
	L	3.745	3.745	0.0000	

Table 26. Piston Pin Measurements (Continued)

Cylinder No.	Location	Dimensions Before	Dimensions After	Wear
4	A	1.1245	1.1245	0.0000
	A'	1.1245	1.1245	0.0000
	B	1.1246	1.1246	0.0000
	B'	1.1246	1.1246	0.000
	C	1.1246	1.1245	-0.0001
	C'	1.1246	1.1245	-0.0001
	L	3.743	3.743	0.0000
5	A	1.1245	1.1245	0.0000
	A'	1.1245	1.1245	0.0000
	B	1.1245	1.1245	0.0000
	B'	1.1245	1.1245	0.0000
	C	1.1245	1.1245	0.0000
	C'	1.1245	1.1245	0.0000
	L	3.745	3.745	0.0000
6	A	1.1245	1.1245	0.0000
	A'	1.1245	1.1245	0.0000
	B	1.1245	1.1245	0.0000
	B'	1.1245	1.1245	0.0000
	C	1.1245	1.1245	0.0000
	C'	1.1245	1.1245	0.0000
	L	3.746	3.746	0.0000

Piston Pins and Measurement Location (Continued)



All dimensions are in inches.

The piston ring gap and tension measurements are shown in table 27, and the measurement locations are shown in figure 21. The gage gaps remained within the new limit specifications for both the oil control and compression rings. All the ring tensions remained within the new limit specifications.

Table 27. Piston Ring Measurements

Piston	Ring No.	Gage Gap (in.) Before	Gage Gap (in.) After	Gage Gap (in.) Wear	Free Gap (in.) Before	Free Gap (in.) After	Free Gap (in.) Wear	Tension (lb) Before	Tension (lb) After	Tension (lb) Wear
1	1	0.049	0.049	0.000	0.731	0.735	0.004	10.8	10.9	0.1
	2	0.049	0.049	0.000	0.724	0.735	0.011	11.0	11.1	0.1
	3	0.020	0.020	0.000	0.406	0.412	0.006	10.7	11.6	0.9
2	1	0.049	0.049	0.000	0.721	0.718	-0.003	11.1	10.9	-0.2
	2	0.049	0.049	0.000	0.722	0.728	0.006	11.1	10.8	-0.3
	3	0.020	0.020	0.000	0.406	0.410	0.004	10.5	10.4	-0.1
3	1	0.048	0.047	-0.001	0.719	0.725	0.006	10.8	10.6	-0.2
	2	0.048	0.045	-0.003	0.710	0.720	0.010	10.8	10.8	0.0
	3	0.021	0.021	0.000	0.392	0.405	0.013	11.9	11.8	-0.1

Table 27. Piston Ring Measurements (Continued)

Piston	Ring No.	Gage Gap (in.)				Free Gap (in.)				Tension (lb)		
		Before	After	Wear		Before	After	Wear		Before	After	Wear
4	1	0.048	0.049	0.001		0.718	0.725	0.007		10.8	10.6	-0.2
	2	0.048	0.049	0.001		0.720	0.727	0.007		10.7	10.6	-0.1
	3	0.020	0.020	0.000		0.411	0.415	0.004		11.6	10.9	-0.7
5	1	0.048	0.046	-0.002		0.722	0.727	0.005		10.9	10.6	-0.3
	2	0.048	0.047	-0.001		0.721	0.725	0.004		10.9	10.8	-0.1
	3	0.020	0.020	0.000		0.396	0.405	0.009		11.1	11.0	-0.1
6	1	0.048	0.048	0.000		0.721	0.726	0.005		10.7	10.7	0.0
	2	0.048	0.048	0.000		0.713	0.718	0.005		10.9	10.9	0.0
	3	0.021	0.021	0.000		0.413	0.420	0.007		11.6	12.1	0.5

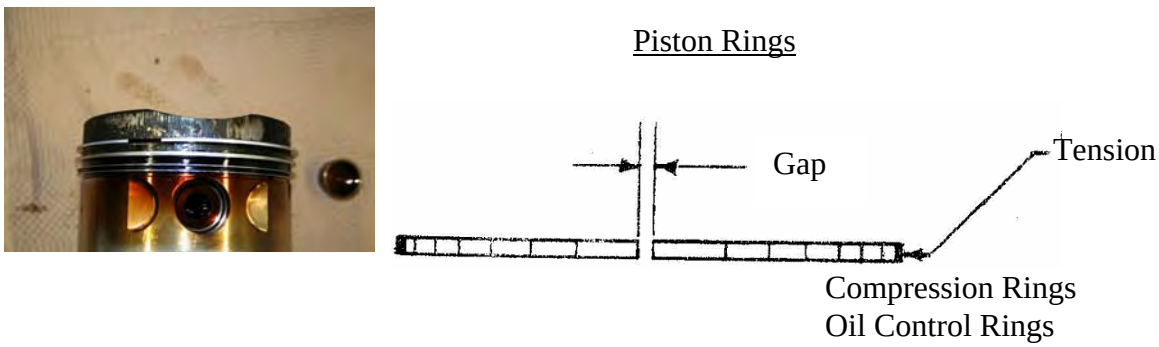


Figure 21. Piston Rings and Measurement Locations

Table 28 shows the piston ring side clearances, and figure 22 shows the measurement locations. All the top ring clearances remained the same throughout the test. All the second compression ring clearances remained within the new specification limits, except for cylinder 2, which was within the allowable service limit of 0.006 inch. All the oil control ring side clearances remained within the new limit specifications.

Table 28. Piston Ring Side Clearance Measurements

Cylinder No.	Ring No.	Dimensions		Wear
		Before	After	
1	1	0.0050	0.0050	0.0000
	2	0.0030	0.0040	0.0010
	3	0.0025	0.0030	0.0005
2	1	0.0050	0.0050	0.0000
	2	0.0030	0.0050	0.0020
	3	0.0025	0.0030	0.0005
3	1	0.0050	0.0050	0.0000
	2	0.0030	0.0040	0.0010
	3	0.0025	0.0020	-0.0005
4	1	0.0050	0.0050	0.0000
	2	0.0030	0.0040	0.0010
	3	0.0025	0.0020	-0.0005
5	1	0.0050	0.0050	0.0000
	2	0.0030	0.0040	0.0010
	3	0.0025	0.0020	-0.0005
6	1	0.0050	0.0050	0.0000
	2	0.0030	0.0030	0.0000
	3	0.0025	0.0020	-0.0005

All dimensions are in inches.

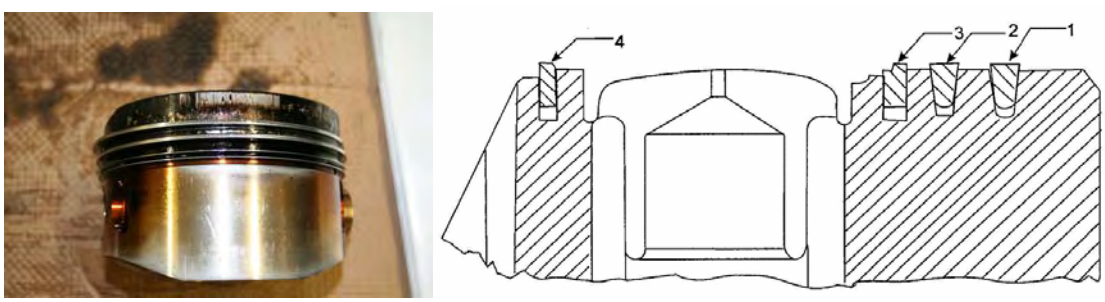


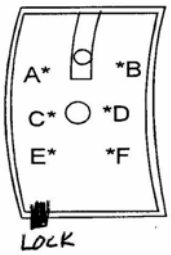
Figure 22. Piston Rings and Side-Clearance Measurement Locations

Table 29 shows the connecting rod bearing thickness measurements and the measurement locations. Figure 23 shows the connecting rod bearings. The measurements show that none of the bearing thickness changes were greater than 1 thousandth of an inch and the photographs show normal wear modes.

Table 29. Connecting Rod Bearing Thickness

Cylinder No.	Location	Rod Side Before	Rod Side After	Rod Side Change	Location	Crankshaft Side Before	Crankshaft Side After	Crankshaft Side Change
1	A	0.0852	0.0854	0.0002	A	0.0850	0.0852	0.0002
	B	0.0850	0.0853	0.0003	B	0.0853	0.0852	-0.0001
	C	0.0850	0.0849	-0.0001	C	0.0851	0.0854	0.0003
	D	0.0852	0.0851	-0.0001	D	0.0854	0.0852	-0.0002
	E	0.0847	0.0855	0.0008	E	0.0848	0.0850	-0.0002
	F	0.0850	0.0855	0.0005	F	0.0848	0.0858	0.0010
2	A	0.0853	0.0849	-0.0004	A	0.0854	0.0857	0.0003
	B	0.0849	0.0852	0.0003	B	0.0851	0.0851	0.0000
	C	0.0855	0.0849	-0.0006	C	0.0849	0.0858	0.0009
	D	0.0853	0.0853	0.0000	D	0.0852	0.0854	0.0002
	E	0.0854	0.0855	0.0001	E	0.0847	0.0855	0.0008
	F	0.0851	0.0852	0.0001	F	0.0854	0.0852	-0.0002
3	A	0.0851	0.0854	0.0003	A	0.0854	0.0850	-0.0004
	B	0.0846	0.0854	0.0008	B	0.0854	0.0853	-0.0001
	C	0.0851	0.0855	0.0004	C	0.0853	0.0858	0.0005
	D	0.0851	0.0853	0.0002	D	0.0852	0.0854	0.0002
	E	0.0853	0.0852	-0.0001	E	0.0853	0.0851	-0.0002
	F	0.0855	0.0853	-0.0002	F	0.0851	0.0854	0.0003
4	A	0.0848	0.0847	-0.0001	A	0.0852	0.0851	-0.0001
	B	0.0848	0.0851	0.0003	B	0.0844	0.0850	0.0006
	C	0.0857	0.0848	-0.0009	C	0.0852	0.0852	0.0000
	D	0.0849	0.0848	-0.0001	D	0.0853	0.0854	0.0001
	E	0.0848	0.0851	0.0003	E	0.0849	0.0854	0.0005
	F	0.0857	0.0851	-0.0006	F	0.0850	0.0855	0.0005
5	A	0.0854	0.0853	-0.0001	A	0.0859	0.0859	0.0000
	B	0.0853	0.0854	0.0001	B	0.0849	0.0856	0.0007
	C	0.0857	0.0852	-0.0005	C	0.0856	0.0852	-0.0004
	D	0.0853	0.0852	-0.0001	D	0.0852	0.0852	0.0000
	E	0.0850	0.0855	0.0005	E	0.0850	0.0850	0.0000
	F	0.0855	0.0853	-0.0002	F	0.0850	0.0855	0.0005
6	A	0.0854	0.0851	-0.0003	A	0.0850	0.0854	0.0004
	B	0.0854	0.0852	0.0002	B	0.0852	0.0859	0.0007
	C	0.0853	0.0852	-0.0001	C	0.0854	0.0858	0.0004
	D	0.0855	0.0854	-0.0001	D	0.0857	0.0858	0.0001
	E	0.0850	0.0851	0.0001	E	0.0849	0.0852	0.0003
	F	0.0848	0.0851	0.0003	F	0.0860	0.0850	-0.0010

Measurement Locations



All dimensions are in inches.

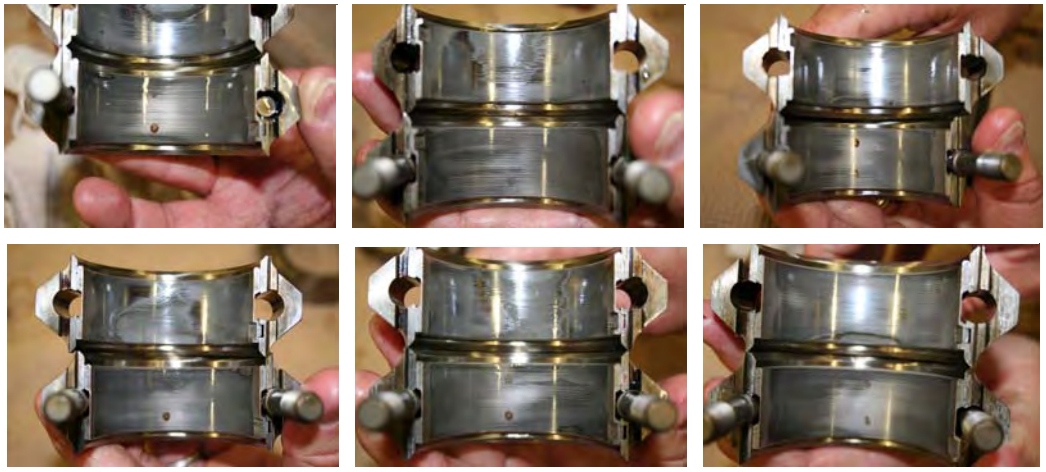


Figure 23. Connecting Rod Bearings

The oil pump gear measurements are shown in table 30, and figure 24 shows the measurement locations. There was visible scoring of wear grooves in the pump housing, and the measurements show there was negligible wear in the engine drive and driven oil pump gears.

Table 30. Oil Pump Gear Measurements

	Location	Dimensions		Wear
		Before	After	
LW 18109	A	1.8604	1.8602	0.0002
	A'	1.8603	1.8602	-0.0001
	B	1.8604	1.8602	0.0002
	B'	1.8609	1.8603	-0.0006
	C	0.7488	0.7488	0.0000
	D	0.7488	0.7485	-0.0003
LW 18110	A	1.8614	1.8614	0.0000
	A'	1.8616	1.8616	0.0000
	B	1.8614	1.8615	0.0001
	B'	1.8610	1.8615	0.0005
	C	0.7487	0.7487	0.0000
	D	0.7486	0.7486	0.0000

All dimensions are in inches.

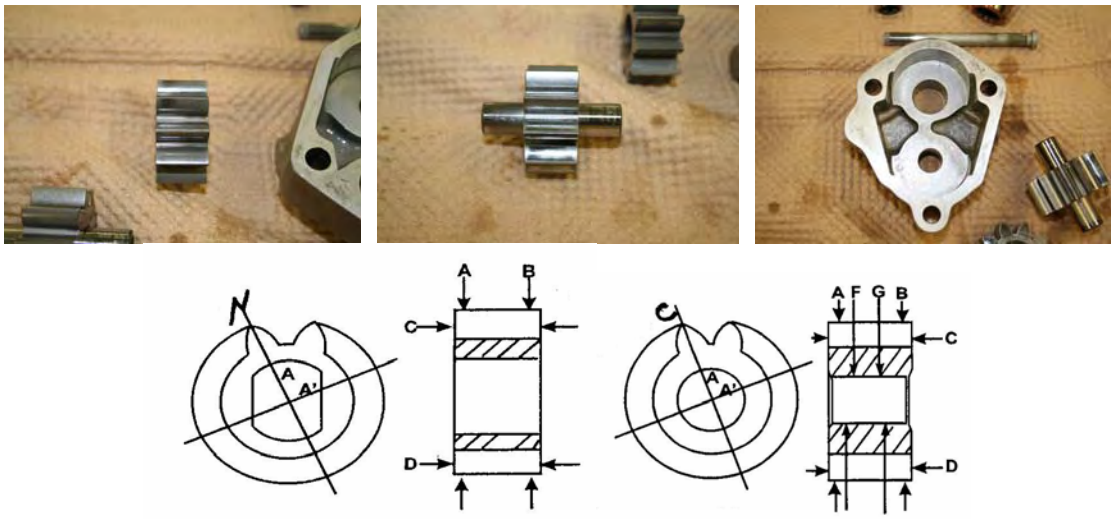


Figure 24. Oil Pump Impellers, Housing, and Measurement Locations

Figure 25 shows the valve rocker arm and pin for the exhaust valve in cylinder 2. All shafts, valve contact surfaces, and bushings showed normal wear modes for all cylinders. There was no noticeable wear grooves or scoring.

Figure 25. Rocker Arm and Pin for the Exhaust Valve in Cylinder 2

Table 31 shows the results of the static cylinder compression tests. All compression measurements were performed with a warm engine. Note, all compression values showed level trends and remained above 70 psig throughout the test. These results also suggest minimal cylinder barrel, piston ring, piston, and valve wear was occurring.

Table 31. Cylinder Compression Results

Engine Hours	Cylinder No. (psig)					
	1	2	3	4	5	6
12.9	72	74	74	74	74	72
50	72	74	76	76	76	72
98.6	72	76	75	74	75	70
148.5	74	74	72	76	76	76
179.2	72	72	76	74	76	72

The evidence for minimal combustion chamber wear was also found in the power baseline results, shown in figures 26 through 32 for the Lycoming IO540-K engine before and after the endurance test. Figure 26 contains corrected brake horsepower (HP) data, as the test was run at 60ºF inlet air temperature and 400ºF maximum cylinder head temperature. The data in figure 26 is for a best-power mixture setting. Full mixture lean-out curves for each respective engine speed tested are shown in figures 27 through 32. In these figures, each curve is for a constant manifold pressure.

The engine power loss was minimal and approximated 3-4 HP, or approximately 1% of takeoff power over the duration of the test. Moreover, the posttest maximum power of 295 HP was within 1.7% of the 300-rated HP.

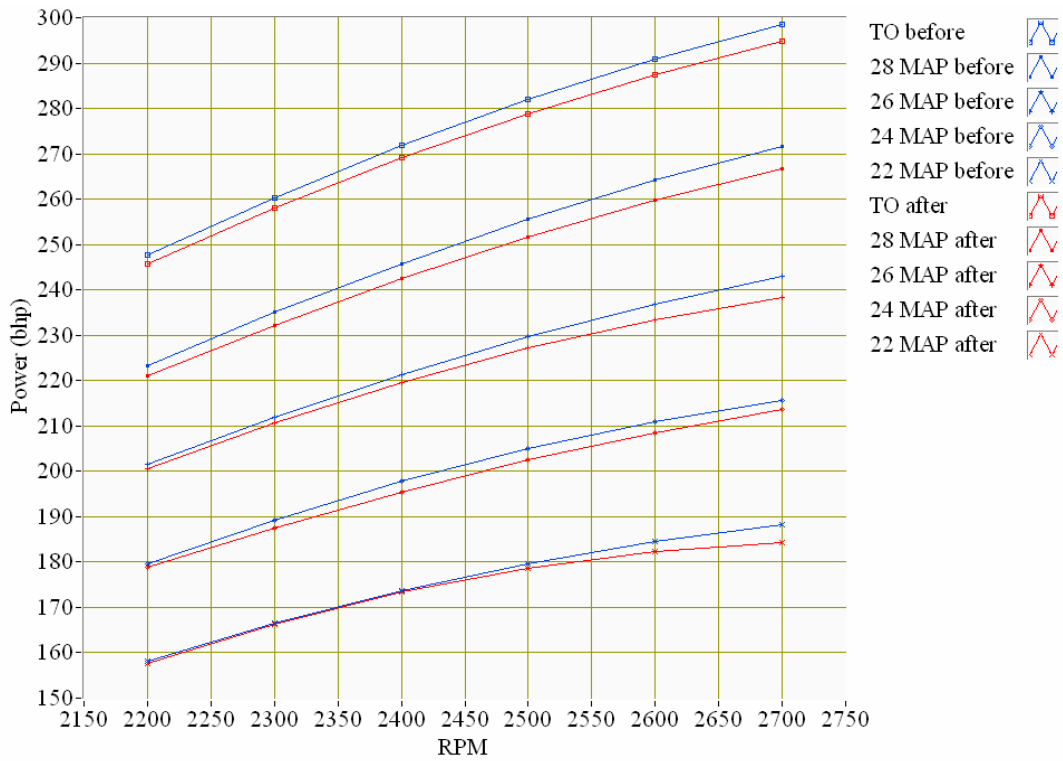


Figure 26. Power Baseline Data Before and After the Endurance Test

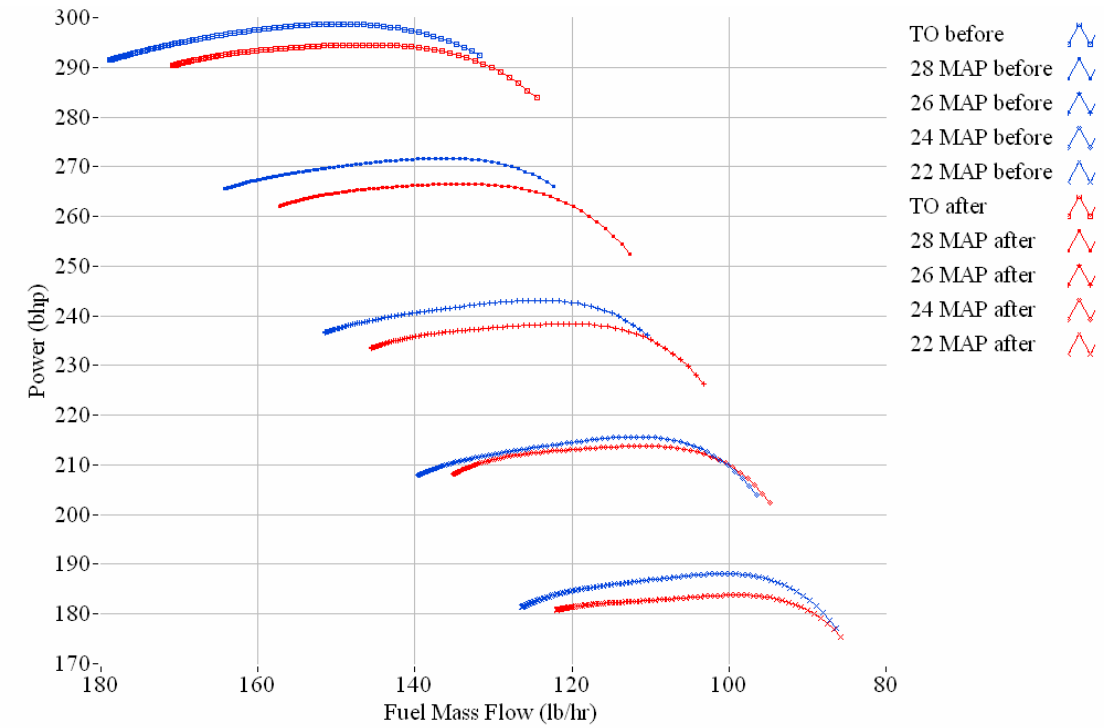


Figure 27. Mixture Lean Curves for 2700 rpm

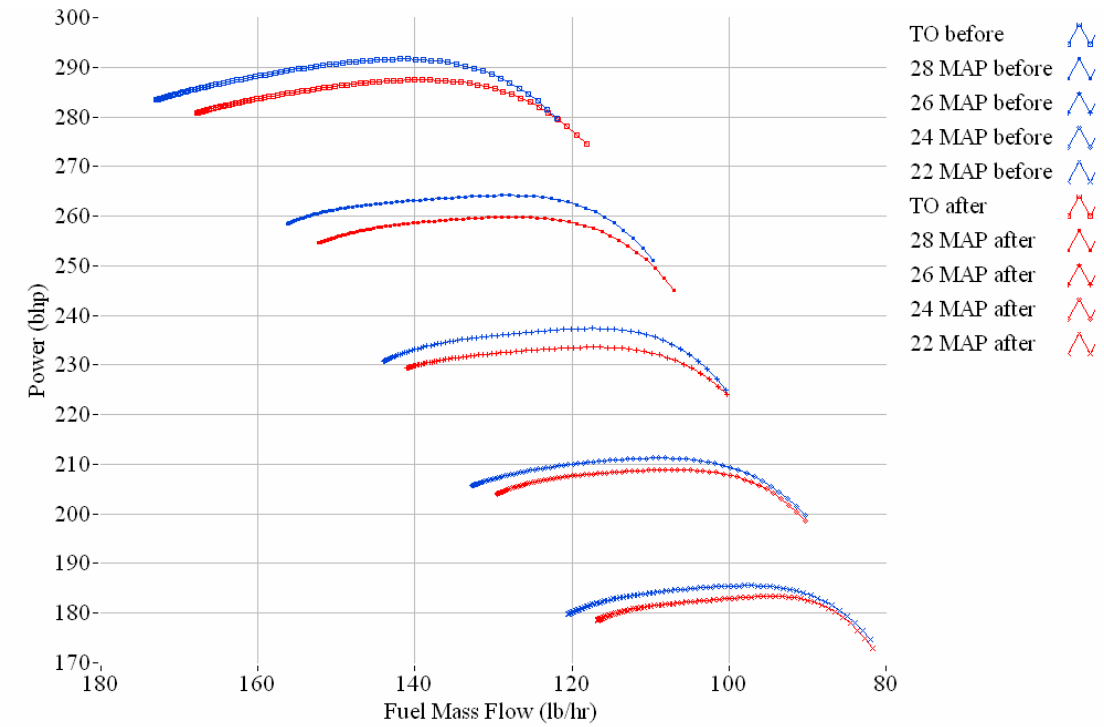


Figure 28. Mixture Lean Curves for 2600 rpm

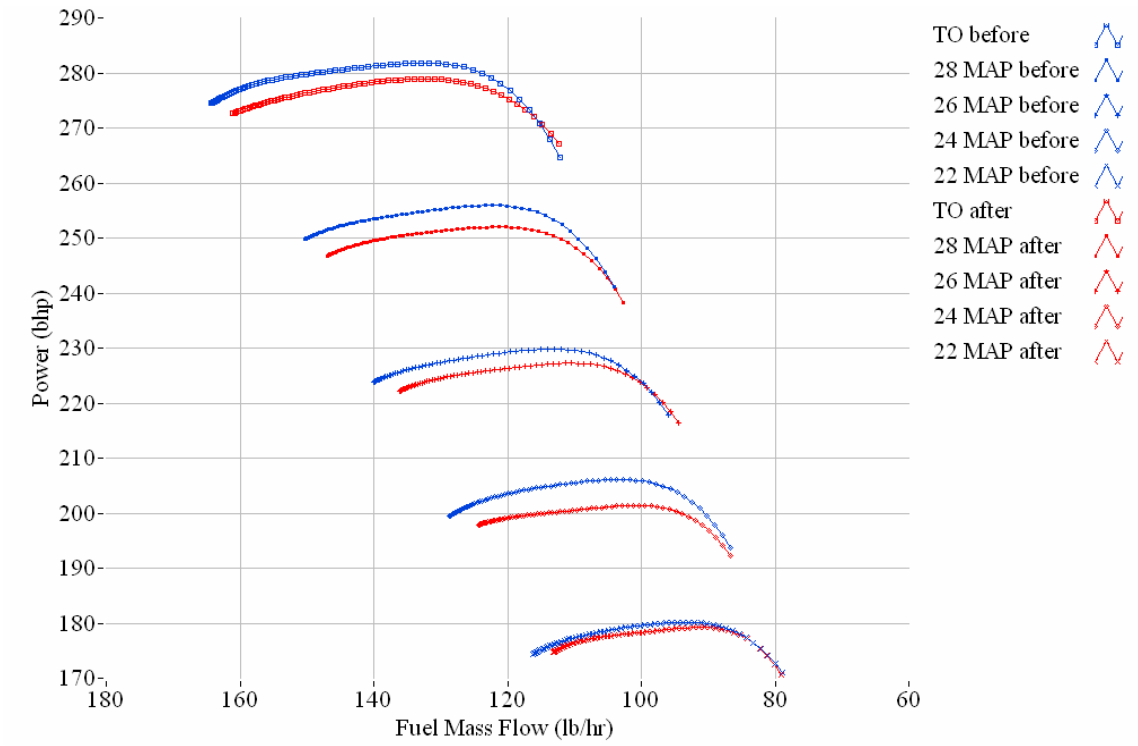


Figure 29. Mixture Lean Curves for 2500 rpm

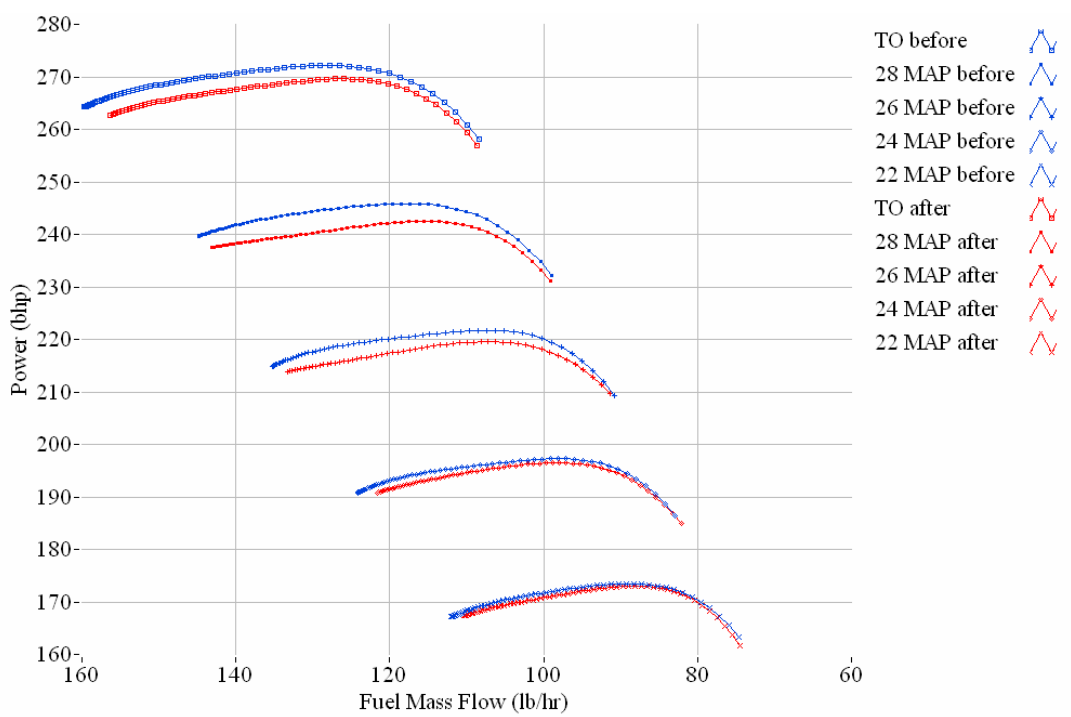


Figure 30. Mixture Lean Curves for 2400 rpm

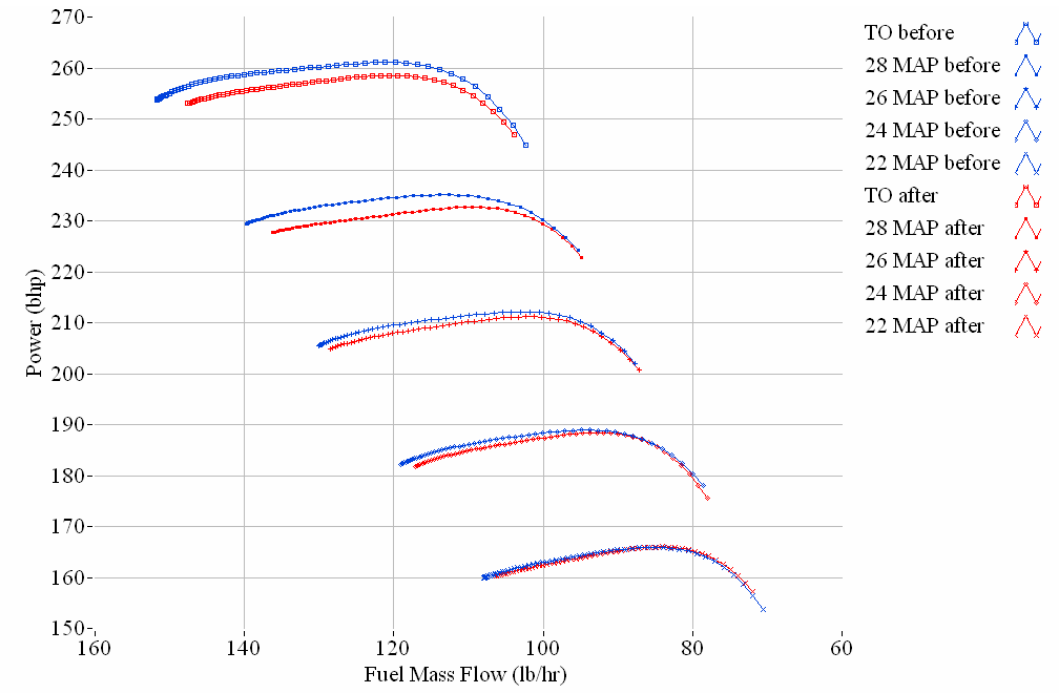


Figure 31. Mixture Lean Curves for 2300 rpm

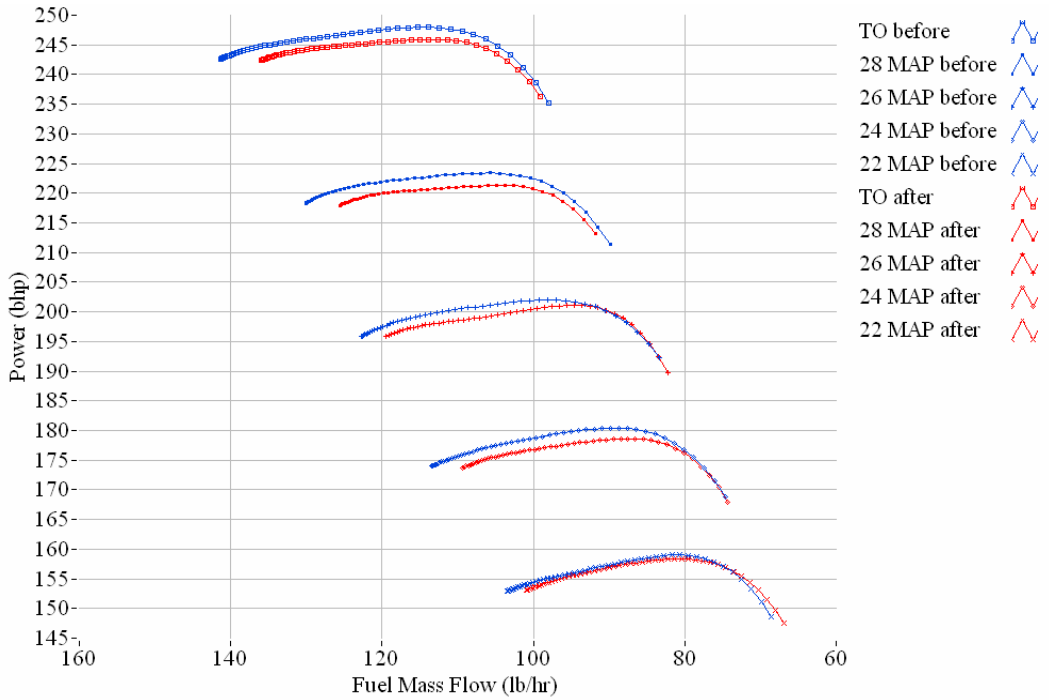


Figure 32. Mixture Lean Curves for 2200 rpm

3.3 ENGINE DEPOSITS.

As discussed in section 3.1 and shown in figure 4, the main component of the Swift binary blend is a heavy aromatic with a high boiling point. One of the major concerns with use of heavy components is the potential for heavy engine deposits. The teardown showed that excessive combustion chamber deposits were not found. This is largely attributable to the use of an aromatic that has strong solvent properties. Figures 33 and 34 show the intake and exhaust valves for cylinders 1 through 3 and 4 through 6, respectively. The valves show light deposit buildup and minimal valve face wear grooves. Figure 35 shows the combustion chambers for all six cylinders. Combustion chamber deposits were light, and the cylinder cross hatching was still visible. Figure 36 shows the piston face. Again, there was light deposit buildup. Figures 34 through 36 show a dark discoloration, darker than typically found with the use of traditional leaded aviation gasoline.

Figure 33. Intake (left) and Exhaust (right) Valve Pictures Taken at the end of Endurance Test (cylinders 1 through 3)

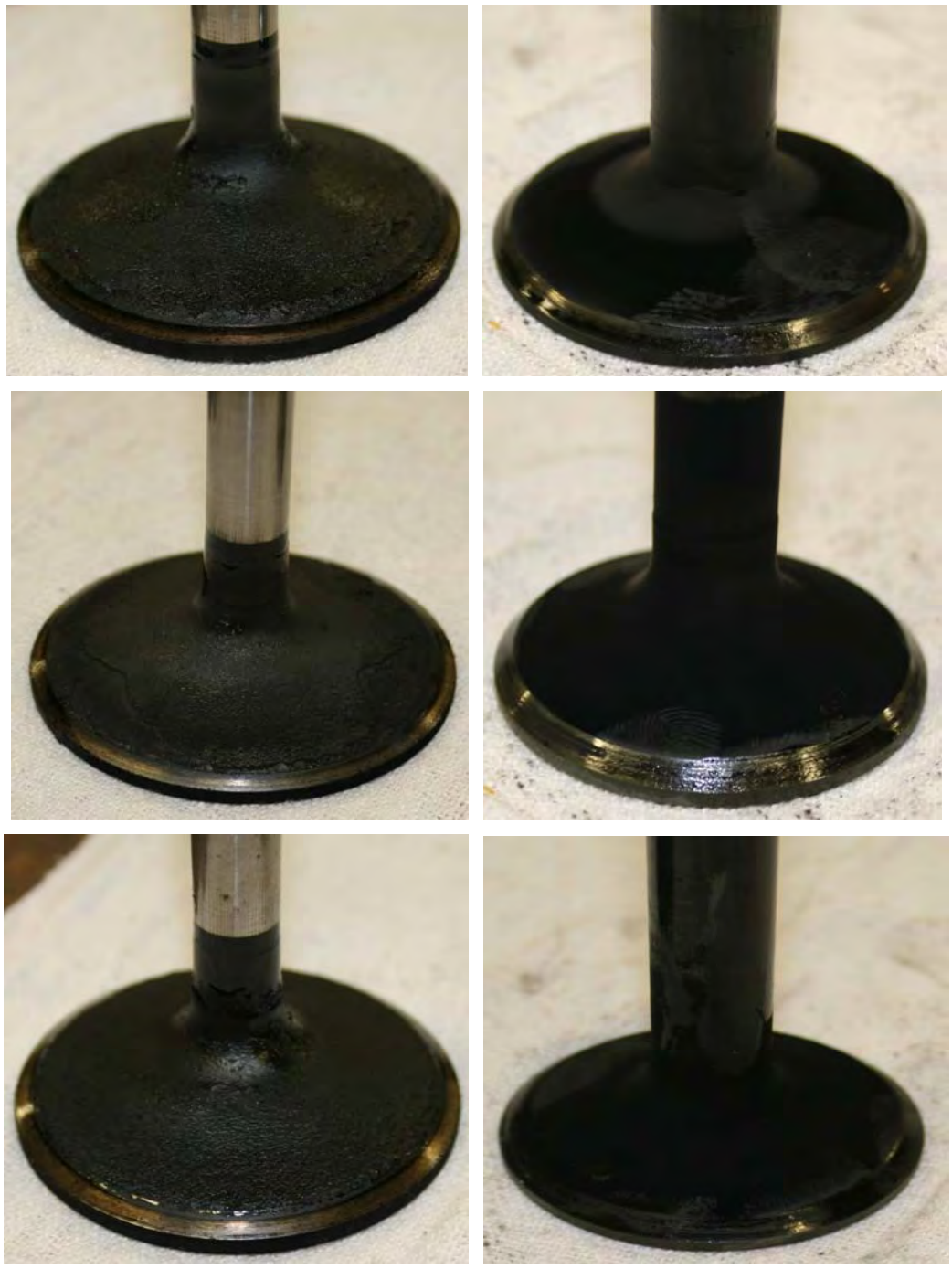


Figure 34. Intake (left) and Exhaust (right) Valve Pictures Taken at the end of Endurance Test (cylinders 4 through 6)

Figure 35. Light Combustion Chamber Deposits for all six Cylinders
(shown from top left to bottom right)

Figure 36. Light Deposit Formation on Piston Faces for all six Cylinders
(shown from top left to bottom right)

The rocker arm covers in figure 37 show very light deposits and some dark discoloration on the valve area.

Figure 37. Light Deposit Formation on Rocker Arms and Rocker Arm Covers
(shown from top left to bottom right)

Figure 38 shows the oil pump housing, crankcase housing bottom, oil sump and induction housing, and accessory housing. These show an almost total lack of varnish, sludge, or deposit buildup in the oil-wetted parts of the engine. Note the absence of wear grooves or scars in the oil pump housing. The dark discoloration observed in the higher-temperature areas previously discussed is not shown in figure 38.

As shown in previous figures, the piston sides and ring lands also averaged light deposits. The oil pickup tube, pushrod tubes, and oil rings were unclogged and all piston rings moved freely.

Table 32 and figure 39 show the nozzle flow test results taken at 50 engine-hour intervals. The results showed that the use of the Swift binary blend heavy component did not result in nozzle deposits or nozzle flow imbalances.

Figure 38. Oil Pump Housing, Crankcase Housing Bottom, Oil Sump and Induction Housing, and Accessory Housing Showing Light Deposit Formation (referenced from top left to bottom right)

Table 32. Nozzle Flow Tests

Engine Hours	Difference From Mean (%)					
0	1.8	3.7	-2.0	1.8	-4.6	-0.7
50	1.1	2.3	-1.3	1.7	-3.7	-0.1
98.6	0.4	2.9	-2.1	1.6	-2.7	-0.2
148.5	1.0	3.4	-2.0	2.8	-5.0	-0.2
179.2	0.1	2.5	-3.4	3.1	-3.4	1.3

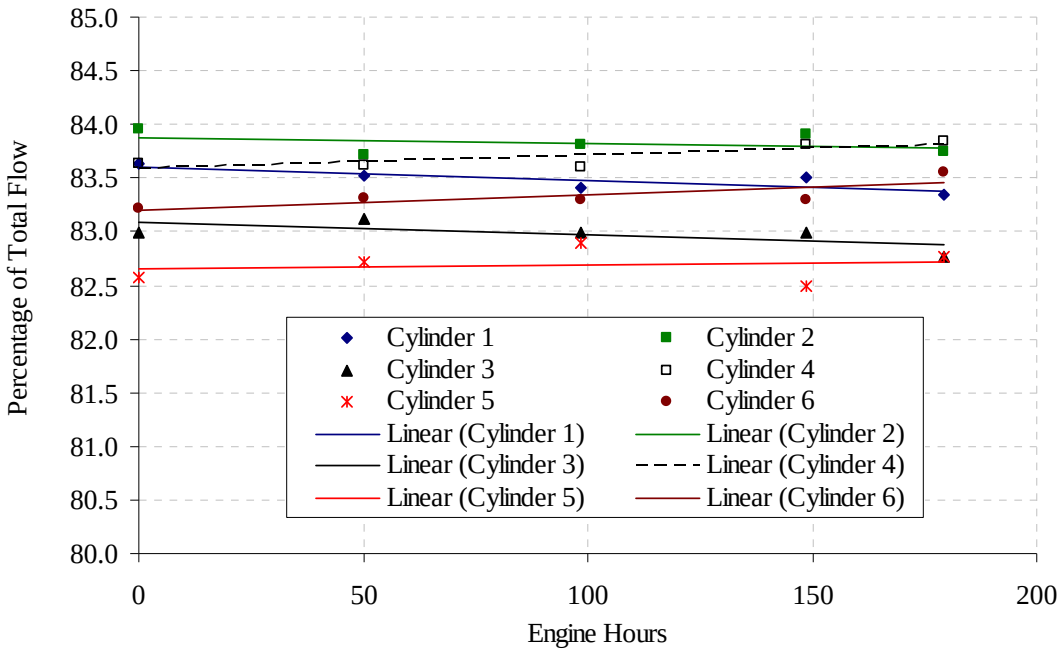


Figure 39. Nozzle Flow Measurements

Figure 40 shows the bottom and top spark plug photographs taken at the end of the test. The plugs were rotated but not cleaned during the test. The photographs show a dark discoloration and light deposit formation.

Figure 40. Spark Plug Photographs Taken Posttest
(top row for top plugs and bottom row for bottom plugs)

A summary deposit formation-rating table is shown in table 33.

Table 33. Sludge, Varnish, and Carbon Deposits Ratings

Description	Rating	Notes
Sludge Deposits		
Rocker arm covers	9.7	10.0 = absence of deposit
Oil sump	9.8	10.0 = absence of deposit
Varnish Deposits		
Rocker arm covers	9.7	10.0 = absence of deposit, 1 = completely covered with varnish
Piston ring lands	8.0	10.0 = absence of deposit, 1 = completely covered with varnish
Clogging		
Push rods	0	0 = unclogged
Oil ring	0	0 = unclogged
Oil pickup tube	0	0 = unclogged
Carbon Deposits		
Grooves 1	0.75	0.75 = light carbon 0 = heavy carbon
Grooves 2	0.75	0.75 = light carbon 0 = heavy carbon
Grooves 3	0.75	0.75 = light carbon 0 = heavy carbon
Intake valves	9.0	10.0 = absence of deposit, 1 = completely covered
Exhaust valves	9.5	10.0 = absence of deposit, 1 = completely covered
Additional Ratings		
Stuck valve lifters	0	0 = free, 10 = stuck
Stuck compression rings	0	0 = free, 10 = stuck
Stuck oil rings	0	0 = free, 10 = stuck
Main bearings	Excellent condition	Visual inspection
Rod bearings	Excellent condition	Visual inspection
Diaphragms	Fuel pump: light cracks; all other: excellent condition	Visual inspection
Wrist pin spalling	None	Visual inspection
Valve stem tip wear	None	Visual inspection

3.4 MATERIAL COMPATIBILITY.

The use of a high-aromatic fuel could also result in material compatibility issues, particularly regarding elastomers, o-rings, and seals. The throttle and mixture tension were measured at the start of each test, and the results are shown in table 34 and figure 41. The lever arm tension increased at the start of the test and then leveled off at the 50 to 100 engine-hour mark.

Table 34. Throttle and Mixture Stiffness

Engine Hours	Lever Arm Resistance (in-lb)	
	Throttle	Mixture
1	2.5	1
7	2.5	1
12.9	2.5	1
14.6	3	1
24.1	3	1.5
33.5	3	1.5
42.8	3.5	1.7
50	3.7	2
53.5	3.5	2
62.8	3.5	2
71.2	3.5	2
80.9	3.5	2
90.1	3.5	2
98.6	3	2
101.8	3	2
111.3	3	2
120.7	3	2
130.1	3	2
139.6	3	2
148.5	3	2
155.8	3	2
164.6	3	2
174	3	2
176.8	3	2

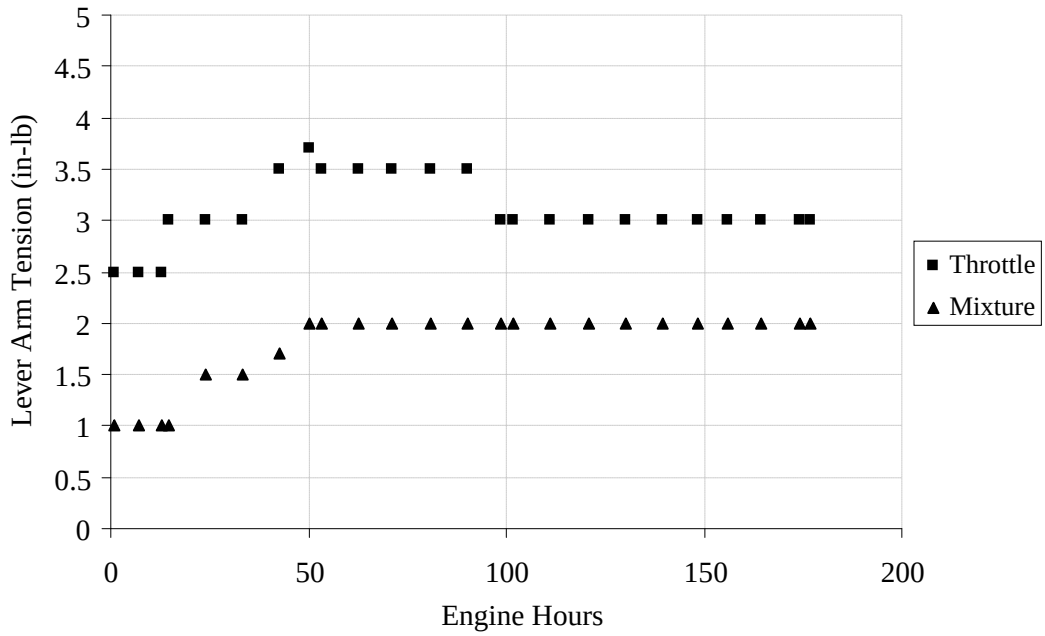


Figure 41. Throttle and Mixture Lever Arm Tension Measurements

Figure 42 shows the diaphragms in the fuel metering unit, fuel pump, and fuel distribution valve. The fuel metering unit and fuel distribution valve diaphragms did not show excess pliability, stiffness, or cracking. The fuel pump diaphragm showed creases. The fuel pump outlet pressure remained within Lycoming's acceptable range during the tests.

Figure 42. Fuel Metering Unit Diaphragm Showing No Marks or Creases (left), Fuel Pump Secondary Diaphragm Showing Marks and Creases (center), and Fuel Distribution Valve Diaphragm Showing No Marks or Creases (right)

4. SUMMARY AND RECOMMENDATIONS.

Swift Enterprises supplied 4500 gallons of a binary blend to the FAA AFETF for a 150-hour engine endurance test. This was a joint effort by the FAA AFETF, Textron Lycoming, and Swift Enterprises. The Swift binary blend's two main components were made in a refinery, not in a bio-process. The 150-hour test used a Lycoming IO540-K engine and followed the 14 CFR 33.47 endurance block test. The test was severe, as most of the test time was spent at maximum-rated power under maximum engine and oil temperatures. Prior to overhaul, the remanufactured

engine was torn down and measured by Textron Lycoming, reassembled, and sent to the AFETF for break-in and testing. At the end of the test the engine was sent back to Lycoming for remeasurement. The engine was broken in, and operated solely on Swift binary blend, which consisted of 82.5% mass mesitylene and 16.6% mass isopentane, with approximately 1% of other hydrocarbon components.

The Swift binary blend met all current aviation gasoline ASTM D 910 specifications for 100LL, except it was unleaded and undyed and had a 3.7% reduced specific energy content, and it did not meet the requirements for distillation slope at the 50%, 90%, and end point temperatures. The fuel weighed an average of 1 lb/gal more than traditional aviation gasoline and, therefore, had roughly 13% more energy per gallon of fuel. The consequence of additional fuel weight on an airframe and the potential to affect pilot operating handbook performance curves were beyond the scope of this research and were not addressed. Fuel storage and aging issues were also beyond the scope of this research and were not addressed. Detonation and power performance of another Swift binary blend were evaluated in a previous FAA report [1].

Using the Swift binary blend resulted in 1% oil dilution, normal engine wear, light engine combustion deposits, light fuel system deposits, and very light oil system deposits. The fuel injector nozzles did not experience visible deposit formation or noticeable fuel distribution issues.

Starting difficulty was noted on mornings after the engine was left to sit overnight. Starting was immediate with a warm engine. It is recommended that start-ability issues be addressed in actual airframes rather than in a test cell environment.

The only material compatibility issue uncovered by this limited test was stretch marks or creases on the fuel secondary pump diaphragm. No noticeable creases, softness, or brittleness were noticed in the fuel-metering unit and distribution valve diaphragms or the throttle and mixture o-rings. The fuel pump outlet pressure remained within Lycoming's acceptable range during the tests. Compatibility of fuel pump elastomers with Swift binary fuel is an area that requires further extensive rig and soak testing.

This type of endurance test cannot adequately address material compatibility issues. These issues should be addressed with a material compatibility study involving all the wetted parts of the engine using typical materials found throughout engine and aircraft fuel systems. Further, it is recommended that this endurance test be repeated using a straight-weight mineral oil without deposit control additives.

This test does not constitute FAA certification, endorsement, or approval of any kind. Further, it is recommended that Swift Enterprises perform further tests to address fit-for-purpose specification properties using a Swift binary blend made from their fermentation process.

5. REFERENCES.

1. Atwood, D., "Full-Scale Engine Detonation and Power Performance Evaluation of Swift Enterprises 702 Fuel," FAA report DOT/FAA/AR-08/53, January 2009.

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3. Atwood, D., "High-Octane and Mid-Octane Detonation Performance of Leaded and Unleaded Fuels in Naturally Aspirated, Piston, Spark Ignition Aircraft Engines," FAA report DOT/FAA/AR-TN07/5, March 2007.