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Spark Ignition Aircraft Engine Endurance Test of Aviation-Grade Ethanol 85

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Final Report

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16. Abstract

For the last several years, the Airport and Aircraft Safety Research and Development Division at the Federal Aviation Administration (FAA) William J. Hughes Technical Center has sponsored research on aviation fuels containing at least 80% ethanol at the South Dakota State University. In parallel, the Airport and Aircraft Safety Research and Development Division at the FAA William J. Hughes Technical Center performed an endurance test on aviation-grade ethanol 85 (AGE-85), a blend of at least 85% ethanol denatured with 2% automotive gasoline, less than 1% biodiesel, and the rest pentane isomerate. A recently overhauled Lycoming IO360-C engine was modified to operate on AGE-85 by adjusting the engine ignition timing to 15° before top dead center (BTDC) from the standard 20° BTDC setting, by increasing the fuel servo injector jet diameter and by replacing the fuel injection nozzles with higher-volume nozzles to allow increased fuel mass flow. Power performance baseline tests and a 150-hour endurance test were performed. The endurance test was performed under severe conditions at best power fuel mixture and used AGE-85 from sealed drums containing less than 0.2% water. The high-stress components of the Lycoming IO360-C engine were measured before and after the 150-hour test. Under the conditions of this test, the results indicated that the engine experienced normal wear except for the exhaust valve faces and stems, which showed a hammered effect. There were minimal combustion and fuel system deposits and a moderate level of intake valve deposits. The engine produced an average of 2.8% more peak horsepower on AGE-85 than isooctane (ISO) but required an average of 56.5% more fuel mass flow. This resulted in a drop in efficiency at maximum power from 0.470 lb/hphr for ISO to 0.716 lb/hphr for AGE-85. The AGE-85 produced exhaust gas temperatures that averaged 20°F higher than ISO at best power mixture strength.

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LIST OF ACRONYMS

100 low-lead	100LL
AGE-85	Aviation-Grade Ethanol 85
ASTM	American Society for Testing Materials
BHP	Brake horsepower
BSFC	Brake-specific fuel consumption
BTDC	Before top dead center
CHT	Cylinder head temperature
EGT	Exhaust gas temperature
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FT	Full throttle
IAT	Inlet air temperature
ISO	Isooctane
MAP	Modified absolute pressure
MON	Motor octane number
rpm	Revolutions per minute
TO	Takeoff

EXECUTIVE SUMMARY

In 2004, the Federal Aviation Administration (FAA) funded the South Dakota State University in a multiyear effort to research the use of aviation-grade ethanol 85 (AGE-85), a blend of at least 85% ethanol denatured with 2% automotive gasoline, less than 1% biodiesel, and pentane isomerate. In a parallel effort, researchers in the Airport and Aircraft Safety Research and Development Division Propulsion and Fuel Systems Branch at the FAA William J. Hughes Technical Center evaluated AGE-85 in an overhauled Lycoming IO360-C, four-cylinder, spark ignition, piston aircraft engine. The engine is type-certificated to operate on either 100 or 100 low-lead (100LL) American Society for Testing and Materials D 910-grade aviation gasoline. The engine fuel control servo was modified with an oversized main metering jet and the fuel distribution nozzles were enlarged to allow increased fuel mass flow. The engine ignition timing was retarded by 5° to 15° before top dead center (BTDC).

The test procedures were similar to those of Title 14 Code of Federal Regulations Parts 33-49. The test evaluated engine endurance performance at severe and controlled conditions addressing such issues as wear, performance, materials compatibility, range, efficiency, oil dilution, and deposit formation. The majority of the testing was performed at full-rated power and engine speed under maximum engine and oil temperatures, at best power fuel mixture setting.

The fuel was tested from sealed drums containing less than 0.2% water on a volume basis. Under the conditions of this test, the results indicated that there was no excessive wear on any of the high-contact, high-stress parts of the engine except for the hammered effect on the exhaust valve faces and seats. This may have been a consequence of operating the engine at the 5° retarded timing. There were minimal piston face and valve deposits and moderate intake valve deposits. There were minimal fuel system deposits and engine varnish and sludge buildup.

Prior to the start of the endurance test and at the completion of the endurance test, a series of power baselines were run using both AGE-85 at the 15° BTDC ignition timing and isooctane (ISO) at the standard ignition timing of 20° BTDC. The engine produced an average of 4.3 (2.8%) more peak horsepower when operating on the AGE-85 than it did when operating on ISO. However, peak power required 39.7 lb/hr (56.5%) more fuel mass flow with the AGE-85 than with ISO. This equates to an average increase of 5.6 gal/hr (35%) fuel volume flow. This reduced the efficiency from an average peak power brake-specific fuel consumption (BSFC) of 0.470 lb/break horsepower (bhp) hr for ISO to 0.716 lb/bhp hr for AGE-85. The AGE-85 produced 1.8% more power at best economy fuel mixture than 100LL but required 55.8% more fuel mass flow. This reduced the average best economy BSFC from 0.415 lb/bhp hr for ISO to 0.640 lb/bhp hr for AGE-85. Average exhaust gas temperatures were 20°F higher with AGE-85 than with ISO at the best power mixture. Using AGE-85 would increase fuel weight by 9% above 100LL values due to its 6.4 lb/gal mass density versus 5.87 lb/gal for 100LL and would reduce engine range by 35%.

This testing showed that without significant modifications to existing engine design beyond retarding the ignition timing, such as increasing cylinder compression ratios, changing valve timing, and derating engine power, adjustments to the fuel schedule for a 100- or 100LL-certificated engine would be required to provide upwards of 57% more fuel mass flow or 35%

more fuel volume flow. Future tests will compare the detonation performance of AGE-85 at standard engine ignition timing to 100LL in a 100/100LL-certificated IO360-A engine.

1. INTRODUCTION.

1.1 PURPOSE.

This research evaluates the power and endurance performance of a blend of 85% denatured ethanol, pentane isomerate, and biodiesel in a recently overhauled and modified four-cylinder Lycoming IO360-C engine.

1.2 BACKGROUND.

The Environmental Protection Agency (EPA) has exempted the general aviation community from compliance with a 1990 Clean Air Act Amendment, which banned the sale of fuels containing lead additives. Now that the general aviation community has become a leading source of airborne lead, the duration of the EPA exemption is uncertain. Furthermore, as lead scavengers such as ethylene dibromide and lead tainted oils face elevated scrutiny, economic pressures to replace the current 100LL general aviation fuel with a high-octane, unleaded alternative are expected to increase. Researchers in the Airport and Aircraft Safety Research and Development Division Propulsion and Fuel Systems Branch at the Federal Aviation Administration (FAA) William J. Hughes Technical Center, along with the Coordinated Research Council Unleaded Avgas Development Subcommittee (which is comprised of aircraft manufacturers, engine manufacturers, petroleum producers, other regulatory agencies, and aircraft owner's and pilot's associations) have tested many blends of high-octane unleaded aviation gasolines in spark ignition piston aircraft engines to provide research toward the development of an unleaded aviation gasoline.

Since 2003, the FAA has funded the South Dakota State University to perform research on aviation-grade ethanol 85 (AGE-85). AGE-85 is comprised of at least 85% ethanol denatured with automotive gasoline, less than 1% biodiesel, and the rest pentane isomerate. In conjunction with this testing, researchers in the Airport and Aircraft Safety Research and Development Division Propulsion and Fuel Systems Branch at the FAA William J. Hughes Technical Center performed a 150-hour endurance test on AGE-85 in an overhauled Lycoming IO360-C engine. The Lycoming IO360-C engine is a four-cylinder, naturally aspirated, 200-horsepower, direct-drive engine and was overhauled to the manufacturer's new limit specifications. This engine is type certificated to operate on 100 or 100 low-lead (100LL) American Society for Testing and Materials (ASTM) D 910 grade fuels.

The fuel system was replaced with a modified fuel system, and the engine was tested for 150 hours at severe and controlled conditions that addressed issues of wear, performance, materials compatibility, oil dilution, deposit formation, start ability, and a host of other issues. The ignition timing had to be modified for operation on AGE-85 from its standard of 20° before top dead center (BTDC) to 15° BTDC to allow for detonation-free operation at best power mixture strength and maximum engine temperatures. The majority of this testing was performed at full-rated power and rated engine speed under maximum engine and oil temperatures. Also, power baseline tests were run using AGE-85 at 15° BTDC ignition timing and using ISO at 20° BTDC ignition timing both before and after the 150-hour test.

At the completion of the test, the engine was sent to Teledyne Mattituck Services for teardown and inspection. The critical high-stress parts of the engine were measured and compared against measurements taken prior to the test and compared against the manufacturer's new and serviceable limits.

1.3 RELATED DOCUMENTS.

- Lycoming Service Instruction Number 1191A, "Cylinder Compression"
- Lycoming Service Instruction 1472, "Removal of Preservative Oil"
- Lycoming Service Instruction 1241C, "Pre-oiling of Engines Prior to Initial Start"
- Lycoming Service Instruction 1427B, "Textron Lycoming Reciprocating Engine Break-in and Oil Consumption Limits"
- Teledyne Continental Motors Service Information Directive SID97-4C
- Teledyne Continental Motors Service Bulletin SB03-3
- 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 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 3524, "Standard Test Method for Diesel Fuel Diluent in Used Diesel Engine Oils by Gas Chromatography"
- ASTM D 5131, "Composition of Hydrocarbon Fraction"
- ASTM D5501, "Ethanol Content, Mass Percent"
- ASTM D 6424, "Standard Practice for Octane Rating Naturally Aspirated Spark Ignition Aircraft Engines"
- AMS–489, "Metals Concentration by Arc Spark Method"
- FAA Advisory Circular 20-24B, "Qualification of Fuels, Lubricants, and Additives for Aircraft Engines"

- FAA Advisory Circular 33-47, "Detonation Testing in Reciprocating Aircraft Engines"
- 14 CFR 33.49, "Endurance Tests"

2. TEST PROCEDURES.

The fuel was supplied in four separate batches. The fuel was analyzed for composition, ethanol content, existent gum, water content, and motor octane number (MON). The standard tests used to create table 1 were previously listed in section 1.3. Table 1 details the results of the certificate of analyses. Two random samples were taken from each batch shipment.

Table 1. AGE-85 Certificate of Analyses

Date	Description	Water Content (mass %)	Existent Gum (mg/100 ml)	Ethanol Content (mass %)	Hydrocarbon Fraction (mass %)	ASTM D 2700 (MON)
8/9/2005	1st batch, drum 4	0.195	53	90.16	9.645	91.7
8/9/2005	1st batch, drum 9	0.197	397	89.50	10.303	91.2
8/17/2005	2nd batch, drum 2	0.201	326	90.79	9.009	91.4
8/17/2005	2nd batch, drum 24	0.206	136	90.19	9.604	91.1

Prior to receiving the Lycoming IO360-C engine, researchers in the Airport and Aircraft Safety Research and Development Division at the FAA William J. Hughes Technical Center requested that the engine overhaul facility not perform the typical procedure of operating the overhauled IO360-C engine on leaded fuel. This was done to prevent engine lead deposits from influencing the AGE-85 test.

Table 2 lists the rated power and compression ratio of the Lycoming IO360-C model engine. The 'IO' in the engine model description refers to fuel injection and opposed cylinder, and the numerical value of the model description refers to the cubic inch cylinder displacement.

Table 2. Lycoming IO360-C Engine Model Specifications

Engine Make and Model	Compression Ratio	Normal Rated Brake Horsepower	Revolutions Per Minute	Ignition Timing (° BTDC)	Cylinders	Bore (inches)	Stroke (inches)	ASTM D 910 Type Certified Fuel
Lycoming IO360-C	8.7:1	200	2700	20*, 15 used for AGE-85	4	5.125	4.375	100, 100LL

* Standard ignition timing

The main metering jet of the Precision RSA-5AD1 fuel injector servo unit was increased in size to 0.11-inch diameter, and the standard fuel injection nozzles were replaced with lower-pressure, higher-volume nozzles. This was done to allow greater fuel mass flows necessary for operation on AGE-85.

The engine was installed in a test stand and coupled to an eddy-current dynamometer via spacers, adaptors, an inertia flywheel, and a drive shaft. The engine was instrumented with sensors as detailed in table 3, and engine parameter data were recorded at a rate of one scan of all channels every second.

Sensors used to measure these parameters were installed at the manufacturer's recommended locations whenever possible and were calibrated prior to any engine testing. After the engine was installed and the instrumentation calibrated, a series of maintenance runs were performed to verify engine systems integrity and instrumentation accuracy. Prior to any engine operation, the mixture cut-off and full-rich settings and the throttle stop and throw positions were checked.

Table 3. Sensors and Installation Locations

Parameter	Sensor Type	Sensor Location
Cylinder head temperatures 1-4	Bayonnet, J-type thermocouple	Manufacturer's specified location
Exhaust gas temperatures 1-4	Band clamp, K-type thermocouple	Exhaust pipe within 2 inches of exhaust flange
Intake air temperature	T-type thermocouple	Intake duct just prior to throttle throat
Intake air pressure	Absolute pressure transducer	Intake duct just prior to throttle throat
Mass airflow rate	Mass flow meter	Straight, smooth section of intake air duct, 6 diameters downstream
Intake air humidity	Probe	Intake air duct
Manifold absolute pressure	Absolute pressure transducer	Intake manifold plenum after the fuel injection unit
Engine speed (revolutions per minute)	Magnetic pickup	Dynamometer shaft
Engine shaft torque	Load cell	Dynamometer
Fuel mass flow rate	Corliolis mass flow meter	After fuel control unit and prior to fuel manifold
Engine cowling air temperature	T-type thermocouple	Engine cowling plenum
Engine cowling air pressure	Gauge pressure transducer	Engine cowling plenum
Fuel temperature	Corliolis mass flow meter	After fuel control unit and prior to fuel manifold
Fuel mass density	Corliolis mass flow meter	After fuel control unit and prior to fuel manifold
Metered fuel pressure	Gauge pressure transducer	Output of fuel metering unit
Fuel pump pressure	Gauge pressure transducer	Output of engine-driven pump
Oil temperature	J-type thermocouple	Return from oil cooler
Oil pressure	Gauge pressure transducer	Manufacturer's location in accessory case
Air-to-fuel ratio left bank	Lambda exhaust gas sensor	Left bank of cylinders common exhaust pipe
Air-to-fuel ratio right bank	Lambda exhaust gas sensor	Right bank of cylinders common exhaust pipe

Lycoming Service Instruction 1472 was followed to remove the preservative oil and replace it with Phillips 66 Type M SAE 20W-50 mineral oil. The engine was then pre-oiled as per the Lycoming Service Instruction 1241C.

Following the engine pre-oiling, the Lycoming Service Instruction 1427B for engine break-in and oil consumption tests were performed.

The engine break-in was performed at the FAA William J. Hughes Technical Center using AGE-85 from sealed drums. The AGE-85 contained less than 0.2% water by volume. At the conclusion of the engine break-in period, when oil consumption had stabilized, the Phillips 66 Type M SAE 20W-50 break-in oil was replaced with Aeroshell 15W50 ashless dispersant oil. This oil type was used throughout the power baselines and endurance test.

2.1 POWER BASELINES.

After the oil consumption stabilized, power baseline tests, which encompassed a combination of manifold absolute pressure (MAP) settings and engine revolutions per minute (rpm) settings, were performed on the Lycoming IO360-C engine using both AGE-85 and ISO. For these tests, the mixture was varied from the full-rich fuel flow position to lean of peak exhaust gas temperature (EGT); the MAP was varied by 2.0-in. Hg increments, and the rpm was varied by increments of 100.

For the power baseline test, the inlet air temperature was maintained at 60° ±3°F, the maximum cylinder head temperature (CHT) was maintained at 400° ±5°F, all other CHTs were maintained within 50°F of the maximum, and the oil temperature was maintained at 200° ±5°F. At each combination of MAP and rpm, the fuel mixture was adjusted from rich of best power to peak EGT while maintaining constant MAP. The AGE-85 test was performed at an ignition timing of 15° BTDC, whereas for the ISO, the standard engine ignition timing of 20° BTDC was used. The timing was retarded by 5° for the AGE-85 out of necessity to allow for adjustment of best power mixture without detonation. Previous investigation at the FAA with a Lycoming IO360-A engine indicated that severe detonation occurred at mixtures slightly lean of best power while operating on AGE-85 at the standard ignition timing of 20° BTDC, even at severely reduced inlet air temperature (IAT) and CHTs. The AGE-85 fuel transitioned from stable combustion at 60°F IAT to heavy detonation at 64°F IAT, with a maximum CHT of 400°F and a fuel mass flow of 48% above the ISO best power fuel mass flow.

2.2 ENDURANCE TEST.

Following the initial power baseline test, the 150-hour endurance test with the Lycoming IO360-C engine began. Table 4 lists the engine parameters maintained throughout the test. The maximum CHT at takeoff (TO) power was reduced from the target value of 475° +5°F to 460° +20°F due to difficulty attaining these elevated temperatures. The mixture was adjusted to best power for operation throughout the endurance test. The combination of the increased latent heat of vaporization of ethanol, the retarded ignition timing, and the substantial increase in fuel mass flow resulted in lower operating CHTs. The cowling air pressure was maintained above 2 inches of water throughout the test.

Table 4. Parameter Settings for Endurance Test

Parameter	Limit
Ignition timing	15° BTDC
Mixture setting	Adjusted for best power
Maximum CHT for TO power	460° +20°F
Maximum CHT for cruise power	> 420°F
All other CHTs	Within 50°F of maximum CHT
IAT	103° +3°F (extreme hot day standard)
Induction air relative humidity	Less than 5%
Oil inlet temperature	245° –10°F (maximum per engine manufacturer's detailed specifications)

The 150-hour endurance test was divided into seven phases. These phases are listed below and follow the requirements outlined in Title 14 Code of Federal Regulations Part 33.49.

a. Thirty hours of alternating periods of 5 minutes at full throttle (FT) and 2700 rpm and 5 minutes at 150 brake horsepower (BHP) and 2450 rpm.

b. Twenty hours of alternating periods of 1.5 hours at FT and 2700 rpm and 0.5 hour at 150 BHP and 2450 rpm.

c. Twenty hours of alternating periods of 1.5 hours at FT and 2700 rpm and 0.5 hour at 140 BHP and 2400 rpm.

d. Twenty hours of alternating periods of 1.5 hours at FT and 2700 rpm and 0.5 hour at 130 BHP and 2350 rpm.

e. Twenty hours of alternating periods of 1.5 hours at FT and 2700 rpm and 0.5 hour at 120 BHP and 2300 rpm.

f. Twenty hours of alternating periods of 1.5 hours at FT and 2700 rpm and 0.5 hour at 100 BHP and 2150 rpm.

g. Twenty hours of alternating periods of 2.5 hours at FT and 2700 rpm and 2.5 hours at 150 BHP and 2450 rpm.

At the start of the endurance test and at intervals of 50 engine hours, maintenance was performed, and a series of engine measurements were taken. Table 5 shows the maintenance schedule.

At each maintenance interval, the spark plugs were removed and inspected, and a cylinder bore scope was employed to ensure that valves, valve surfaces, cylinder dome and walls, and piston faces were in visibly healthy condition. A compression test was performed with the engine

warm using a differential pressure tester with a master orifice device. The differential test procedures followed those outlined in the Lycoming Service Instruction Number 1191A.

The fuel inlet screen (finger screen) was removed, cleaned, reinstalled, and safety wired. The system was then pressure checked for evidence of leaks at the sealing gasket. The fuel nozzles were inspected for deposits and cleaned, if necessary, with acetone.

The engine cylinder assembly was inspected for evidence of overheating, leakage between exhaust ports and pipes, and warped exhaust port flanges. Baffling was inspected for condition and security.

Table 5. IO360-C Engine Maintenance Schedule

Engine Cumulative Hours	Magneto Timing	Oil/Filter Service	Oil Analysis	Cylinder Compression Surveys	Rated Power Surveys	Valve Wear Surveys	Spark Plug Visual	Bore Scope Inspection
0	X	X	X	X	X	X	X	
Start of Endurance Test	X	X	X	X		X	X	X
50	X	X	X	X		X	X	X
100	X	X	X	X		X	X	X
150	X	X	X	X		X	X	X
End of Endurance Test	X	X	X	X	X	X	X	X

The oil system was drained and the spin-on oil filter was changed. The oil pump scavenge screen was also removed and inspected for metal particles and contamination. The screen was then thoroughly cleaned, reinstalled, and safety wired. New gaskets were installed. The system was then serviced to the proper level with Aeroshell 15W-50 multiviscosity oil. The unleaded avgas program used Aeroshell 15W-50 multiviscosity oil during the test and any servicing of the engine with oil was recorded. Figure 1 shows the oil filter inspection where the filter was cut open and a magnet was used on the filter membrane to investigate for the presence of larger metallic particles.

All fluid-carrying lines were inspected for possible leaks or chafing. Electrical wiring was inspected for proper connections, security, and evidence of chafing as well.

Cylinder differential pressure (compression) tests were performed per Teledyne Continental Aircraft Engine Service Bulletin M84-15.

A series of valve recession measurements were taken using a Cessna ULA-017 Gauge Assembly and a depth micrometer. The installation of the gauge assembly and measurement method is shown in figures 2 and 3. Prior to measuring the exhaust valve recession, the valve stem rotor cap was removed to prevent errant measurements.

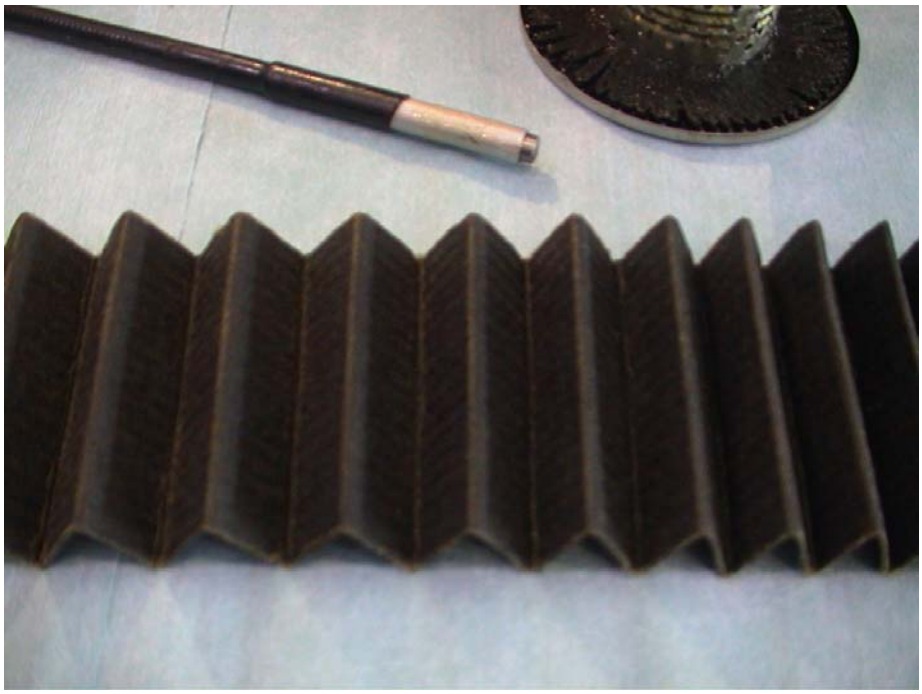

Figure 1. Oil Filter Inspection

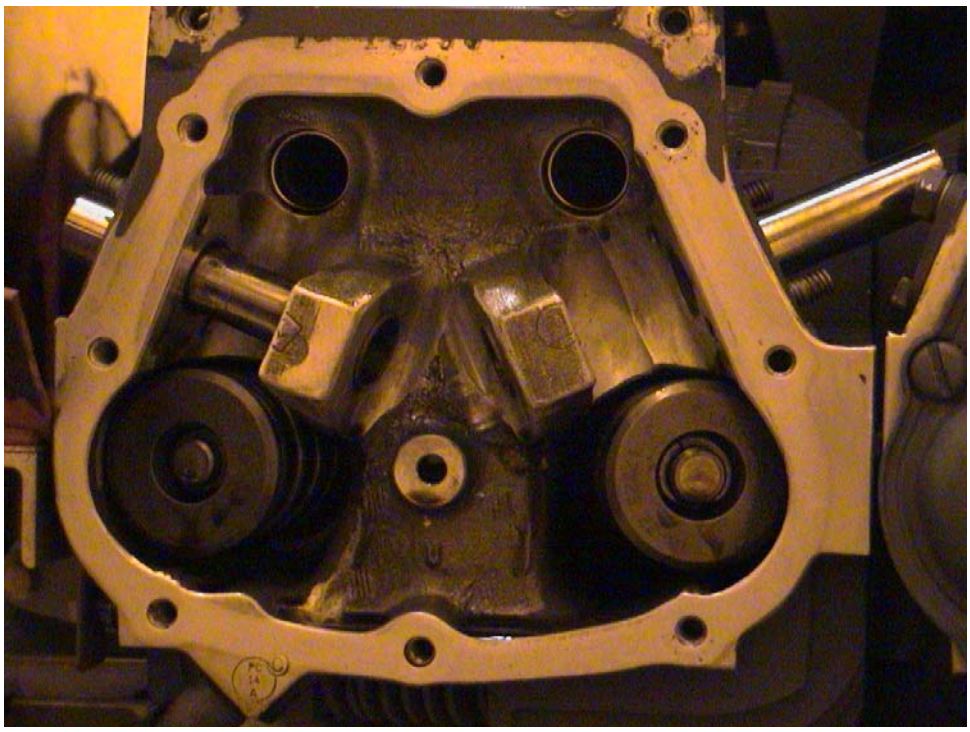

Figure 2. Lycoming IO360-C Cylinder With Valve Covers, Gasket Material, and Rocker Arms Removed

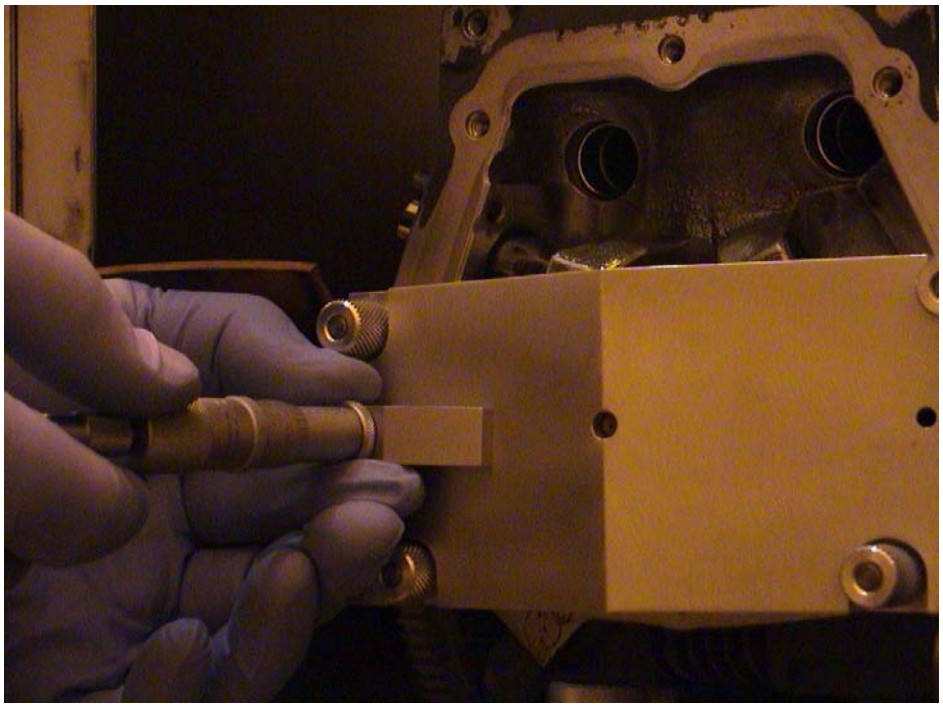

Figure 3. Installation of Cessna ULA-017 Gauge Assembly and Measurement of Valve Stem Height

Upon completion of the inspection, the engine cowling was reinstalled and a performance engine run-up test was completed. At this time, the engine was inspected for evidence of oil leaks and proper operation.

3. RESULTS AND DISCUSSIONS.

The Lycoming IO360-C oil consumption stabilized to 0.21 quart per hour after 9.3 hours of break-in operations using AGE-85. This is well below the engine manufacturer's allowable oil consumption limits during engine break-in of 0.89 quart per hour. After the engine was broken-in using AGE-85, a differential compression test was performed and valve height measurements were taken.

3.1 POWER BASELINES.

Power baseline tests were performed on the Lycoming IO360-C engine using both ISO and AGE-85. The ISO was tested at the standard ignition timing of 20° BTDC, whereas the AGE-85 was tested at an ignition timing of 15° BTDC. Figures 4 through 9 show the power comparison between the AGE-85 and ISO for varying fuel mass flow rates at each respective rpm. The power was corrected for temperature, barometric pressure, and humidity to standard day, sea level conditions. The power curves at the top of the charts are for FT with the curves lower on the chart for reduced MAP. The horsepower versus fuel mass flow curves clearly show that the AGE-85 produced slightly higher peak power than ISO but required a substantially increased fuel mass flow.

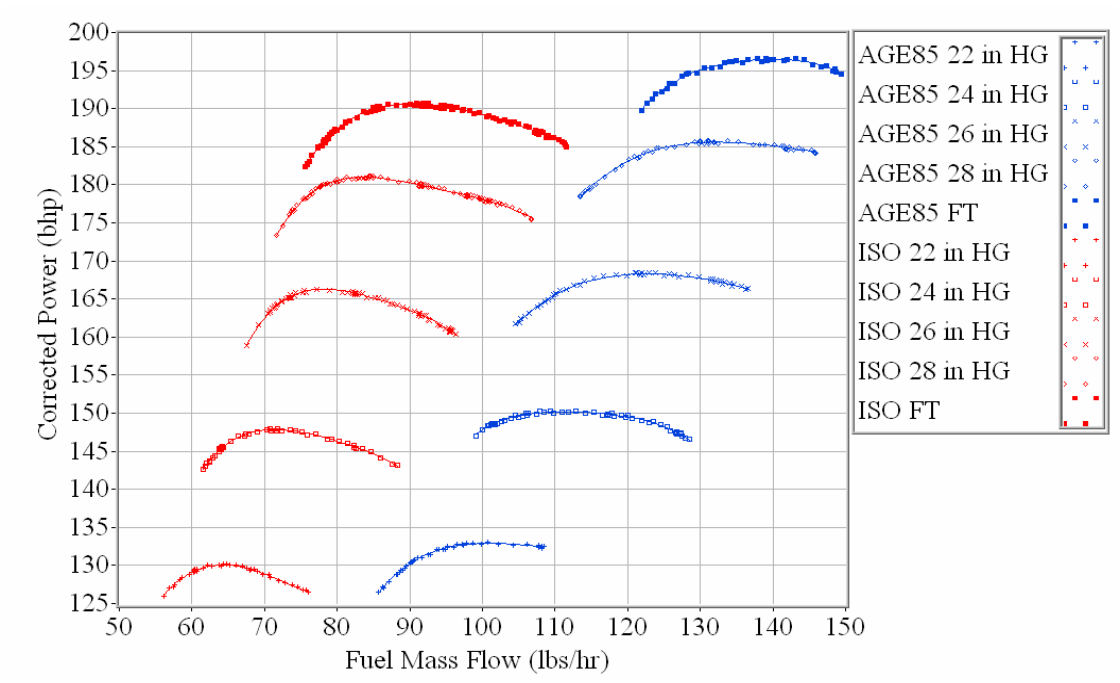

Figure 4. Corrected Power at 2700 rpm vs Fuel Mass Flow

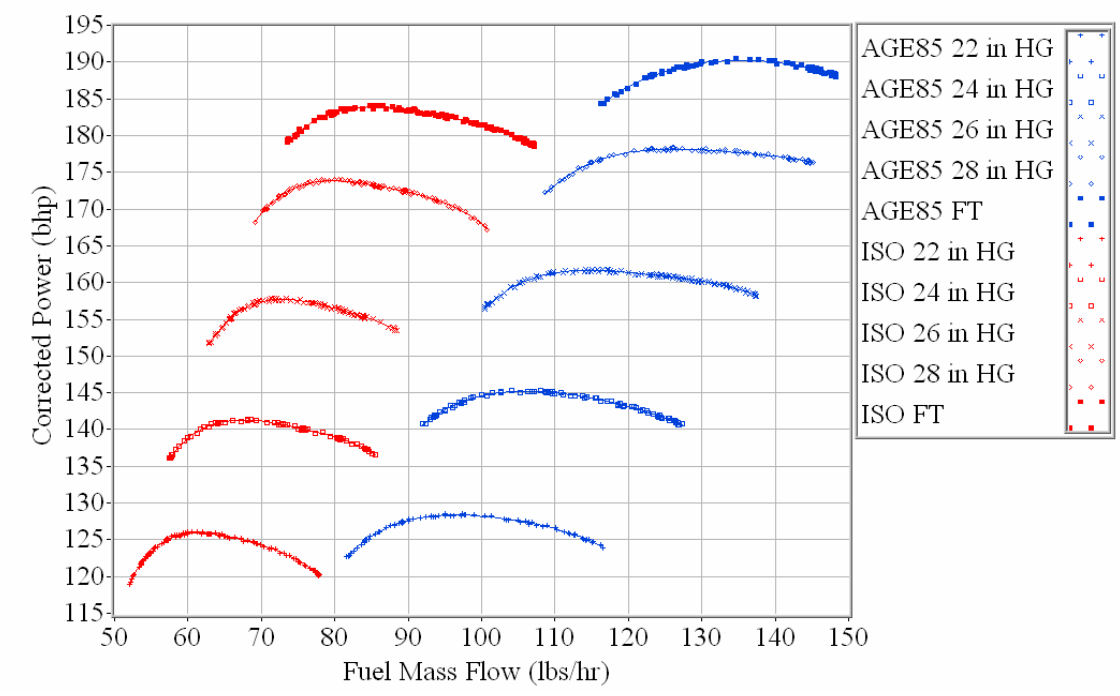

Figure 5. Corrected Power at 2600 rpm vs Fuel Mass Flow

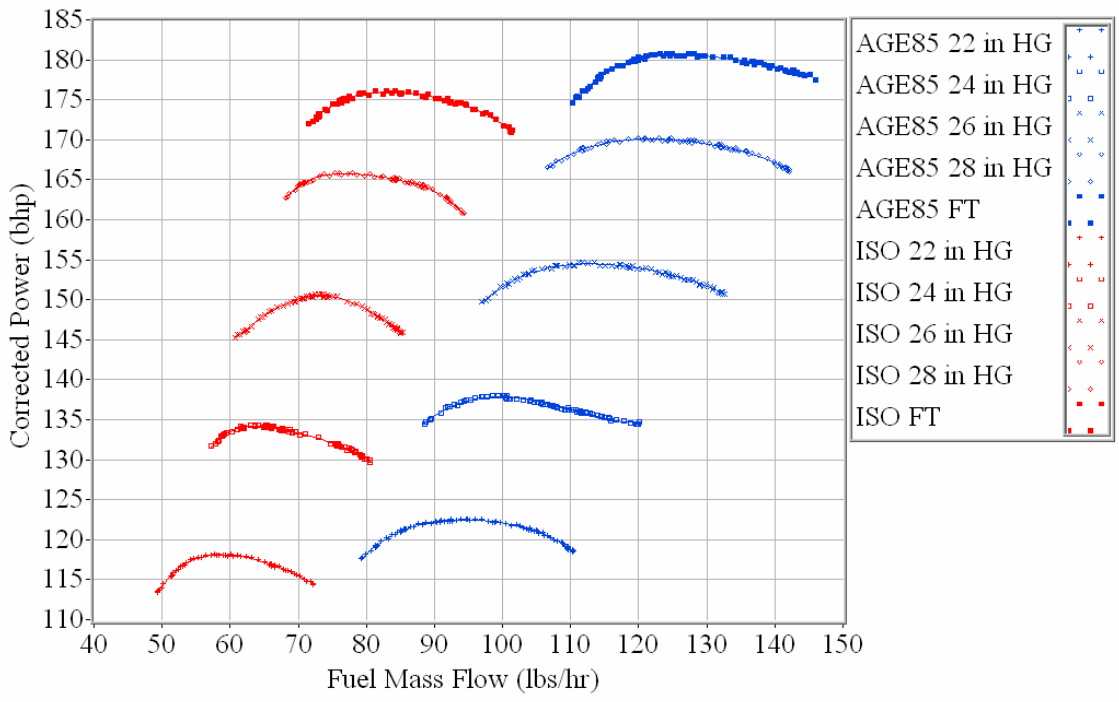

Figure 6. Corrected Power at 2500 rpm vs Fuel Mass Flow

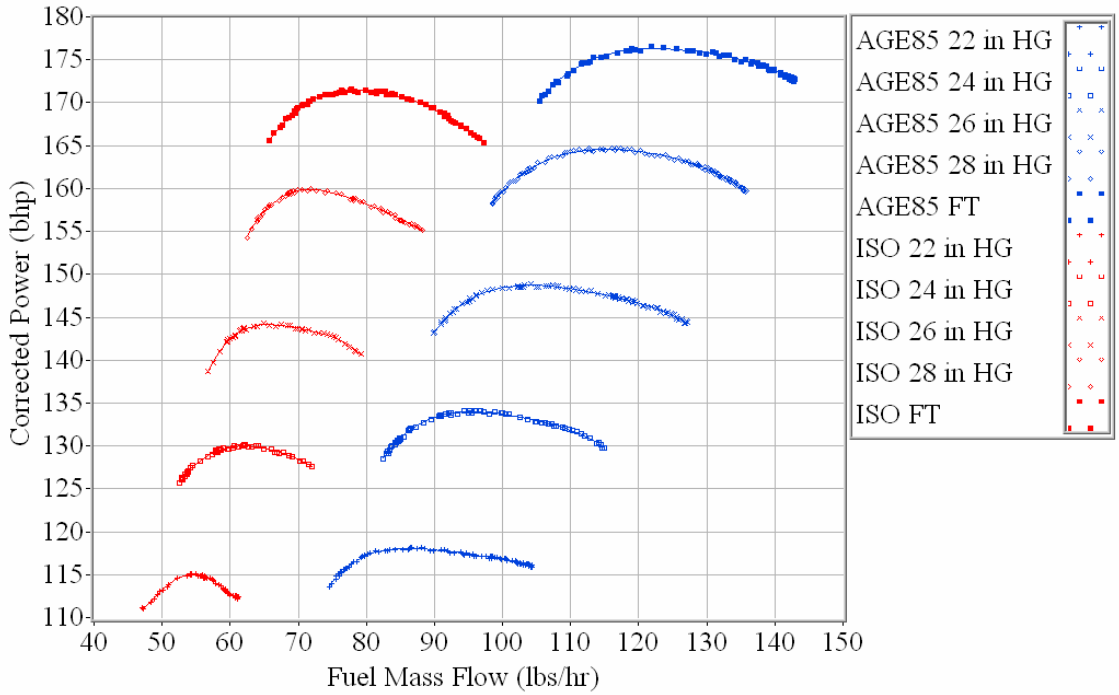

Figure 7. Corrected Power at 2400 rpm vs Fuel Mass Flow

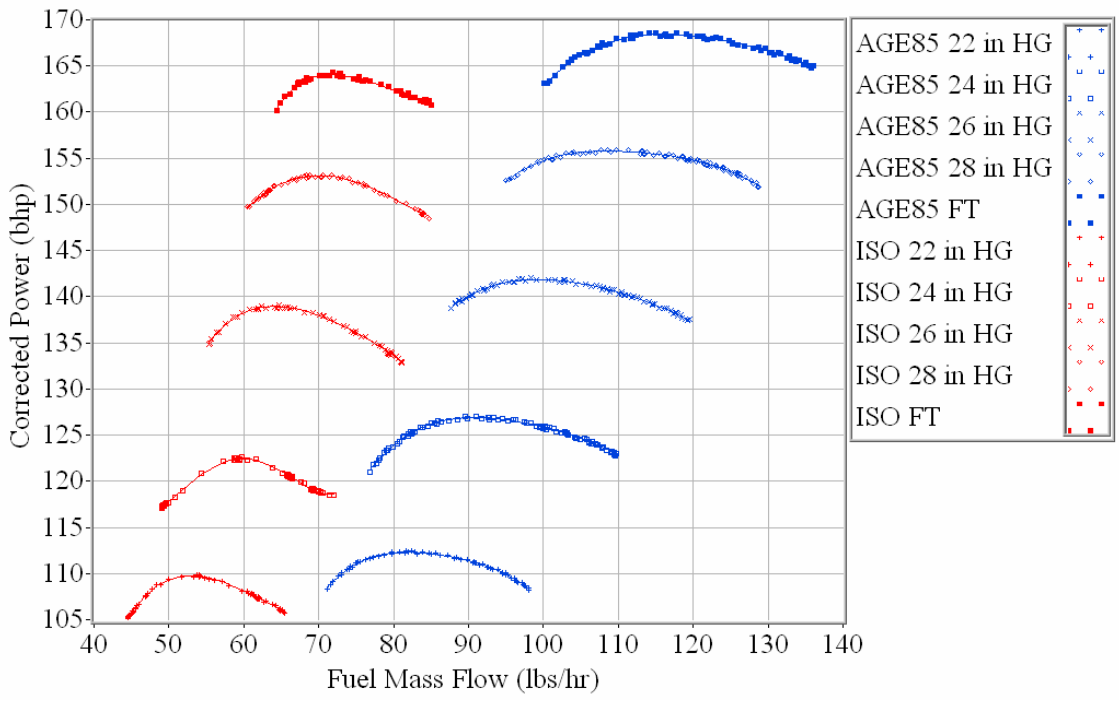

Figure 8. Corrected Power at 2300 rpm vs Fuel Mass Flow

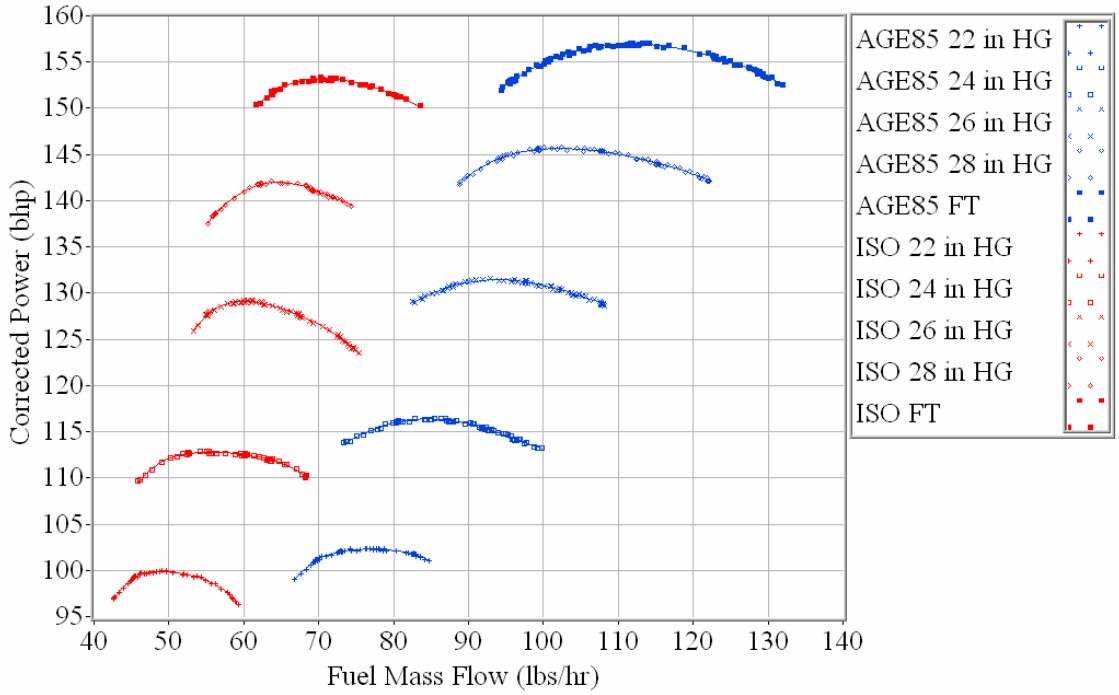

Figure 9. Corrected Power at 2200 rpm vs Fuel Mass Flow

Table 6 provides a peak power summary of the data shown in figures 4 through 9. The table shows that the AGE-85 produced an average of 4.3 more peak horsepower (2.8%) than ISO. This was so even with ignition retarded by 5° for the AGE-85. Retarding the timing by 5° from the standard setting will usually result in a loss in power. The peak power on AGE-85 occurred at a mixture setting on average of 39.7 lb/hr (56.5%) higher fuel mass flow than ISO.

Table 6. Peak Power Comparison Between AGE-85 and ISO

	Peak Power (Corrected bhp)				Fuel Mass Flow at Peak Power (lb/hr)			
Power Setting	ISO	AGE-85	Power Difference (bhp)	Power Difference (%)	ISO	AGE-85	Fuel Mass Flow Difference (lb/hr)	Fuel Mass Flow Difference (%)
TO	191.1	197.0	5.9	3.1	90.1	137.8	47.7	53.0
28-in. Hg, 2600 rpm	173.9	178.6	4.7	2.7	79.6	124.9	45.3	56.9
26-in. Hg, 2600 rpm	157.8	162.0	4.2	2.7	73.7	115.3	41.5	56.3
24-in. Hg, 2400 rpm	130.2	134.3	4.2	3.2	61.4	97.2	35.7	58.2
22-in. Hg, 2200 rpm	101.2	103.7	2.5	2.5	48.9	77.3	28.4	58.2
		Average	4.3	2.8		Average	39.7	56.5

The increase in fuel mass flow required with AGE-85 to produce the equivalent unit of power as ISO resulted in a loss in efficiency, as measured by the brake-specific fuel consumption (BSFC), which is shown in figure 10. The BSFC is a measure of power output for a given fuel mass input expressed as the division of the fuel mass flow by the corrected brake horsepower output. The lower the BSFC, the greater the power output for a given fuel mass flow and the better the efficiency. The better the efficiency, the greater the distance traveled for a given weight of fuel.

Figure 10 shows the BSFC plotted versus fuel mass flow for the data shown in figures 4 through 9. The figure clearly shows that AGE-85 had BSFCs that were significantly higher, and efficiencies correspondingly lower, than ISO at all power settings.

Using the data in table 6 and dividing the fuel mass flow at peak power by the peak corrected horsepower shows the efficiency at peak power for ISO was 0.471 lb/bhp hr, and for AGE-85, it was 0.700 lb/bhp hr at the TO power condition. The average peak power BSFC was 0.470 lb/bhp hr for ISO and 0.716 lb/bhp hr for AGE-85.

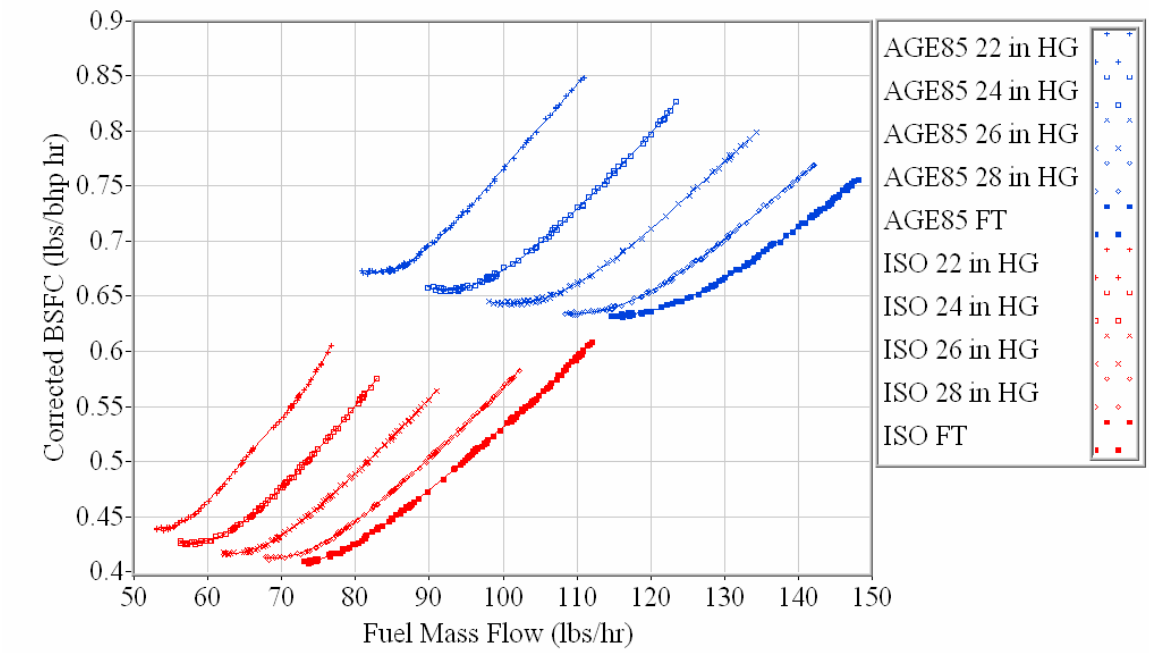

Figure 10. Corrected BSFC vs Fuel Mass Flow

Note in figure 10 that the BSFC shows a cupping effect at the bottom of the curves. It is this inflection point that gives the best economy, which is the mixture setting where there is the best advantage of fuel consumption versus power output. Table 7 shows the best economy comparison between the AGE-85 and ISO for the data presented in figure 10. The best economy BSFC was 0.415 lb/hp hr for ISO and 0.640 lb/hp hr for the AGE-85. Best economy operation on AGE-85 produced an average of 2.6 (1.8%) greater horsepower at 32.3 lb/hp (56.3%) greater fuel mass flow.

Figures 11 through 14 show the power performance and average exhaust gas temperature for both ISO and AGE-85 versus fuel mass flow for TO, 28-in. Hg and 2600 rpm, 26-in. Hg and 2600 rpm, and 24-in. Hg and 2400 rpm, respectively. The summary peak EGT and best economy EGT data from figures 11 through 14 are shown in the last two columns of table 7.

Typically, peak EGTs occur at stoichiometry, near best economy, where there is neither excess fuel nor excess air. The AGE-85 average EGT at best economy mixture was slightly higher than ISO at TO, wide open throttle setting, but was slightly lower at the part throttle operation. The same trend was found for the maximum EGT. This difference in EGT may have been less pronounced than anticipated due to the retarded ignition timing for operation on AGE-85 and due to the adjustment of the cooling air pressure to maintain fixed CHTs. Retarding the ignition timing shifts the energy release later in the cycle resulting in higher EGTs than would be experienced at the standard ignition timing.

Table 7. Best Economy Comparison Between Age-85 and ISO

Power Setting	Lowest Corrected BSFC (lb/bhp hr)	Fuel Flow at Lowest Corrected BSFC (lb/hr)	Corrected BHP at Lowest Corrected BSFC (lb/bhp hr)	Average EGT at Lowest Corrected BSFC (ºF)	Max EGT (ºF)
ISO TO	0.411	70.9	177.3	1595	1602
ISO 28-in. Hg, 2600 rpm	0.406	63.7	161.1	1593	1594
ISO 26-in. Hg, 2600 rpm	0.412	61.0	146.7	1595	1596
ISO 24-in. Hg, 2400 rpm	0.416	51.2	120.1	1575	1576
ISO 22-in. Hg, 2200 rpm	0.430	40.2	92.2	1549	1553
AGE-85 TO	0.631	113.3	181.6	1607	1608
AGE-85 28-in. Hg, 2600 rpm	0.629	101.0	162.4	1589	1589
AGE-85 26-in. Hg, 2600 rpm	0.637	94.0	148.8	1589	1589
AGE-85 24-in. Hg, 2400 rpm	0.637	79.0	123.6	1557	1558
AGE-85 22-in. Hg, 2200 rpm	0.664	61.2	93.8	1548	1549

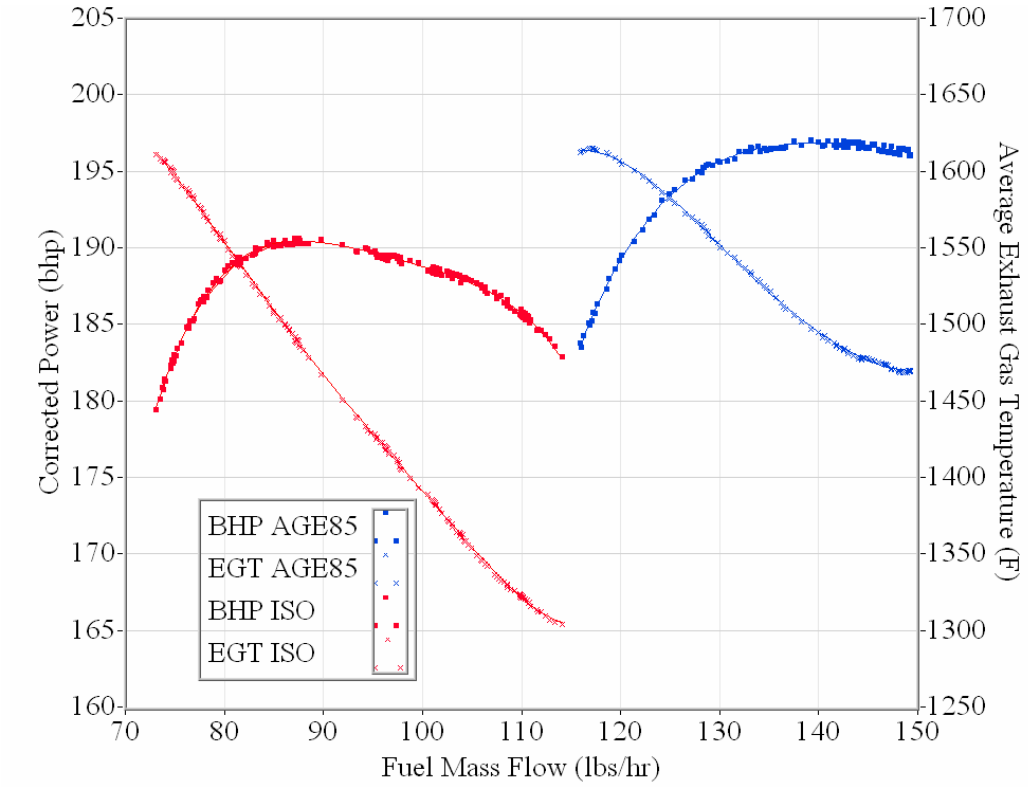

Figure 11. Corrected Power and Average EGT vs Fuel Mass Flow at FT and 2700 rpm

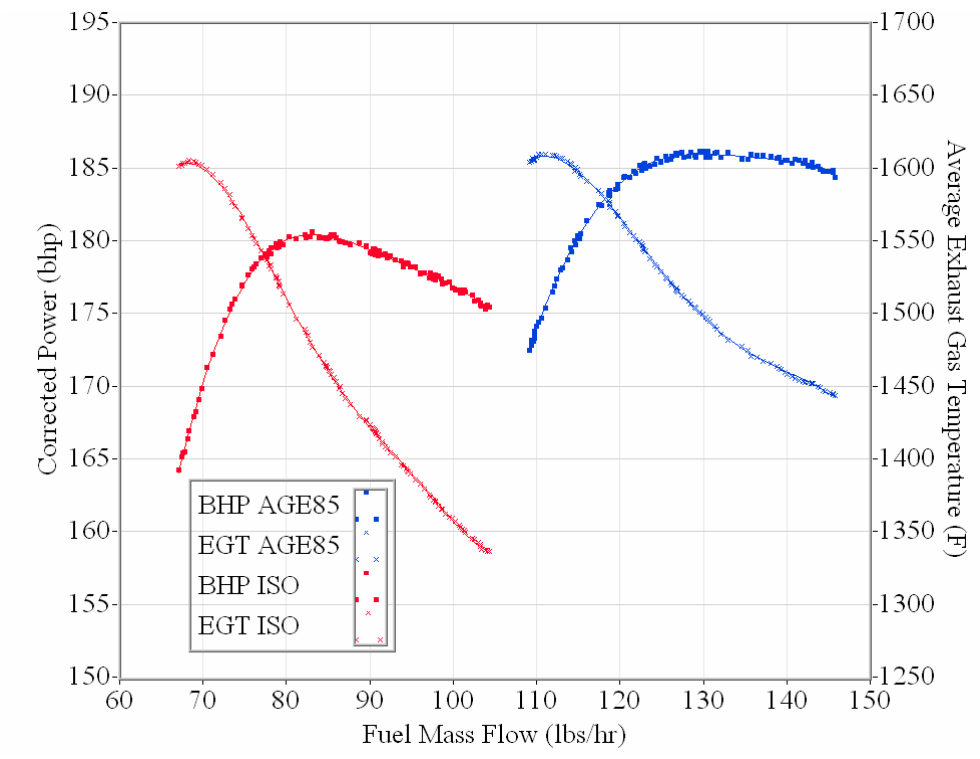

Figure 12. Corrected Power and Average EGT vs Fuel Mass Flow at 28-in. Hg and 2600 rpm

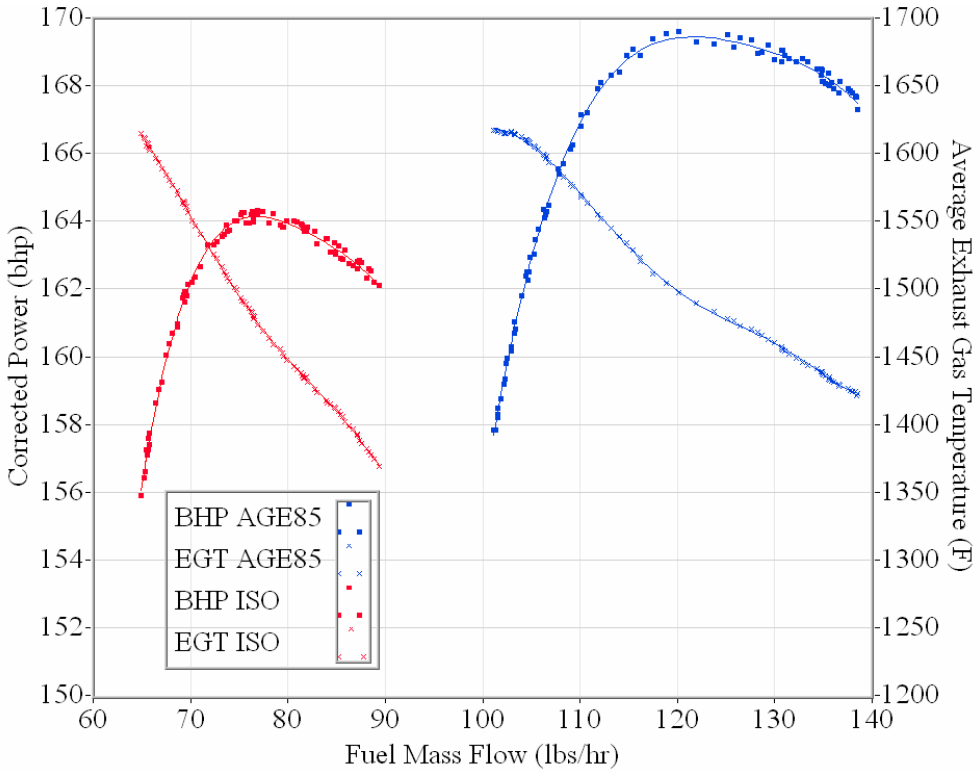

Figure 13. Corrected Power and Average EGT vs Fuel Mass Flow at 26-in. Hg and 2600 rpm

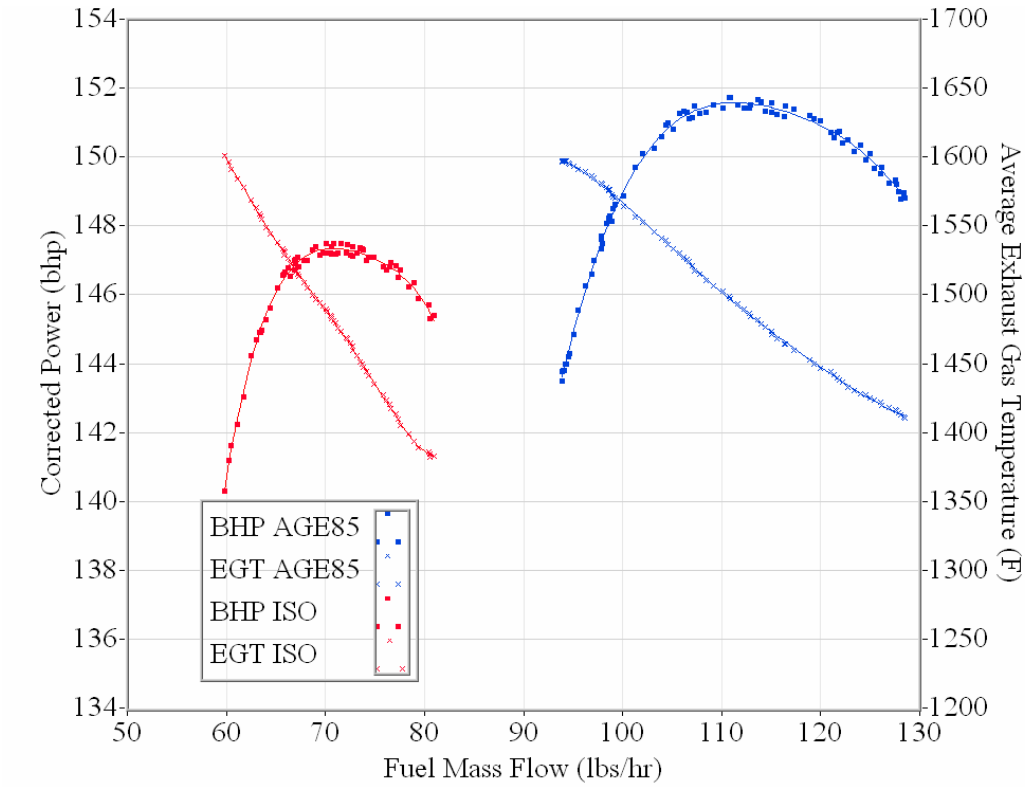

Figure 14. Corrected Power and Average EGT vs Fuel Mass Flow at 24-in. Hg and 2600 rpm

Figures 15 through 18 show the power performance and average EGT for both ISO and AGE-85 plotted against fuel volume flow for TO, 28-in. Hg and 2600 rpm, 26-in. Hg and 2600 rpm, and 24-in. Hg and 2400 rpm, respectively. These figures show that the AGE-85 fairs better on a volume flow basis due to its higher mass density than ISO. The mass density was measured to be 6.4 lb/gal for AGE-85 and 5.7 lb/gal for ISO. On a volume flow basis, the peak power occurred at an average fuel volume flow 5.6 gal/hr (35%) greater for AGE-85 than ISO. Even on a volume flow basis, this is still a substantial increase in fuel consumption required for operation on AGE-85. The current 100LL aviation gasoline has a density of 5.87 lb/gal at 59ºF. Given the same volume of fuel, using AGE-85 would increase the fuel weight by 9% above the current 100LL and would decrease engine range by 35%.

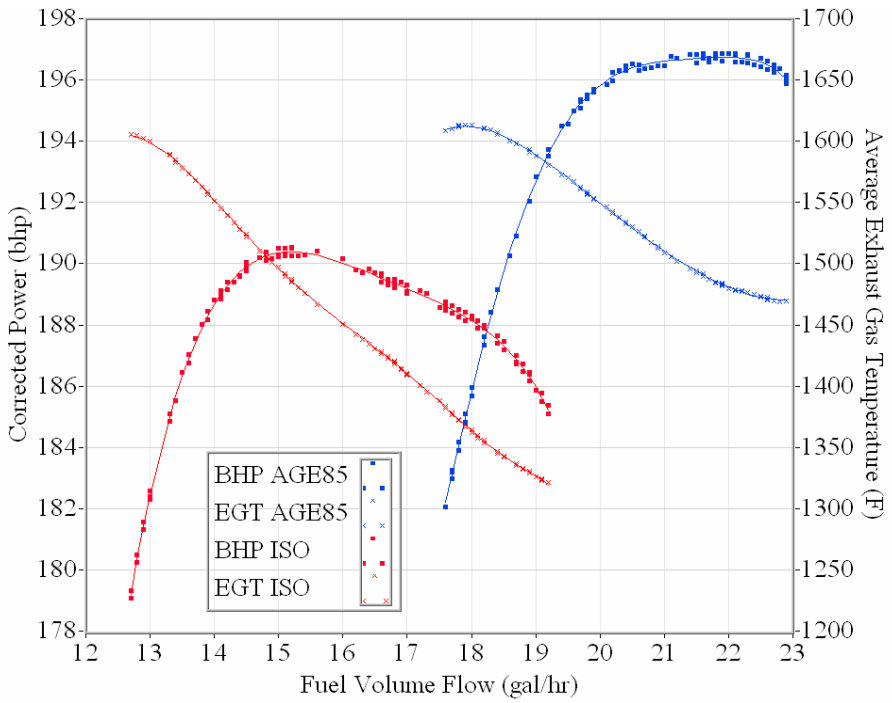

Figure 15. Corrected Power and Average EGT vs Fuel Volume Flow at FT and 2700 rpm

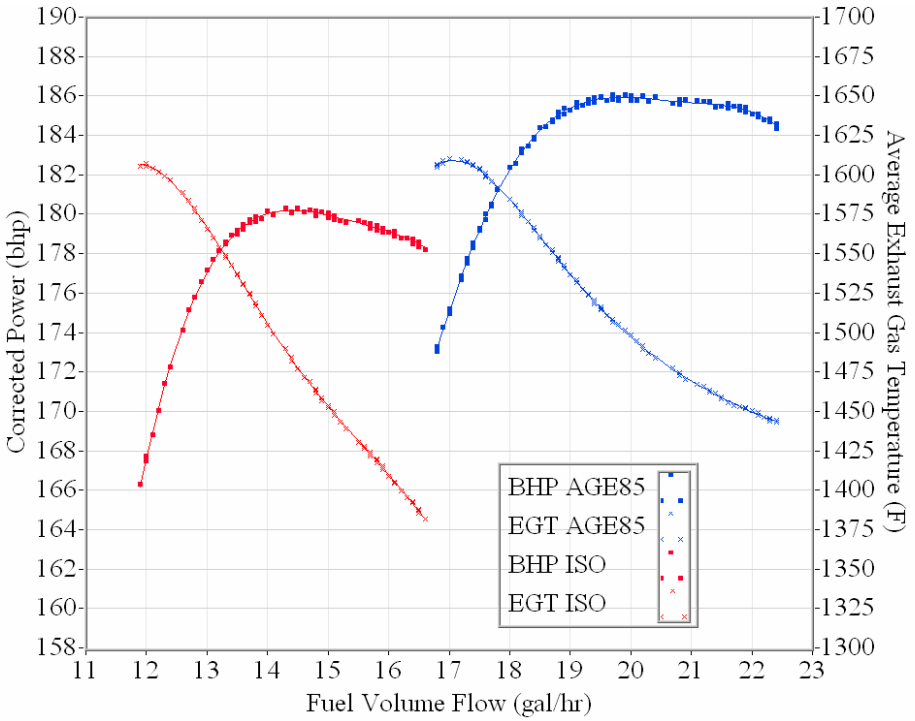

Figure 16. Corrected Power and Average EGT vs Fuel Volume Flow at 28-in. Hg and 2600 rpm

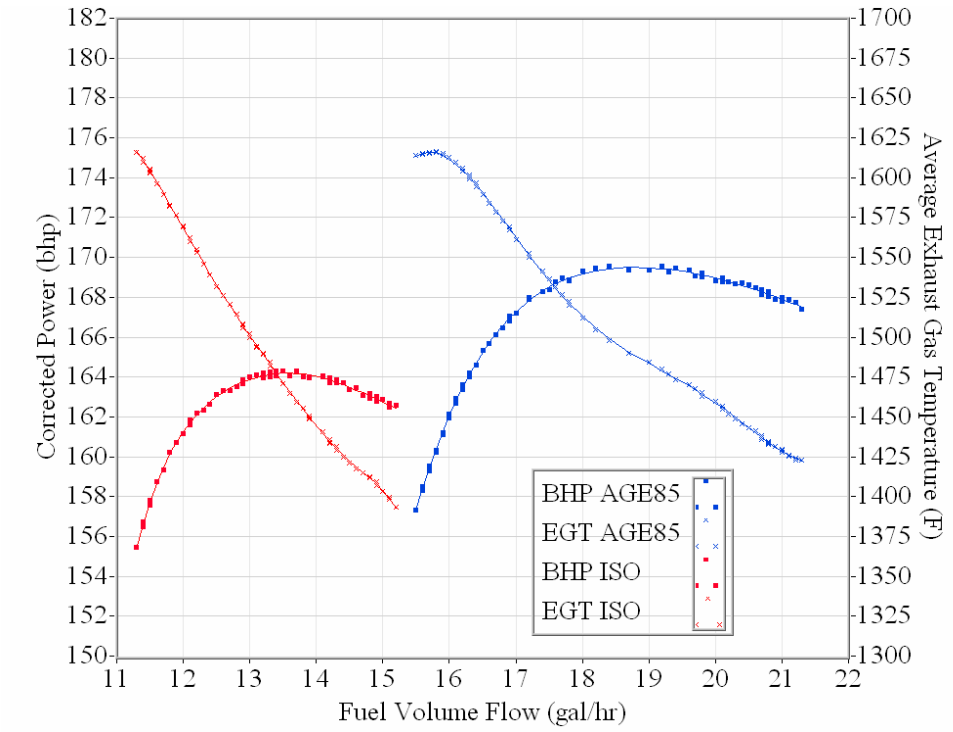

Figure 17. Corrected Power and Average EGT vs Fuel Volume Flow at 26-in. Hg and 2600 rpm

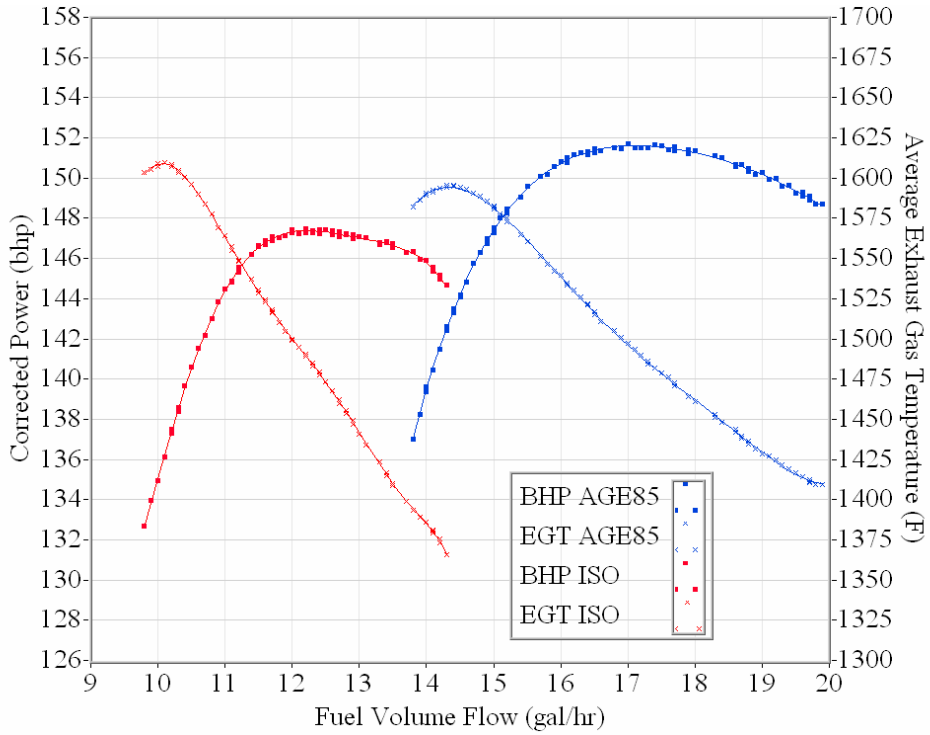

Figure 18. Corrected Power and Average EGT vs Fuel Volume Flow at 24-in. Hg and 2400 rpm

Table 8 provides a summary of the exhaust gas data that was presented in figures 11 through 14. The EGT at the best power mixture, shown in column 4 of table 8, was higher by an average of 20° F for the AGE-85 than ISO, even with the 56.5% increase in fuel mass flow. This difference was more pronounced at the higher engine rpm settings of 2600 and 2700 and MAP settings above 26-in. Hg, where the AGE-85 average EHT was 32°F higher at best power than it was on ISO. At the lower rpm settings of 2400 and 2200, the best power average EGT was lower when operating on AGE-85 than ISO. Some of this elevated EGT for AGE-85 is due to operation at 5° retarded ignition timing and is due to varying the cooling air pressure to maintain fixed CHTs.

The last two columns of table 8 show that the peak power on ISO occurred on average 136ºF rich of the maximum EGT, and for AGE-85, peak power occurred on average 110ºF rich of the maximum EGT. This data suggests that the maximum power occurred at leaner mixtures relative to stoichiometry for AGE-85 than ISO.

Table 8. Exhaust Gas Summary

Power Setting	Max Corrected Power (Bhp)	Fuel Flow at Max Corrected Power (lb/hr)	Corrected BSFC at Max Corrected Power (lb/Bhp hr)	Average EGT at Max Corrected Power (ºF)	Max EGT (ºF)	Difference: Max EGT Minus EGT at Max Corrected Power (ºF)
ISO TO	191.1	90.1	0.475	1467	1602	136
ISO 28-in. Hg, 2600 rpm	173.9	79.6	0.461	1462	1594	132
ISO 26-in. Hg, 2600 rpm	157.8	73.7	0.468	1456	1596	140
ISO 24-in. Hg, 2400 rpm	130.2	61.4	0.474	1435	1576	142
ISO 22-in. Hg, 2200 rpm	101.2	48.9	0.483	1422	1553	132
AGE-85 TO	197.0	137.8	0.700	1507	1608	101
AGE-85 28-in. Hg, 2600 rpm	178.6	124.9	0.700	1486	1589	103
AGE-85 26-in. Hg, 2600 rpm	162.0	115.3	0.714	1477	1589	112
AGE-85 24-in. Hg, 2400 rpm	134.3	97.2	0.728	1448	1558	110
AGE-85 22-in. Hg, 2200 rpm	103.7	77.3	0.754	1424	1549	125

Figures 19 through 22 show the power performance and average EGT for both ISO and AGE-85 versus air-to-fuel-ratio for TO, 28-in. Hg and 2600 rpm, 26-in. Hg and 2600 rpm, and 24-in. Hg and 2400 rpm, respectively. These figures illustrate further that the AGE-85 required much richer mixtures than ISO.

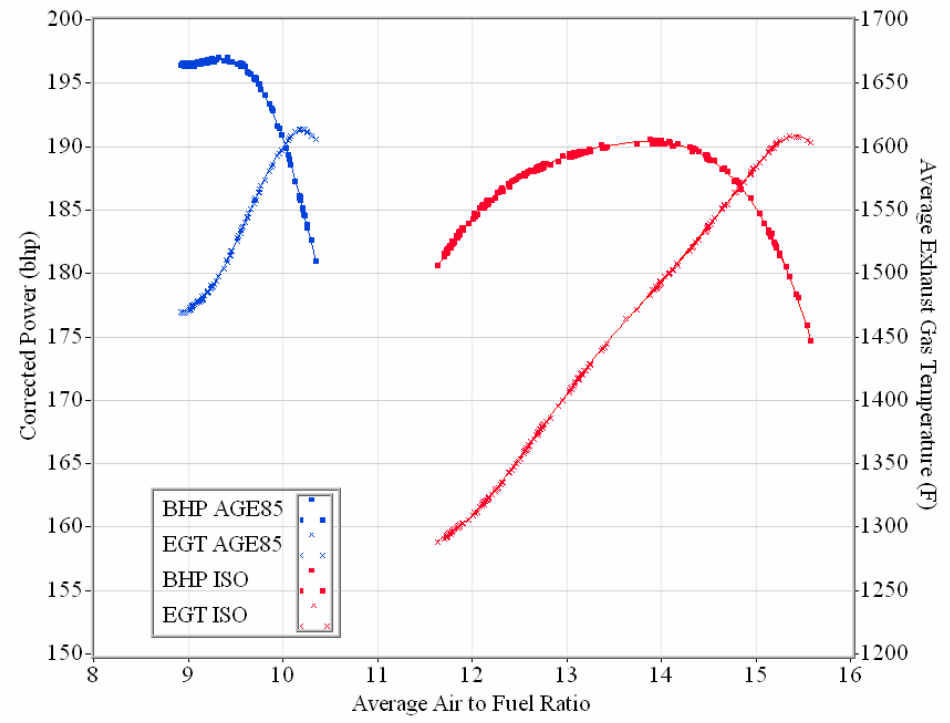

Figure 19. Corrected Power and Average EGT vs Air-to-Fuel Ratio at FT and 2700 rpm

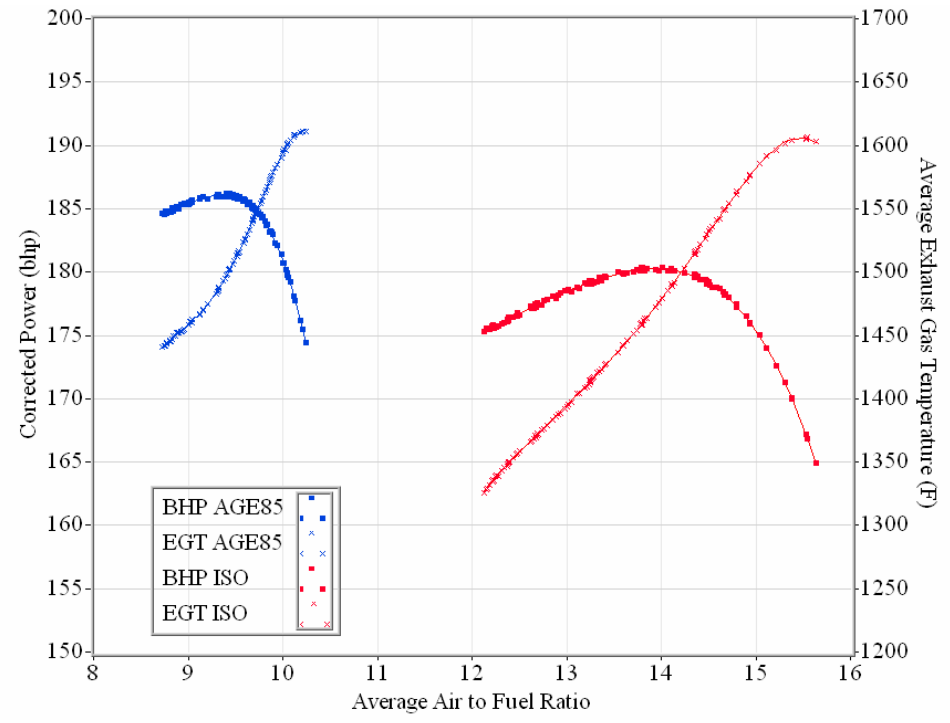

Figure 20. Corrected Power and Average EGT vs Air-to-Fuel Ratio at 28-in. Hg and 2600 rpm

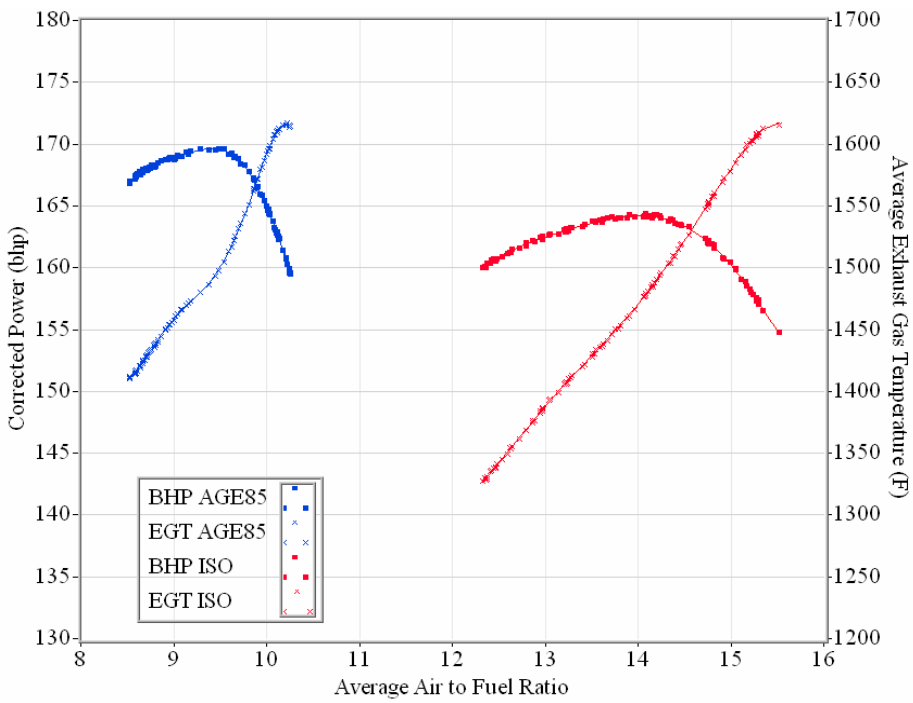

Figure 21. Corrected Power and Average EGT vs Air-to-Fuel Ratio at 26-in. Hg and 2600 rpm

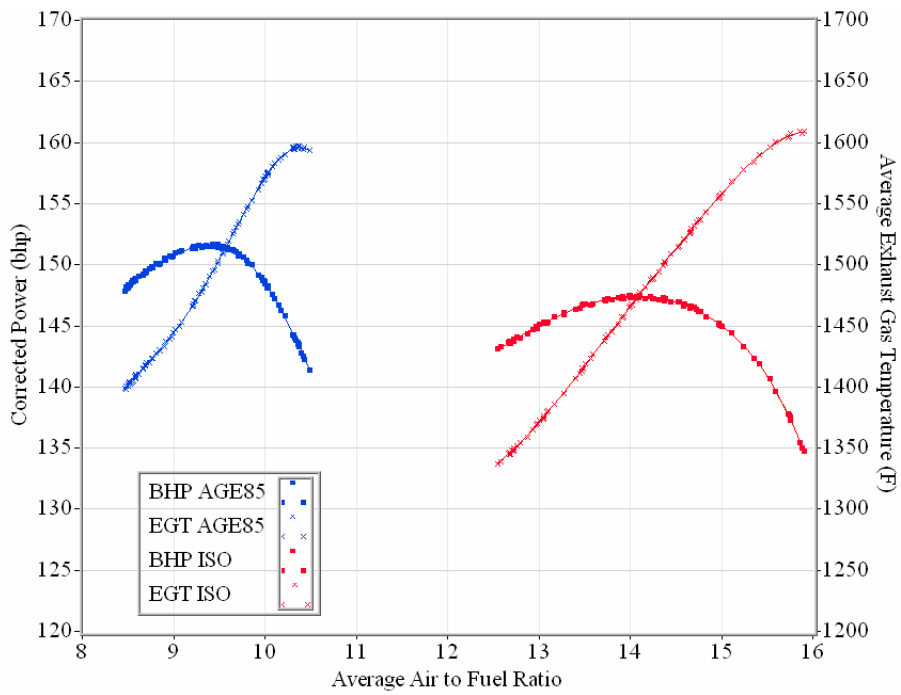

Figure 22. Corrected Power and Average EGT vs Air-to-Fuel Ratio at 24-in. Hg and 2400 rpm

Figures 23 through 26 show the same data from figures 19 through 22 plotted versus equivalence ratio instead of air-to-fuel ratio. The equivalence ratio is a measure of the stoichiometric air-to-fuel ratio to the actual air-to-fuel ratio. The stoichiometric air-to-fuel ratio is the ratio where

there is neither excess air nor excess fuel. Ideally, this is the mixture setting where peak EGT occurs, best economy occurs at a mixture strength slightly lean of stoichiometry, and best power occurs at a mixture strength rich of stoichiometry.

Equivalence ratio values greater than 1 indicate mixture settings rich (more fuel for a given amount of air) of stoichiometry, and values less than 1 indicate mixture strength lean (less fuel for a given amount of air) of stoichiometry.

Figures 23-26 show that peak EGT operation for ISO occurred at a slightly richer mixture than for AGE-85, and the AGE-85 produced more power at a given equivalence ratio.

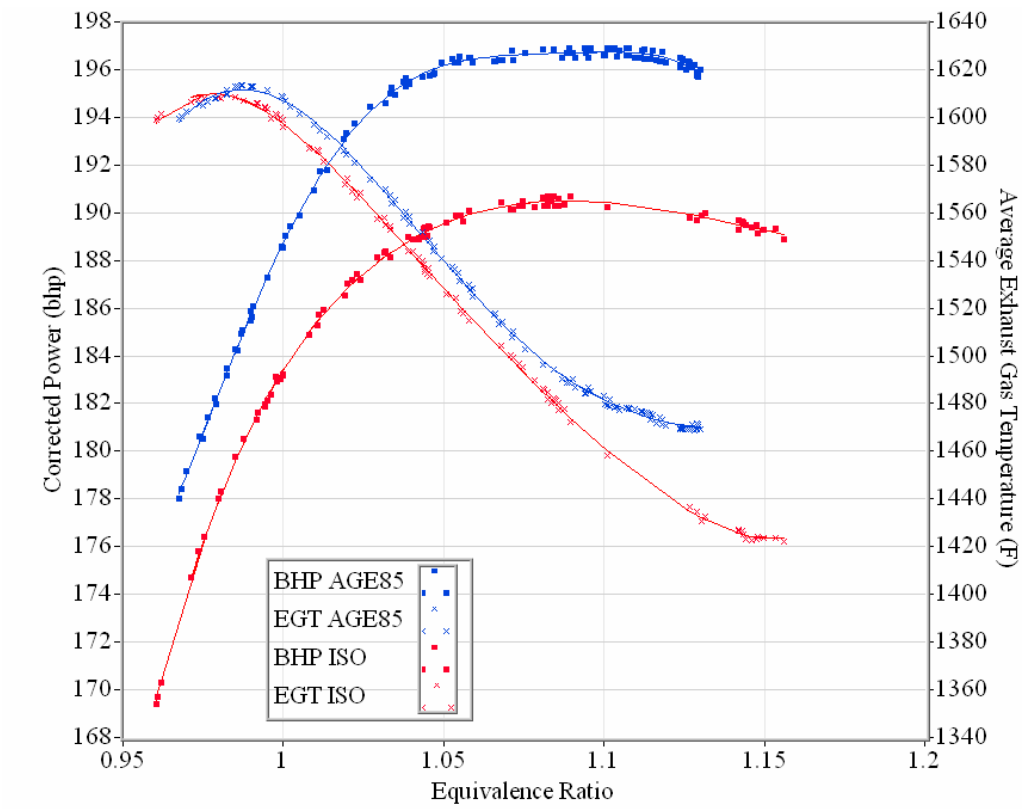

Figure 23. Corrected Power and Average EGT vs Equivalence Ratio at FT and 2700 rpm

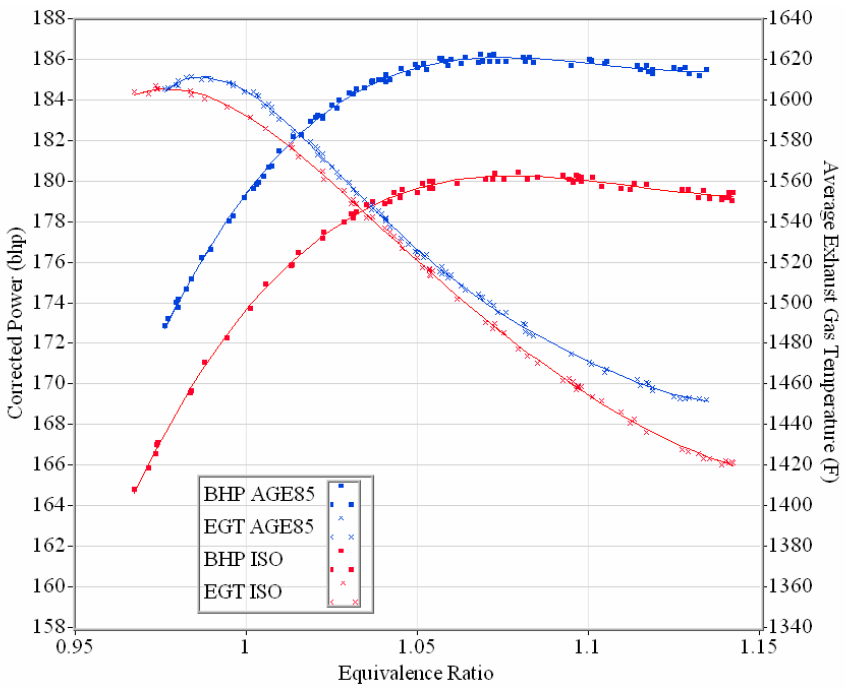

Figure 24. Corrected Power and Average EGT vs Equivalence Ratio at 28-in. Hg and 2600 rpm

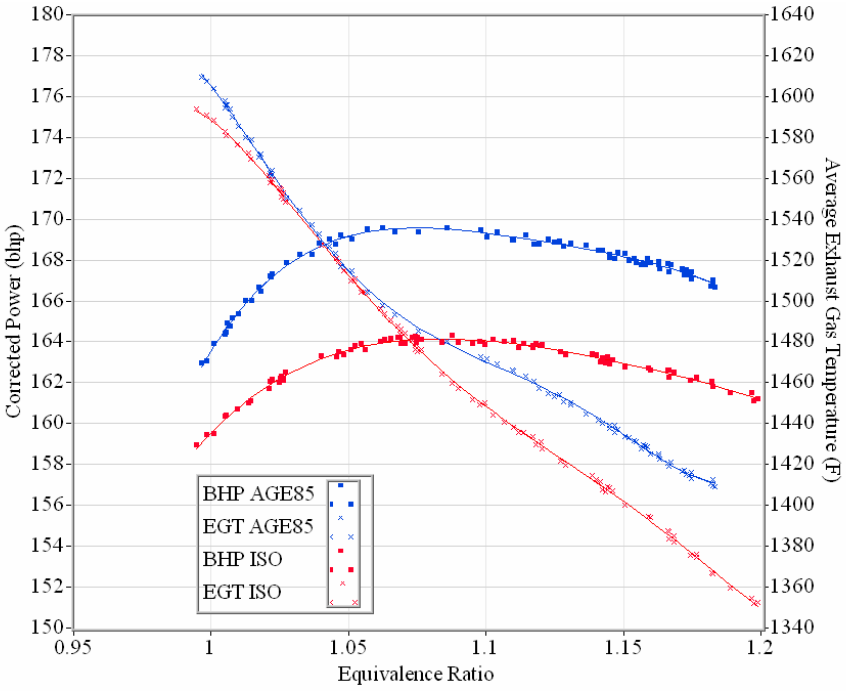

Figure 25. Corrected Power and Average EGT vs Equivalence Ratio at 26-in. Hg and 2600 rpm

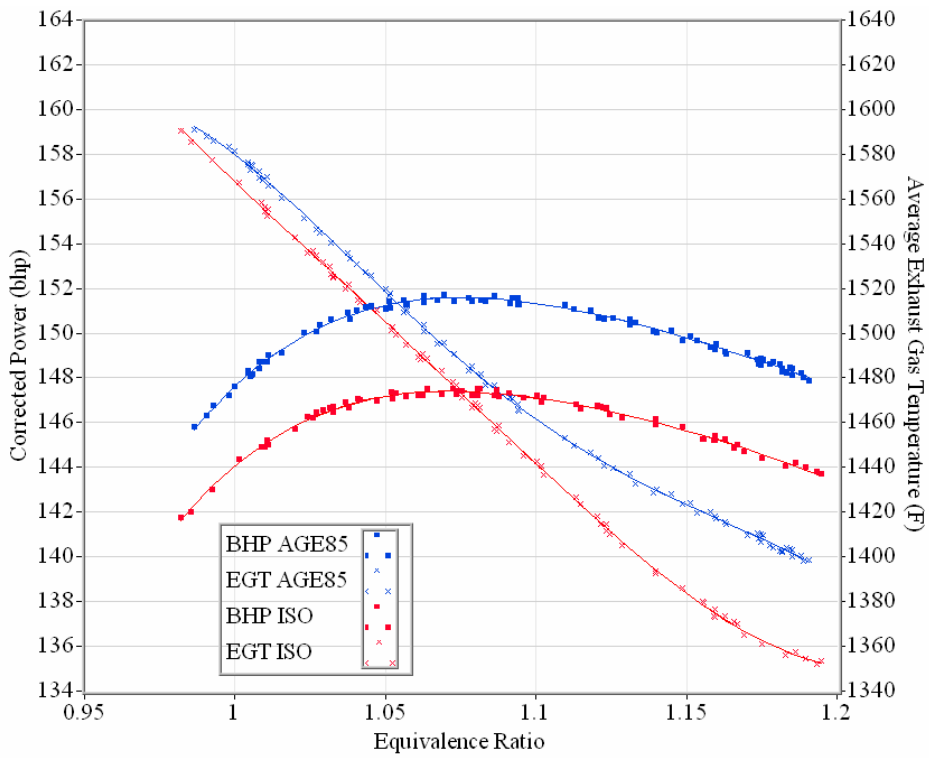

Figure 26. Corrected Power and Average EGT vs Equivalence Ratio at 24-in. Hg and 2400 rpm

Table 9 provides summary equivalence ratios based on the data from figures 23 through 26.

Table 9. Best Economy and Peak Power Air-to-Fuel Ratios and Equivalence Ratios

Power Setting	Best Economy Air-to-Fuel Ratio	Peak Power Air-to-Fuel Ratio	Best Economy Equivalence Ratio	Peak Power Equivalence Ratio
ISO TO	15.4	13.8	0.983	1.107
ISO 28-in. Hg, 2600 rpm	15.5	13.9	0.974	1.087
ISO 26-in. Hg, 2600 rpm	15.6	14.1	0.969	1.075
ISO 24-in. Hg, 2400 rpm	16.2	14.5	0.931	1.057
ISO 22-in. Hg, 2200 rpm	16.2	14.8	0.936	1.058
AGE-85 TO	10.3	9.3	0.977	1.079
AGE-85 28-in. Hg, 2600 rpm	10.4	9.3	0.965	1.067
AGE-85 26-in. Hg, 2600 rpm	10.5	9.5	0.962	1.060
AGE-85 24-in. Hg, 2400 rpm	10.8	9.6	0.935	1.045
AGE-85 22-in. Hg, 2200 rpm	10.8	9.0	0.938	1.052

The data in table 9 shows that best economy occurred slightly lean of stoichiometry and the peak power occurred rich of stoichiometry. These results represent an average by measuring the air-to-fuel ratio of all six cylinders using two sensors and then plotting the data against total power

output from all six cylinders. Piston aircraft engine fuel delivery systems are notorious for exhibiting different leaning patterns in different cylinders. The air-to-fuel ratio is not consistent across all cylinders at a given mixture setting, and adjustment of the mixture can vary the differences between cylinders.

Figure 27 plots the best economy and peak power equivalence ratios for each power setting.

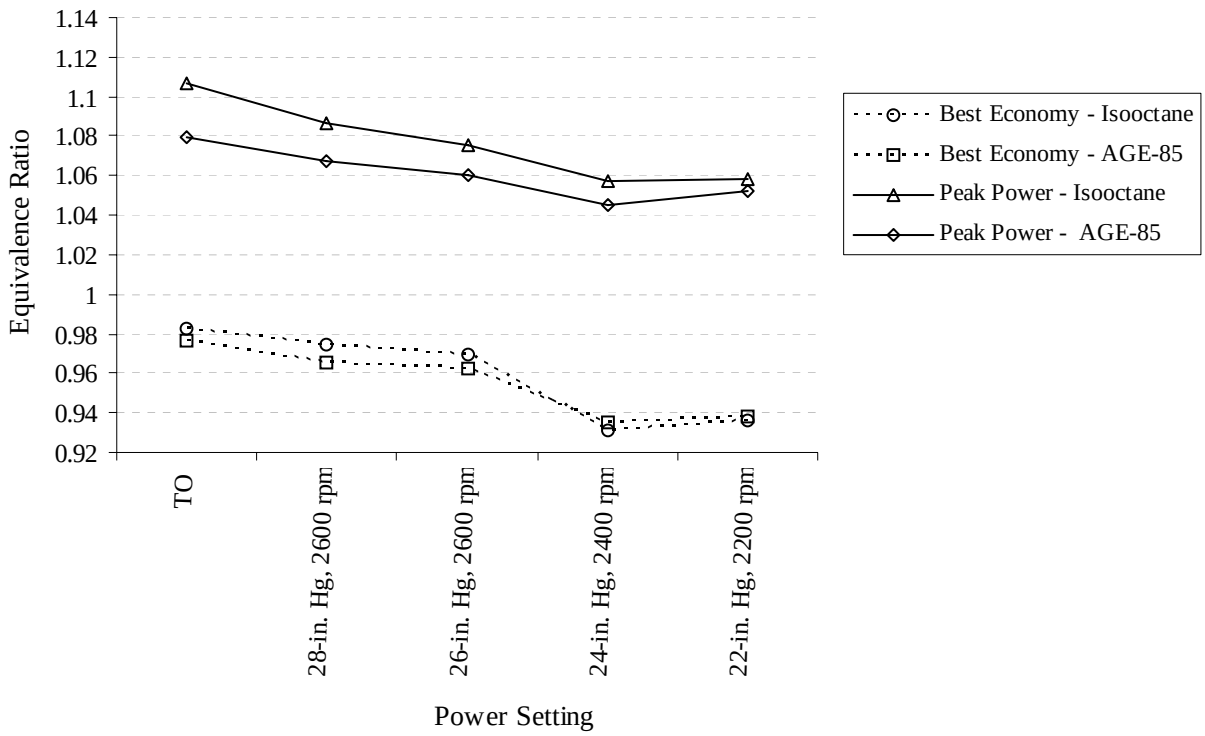

Figure 27. Equivalence Ratio vs Power Setting

The equivalence ratio increased with increasing power setting and was higher for ISO at the peak power mixture setting. This shows that ISO required richer mixtures, relative to its stoichiometric mixture setting, than AGE-85 at the peak power settings. This was previously shown using EGT data in table 8. The best economy equivalence ratios were similar for both fuels, which is as expected because they should occur at mixture settings slightly lean of stoichiometry, equivalence ratio of one.

3.2 ENDURANCE TEST.

A 150-hour endurance test was run at maximum operating temperatures, and best power fuel mixture setting, using AGE-85. The AGE-85 was in sealed drums that contained less than 0.2% water by volume. The drums were opened immediately prior to use and were not exposed to the atmosphere for any length of time.

At the beginning of the test and after every 50 hours of engine operation an oil sample was taken and analyzed for viscosity changes, fuel dilution, acidity, and metals concentration. The results are shown in table 10.

Table 10. Oil Analyses

	Sample Date (2005)	8/18	9/6	9/19	10/11	10/20	10/31
	Eng. Hours	9.3	49.9	50.2	50.6	29.2	33.5
Test Method	Description	Engine Break-In 20W-50 Mineral Oil	15W-50 Ashless Dispersant	15W-50 Ashless Dispersant	15W-50 Ashless Dispersant	15W-50 Ashless Dispersant	15W-50 Ashless Dispersant
ASTM D 664	Acid Number, mg KOH/g	0.7	1.9	1.8	1.5	1.3	1.5
ASTM D 445	Viscosity, mm^2/s						
	40°C	132.7	179.1	182.8	164.9	145.1	142.0
	100°C	16.90	22.54	22.68	21.07	19.44	19.23
ASTM D 3525	Fuel Dilution, mass %	0.09	0.08	0.06	0.06	0.07	0.41
JOAP	Metals by Arc Spark, parts per million						
	Iron	13	32	28	22	13	18
	Lead	4	11	10	10	5	7
	Copper	18	33	20	16	12	15
	Chromium	4	5	4	3	2	3
	Aluminum	8	27	26	20	11	13
	Nickel	1	4	2	2	1	1
	Tin	2	10	6	5	3	3
	Silicon	8	8	7	5	3	4
	Sodium	10	15	11	15	7	9
	Zinc	14	13	9	7	5	5
	Calcium	15	8	4	4	3	3
	Magnesium	1	3	1	1	1	1
	Molybdenum	1	1	-	-	-	-
	Potassium	73	19	7	6	6	7
	Phosphorous	27	304	333	388	352	334

KOH = potassium hydroxide

The oil analyses indicated that neither fuel dilution nor oil degradation had occurred. The acid number of the oil was low and showed a level trend, and the same trend occurred with the oil viscosity. Fuel dilution was measured to be less than 0.1%. The metals analyses showed low values and declining trends, which is a normal wear pattern. The high levels of phosphorous were from phosphorous-based oil additives.

The oil filter was cut open and the filter medium was inspected for metal particles, as previously shown in figure 1. No significant amount of metallic particles were found at any of the inspection intervals.

Table 11 lists the valve recession measurements. The first row of the table for a given date shows the initial depth of the valve stem, as measured with a micrometer. The second row shows the second valve stem height measurement with the number of engine hours listed since the last measurement. The third row shows the change in valve depth from the original measurement with the number of engine hours listed since the initial measurement.

Table 11. Valve Recession Measurements

			Intake Valves (inches)				Exhaust Valves (inches)			
Date	Engine Hours	Test Hours	1	2	3	4	1	2	3	4
8/18/2005	9.3	0.0	1.4300	1.4280	1.4310	1.4270	1.4850	1.4790	1.4870	1.4900
9/6/2005	59.2	49.9	1.4295	1.4270	1.4310	1.4270	1.4810	1.4730	1.4820	1.4860
	wear/49.9		0.0005	0.0010	0.0000	0.0000	0.0040	0.0060	0.0050	0.0040
9/19/2005	109.4	100.1	1.4290	1.4280	1.4310	1.4275	1.4750	1.4660	1.4750	1.4820
	wear/50.2		0.0005	-0.0010	0.0000	-0.0005	0.0060	0.0070	0.0070	0.0040
	wear/100.1		0.0010	0.0000	0.0000	-0.0005	0.0100	0.0130	0.0120	0.0080
10/13/2005	160.0	150.7	1.4290	1.4270	1.4310	1.4270	1.4700	1.4620	1.4710	1.4780
	wear/50.6		0.0000	0.0010	0.0000	0.0005	0.0050	0.0040	0.0040	0.0040
	wear/150.7		0.0010	0.0010	0.0000	0.0000	0.0150	0.0170	0.0160	0.0120
10/25/2005	189.2	179.9	1.4290	1.4270	1.4310	1.4270	1.4670	1.4580	1.4670	1.4760
	wear/29.2		0.0000	0.0000	0.0000	0.0000	0.0030	0.0040	0.0040	0.0020
	wear/179.9		0.0010	0.0010	0.0000	0.0000	0.0180	0.0210	0.0200	0.0140
10/31/2005	193.5	184.2	1.4290	1.4270	1.4310	1.4270	1.4660	1.4580	1.4670	1.4750
	wear/4.3		0.0000	0.0000	0.0000	0.0000	0.0010	0.0000	0.0000	0.0010
	wear/184.2		0.0010	0.0010	0.0000	0.0000	0.0190	0.0210	0.0200	0.0150

Figure 28 shows the exhaust valve recession plotted versus total engine hours. The change in valve recession was consistent over time and did not show accelerating wear. The total intake valve recession was less than 0.001 inch, and the average exhaust valve recession over the 150-hour test was found to be 0.01875 inch with a maximum value of 0.0210 inch in cylinder 2. These values are on the high side of the normal expected range for a test this severe and this duration. Both the exhaust valve faces and exhaust valve seats showed a hammered effect, which was partly due to the necessity of running the engine with the ignition timing retarded by 5°.

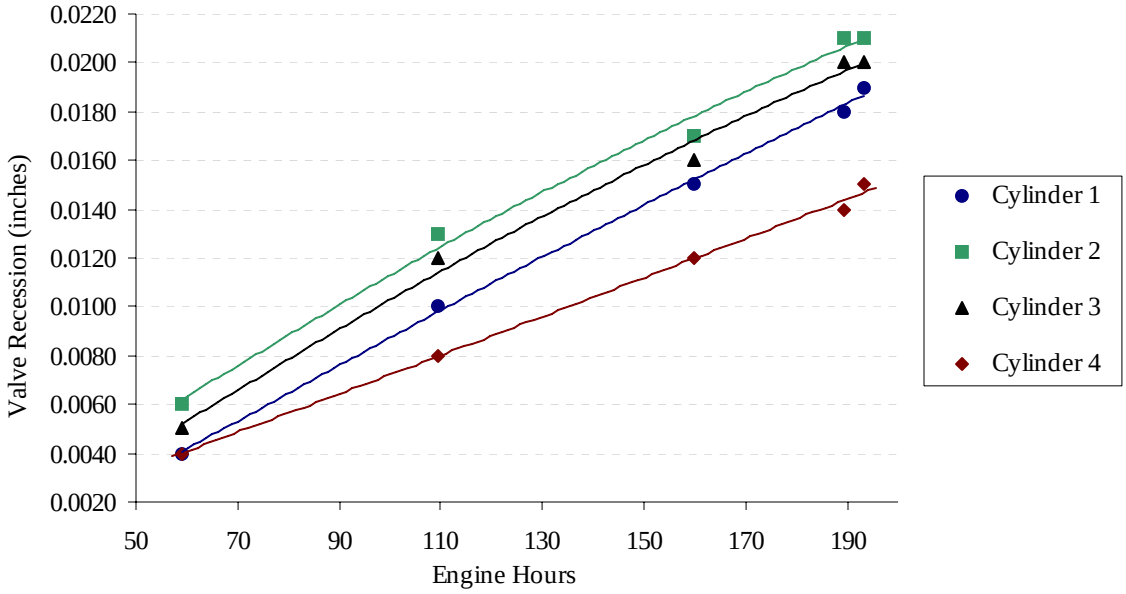

Figure 28. Exhaust Valve Recession

Table 12 shows the cylinder compression measurements. The engine was still showing pressures above 70 psig out of 80 psig applied at the end of the test. Typically, a value above 60 psig is considered acceptable.

Table 12. Cylinder Compression Measurements

			Compression/80 psig			
Date	Engine Hours	Test Hours	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
8/18/2005	9.3	0.0	64	68	74	77
9/6/2005	59.2	49.9	78	74	74	76
9/19/2005	109.4	100.1	75	76	76	77
10/13/2005	160.0	150.6	76	76	74	74
10/31/2005	193.5	184.2	75	77	77	76

Figures 29 through 31 show the combustion chamber of cylinder 1 after 9.3 engine hours of operation. There were no visible deposits on the spark plugs, piston faces, or valves. Also, the cylinder wall crosshatching, which is machined at the factory, is still visible.

Figures 32 through 35 show cylinder 1 after 59.2 hours of operation. Note the accumulation of oil deposits on the bottom of the piston face and the fuel stains on the exhaust valve faces.

Figure 29. Top of Piston Face of Cylinder 1 After 9.3 Engine Hours

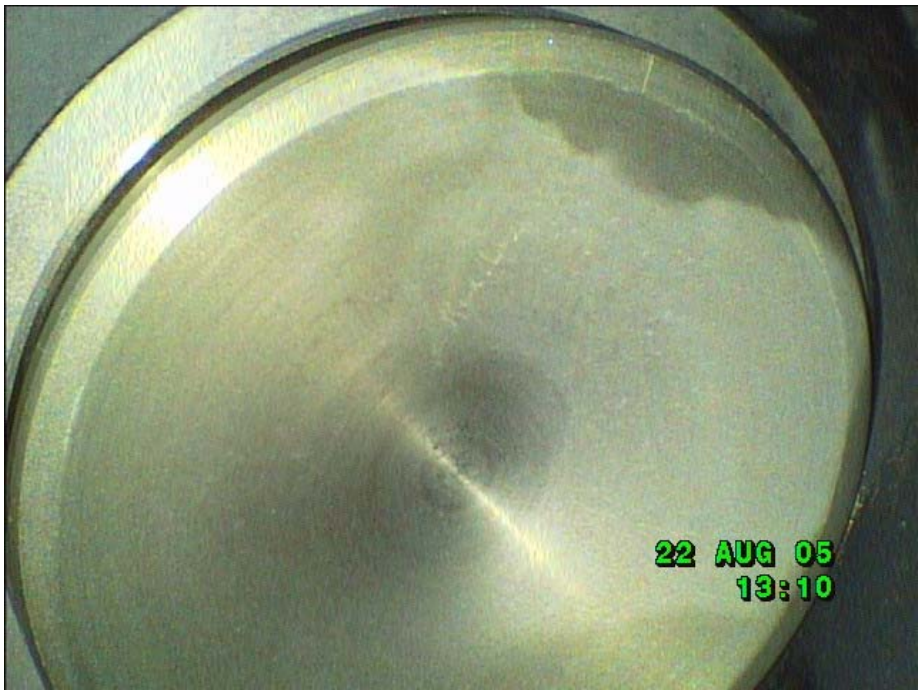

Figure 30. Intake Valve Face of Cylinder 1 After 9.3 Engine Hours

Figure 31. Exhaust Valve Face of Cylinder 1 After 9.3 Engine Hours

Figure 32. Top of Piston Face of Cylinder 1 After 59.2 Engine Hours

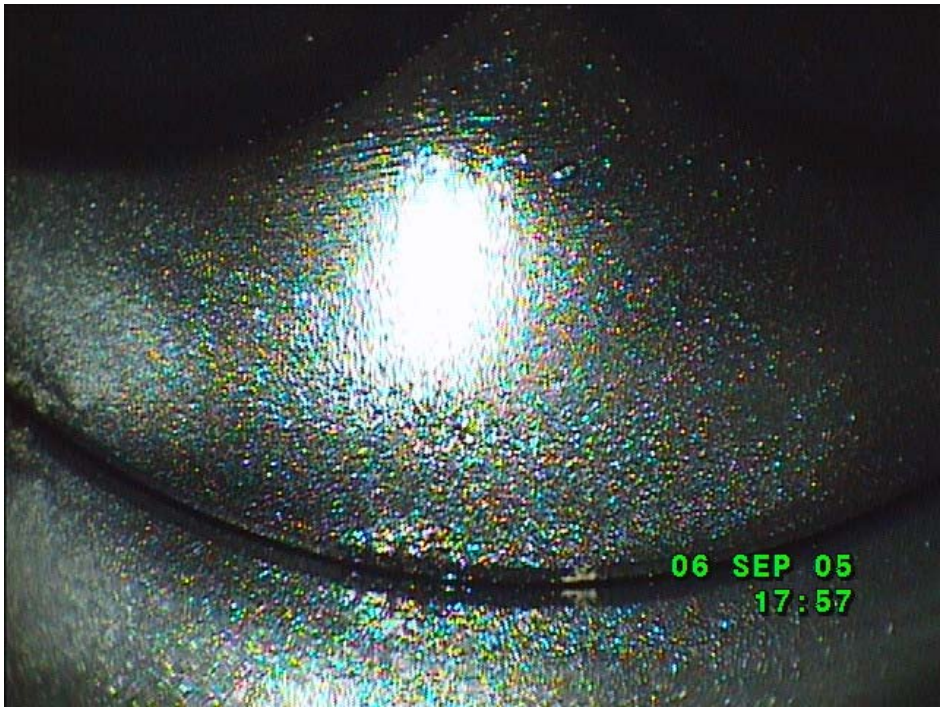

Figure 33. Bottom of Piston Face and Cylinder Wall for Cylinder 1 After 59.2 Engine Hours

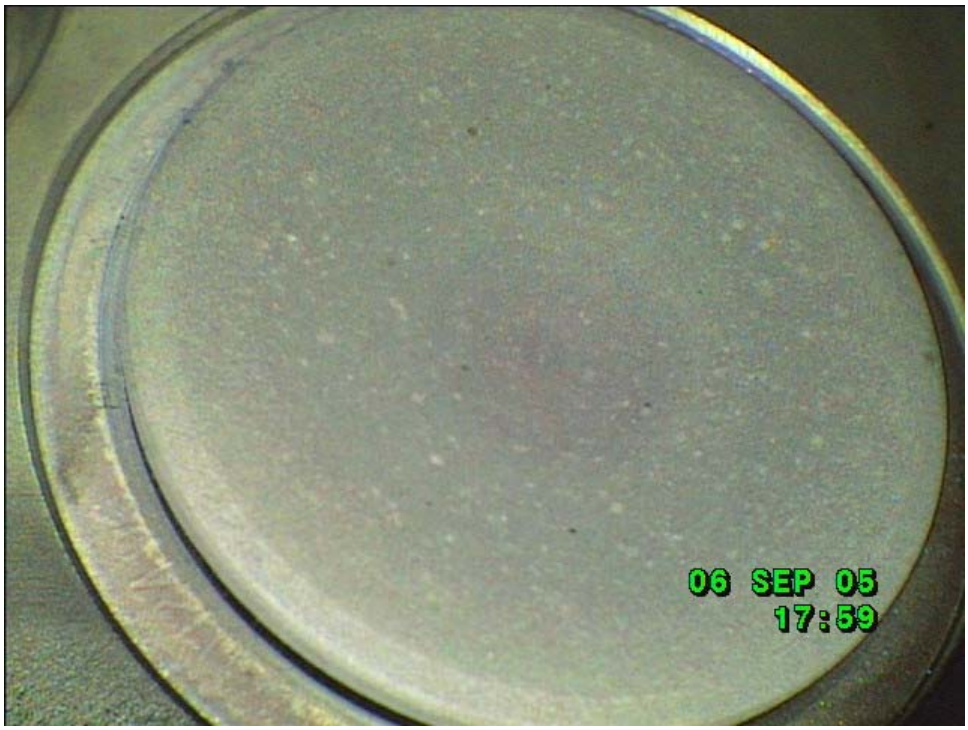

Figure 34. Exhaust Valve Face for Cylinder 1 After 59.2 Engine Hours

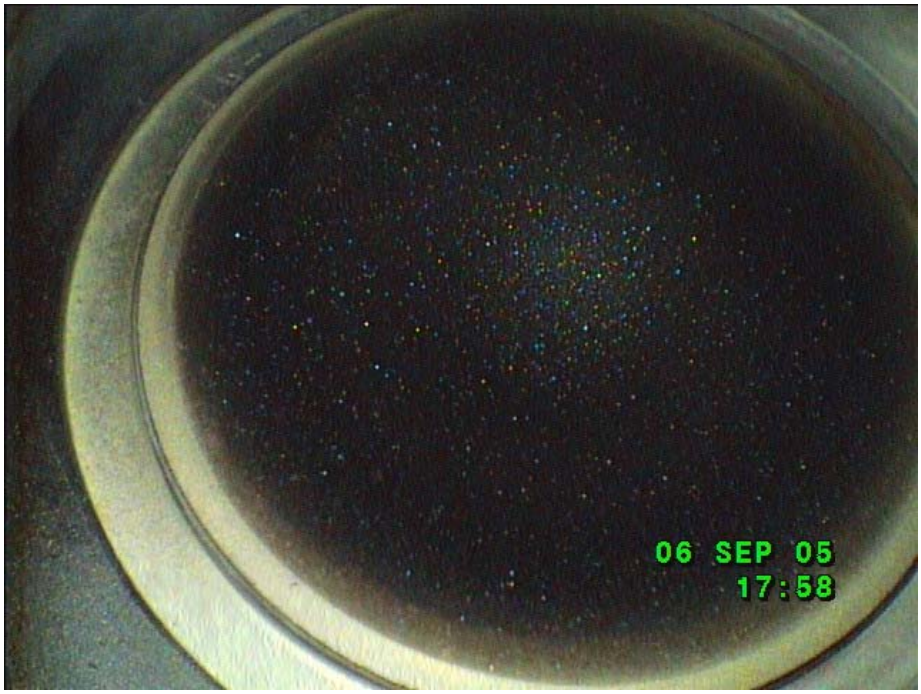

Figure 35. Intake Valve Face for Cylinder 1 After 59.2 Engine Hours

High-stress engine components were measured after the overhaul and at the end of the endurance test, which can be found in appendix A. The front, rear, and middle main crankshaft journals experienced normal wear, as did the four crankshaft connecting rod journals (see figures 36 through 42).

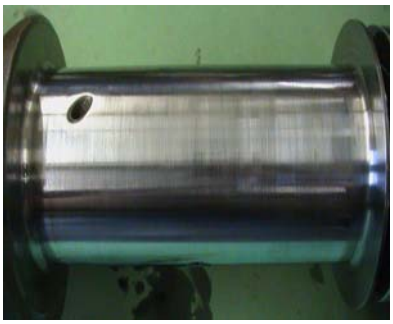

Figure 36. Posttest Crankshaft Front Main Journal

Figure 37. Posttest Crankshaft Middle Main Journal

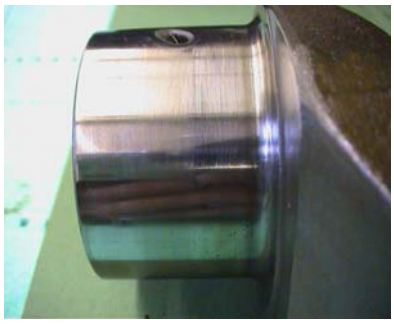

Figure 38. Posttest Crankshaft Rear Main Journal

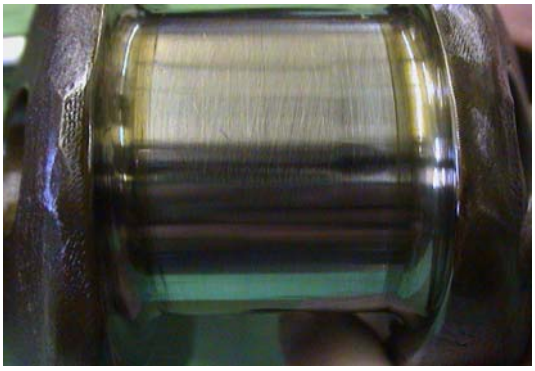

Figure 39. Posttest Crankshaft Connecting Rod Journal Cylinder 1

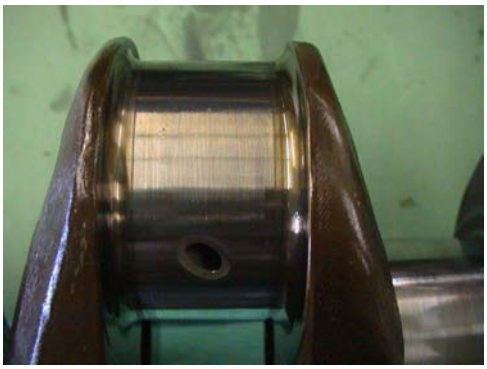

Figure 40. Posttest Crankshaft Connecting Rod Journal Cylinder 2

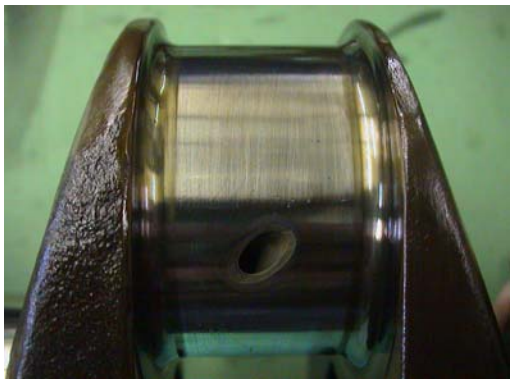

Figure 41. Posttest Crankshaft Connecting Rod Journal Cylinder 3

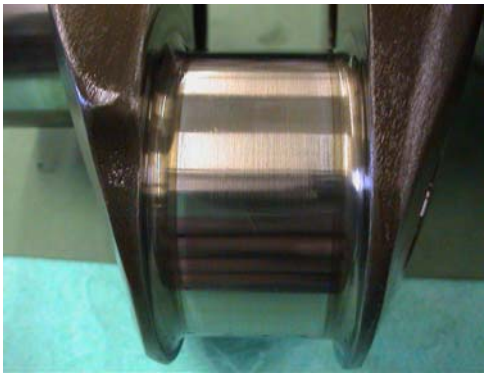

Figure 42. Posttest Crankshaft Connecting Rod Journal Cylinder 4

The crankshaft journal bearings experienced normal wear patterns, as shown in figures 43 through 45.

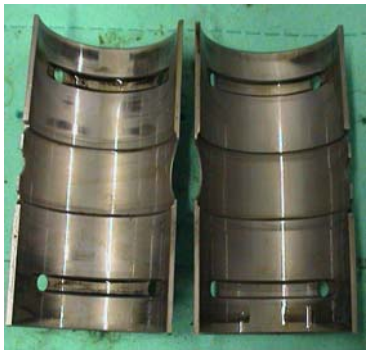

Figure 43. Posttest Front Main Crankshaft Bearing

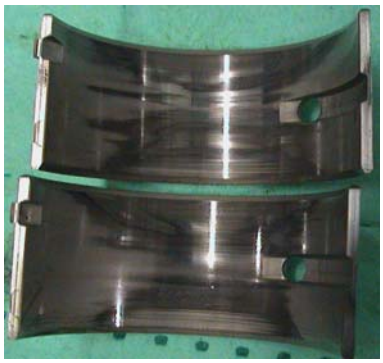

Figure 44. Posttest Middle Main Crankshaft Bearing

Figure 45. Posttest Rear Main Crankshaft Bearing

The piston connecting rod bearings, shown in figures 46 through 49, experienced normal wear.

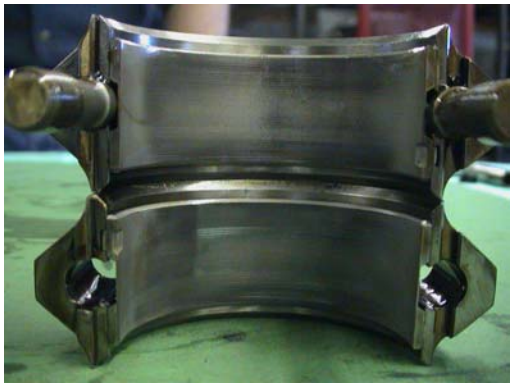

Figure 46. Posttest
Connecting Rod Bearing Cylinder 1

Figure 47. Posttest
Connecting Rod Bearing Cylinder 2

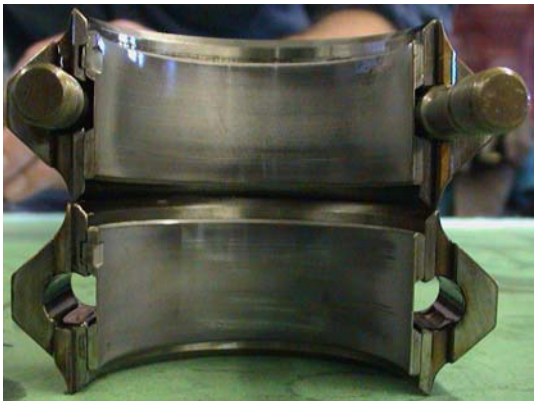

Figure 48. Posttest Connecting Rod Bearing Cylinder 3

Figure 49. Posttest Connecting Rod Bearing Cylinder 4

The camshaft front, middle, and rear bearing diameters, shown in figures 50 through 52, were within the manufacturer's new limit specifications at the end of the test.

Figure 50. Posttest
Camshaft Front Main
Bearing

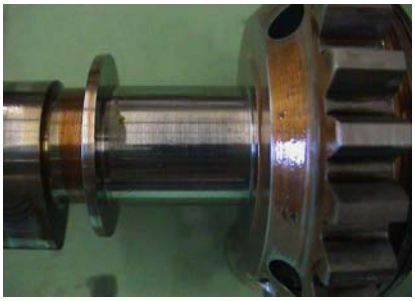

Figure 51. Posttest
Camshaft Middle Main
Bearing

Figure 52. Posttest
Camshaft Rear Main
Bearing

The camshaft lobes, shown in figure 53, experienced normal wear.

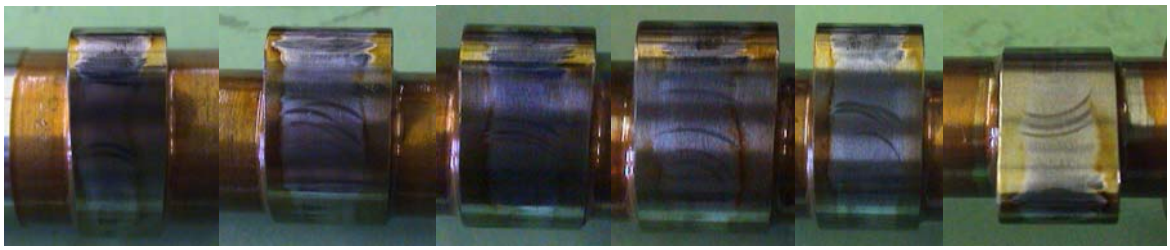

Figure 53. Posttest Camshaft Lobes

The crankcase main bearing bores were all within the manufacturer's new limit specifications at the end of the test. The crankcase halves are shown in figure 54. There was minimal varnish or sludge buildup.

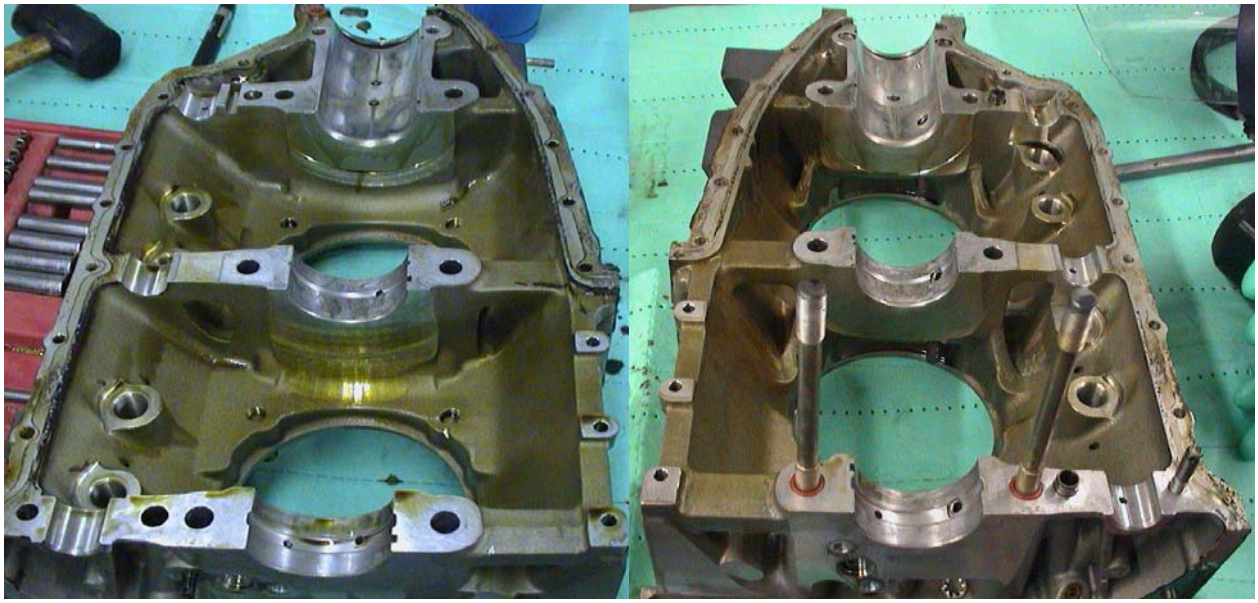

Figure 54. Posttest Crankcase Halves

The piston pin bores were within the manufacturer's new limit specifications at the end of the test, and the piston skirt measurements were within the manufacturer's service limit specifications. The top, middle, and bottom piston ring side clearances were all within the manufacturer's new limit specifications at the end of the test. All the piston faces showed light deposits, and all piston rings moved freely. Piston skirts displayed more discoloration than is normally seen with leaded fuels and slight scuffing. There was also some scuffing at the side of the piston above the top compression ring (see figures 55 through 57).

Figure 55. Posttest Piston Pin Bores—Cylinders 1 Through 4 (Left to Right)

Figure 56. Posttest Piston Sides—Cylinders 1 Through 4 (Left to Right)

Figure 57. Posttest Piston Faces—Cylinders 1 Through 4 (Left to Right)

A typical piston pin is shown in figure 58. There was normal wear on all piston pins.

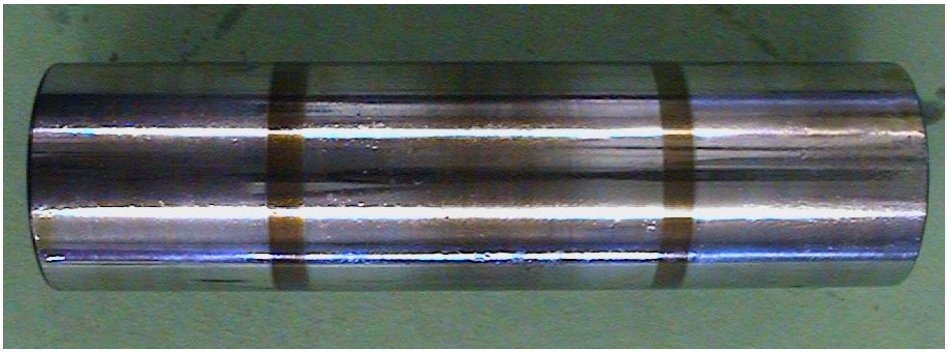

Figure 58. Posttest Piston Pin

Figure 59 shows a combustion chamber photograph taken during the engine teardown at the end of the test. Some of the cylinder crosshatching was still visible on the cylinder walls. The chambers showed normal wear with minimal deposits and some light scuffing on the cylinder barrel.

Figure 59. Posttest Combustion Chamber

The intake and exhaust valve tappets' outer diameters and bores were within the manufacturer's new limit specifications at the end of the test. Figure 60 shows the tappet body faces. The wear pattern was normal. There was no visible evidence of spalling or pitting of faces, and the Rockwell Hardness marks were still visible.

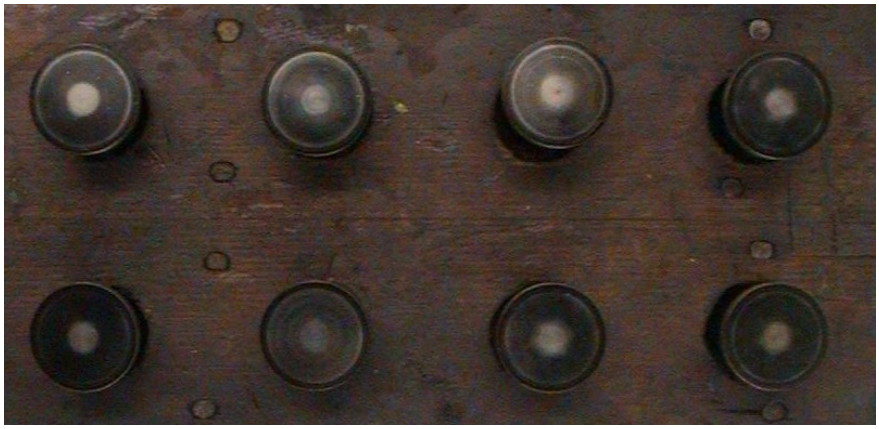

Figure 60. Posttest Valve Tappet Body Faces

The intake valve stem diameter, guide diameters, and valve guide clearance were all within the manufacturer's new limit specifications at the end of the test. Both the intake and exhaust seats showed a hammered effect and were out of the allowable service limits at the end of the test. This may have been partly due to having to retard the ignition timing by 5°. Figures 61 and 62 show the intake and exhaust valve deposit buildup and the damage to the exhaust valve faces. Figure 62 shows the hammered effect on the exhaust valves with ridges formed on the valve faces.

Figure 61. Posttest Intake Valves 1 Through 4 (Left to Right)

Figure 62. Posttest Exhaust Valves 1 Through 4 (Left to Right)

The exhaust valve stems showed no wear, but the valve guides showed significant wear. All the valve guides were out of the manufacturer's service limits at the end of the test, as were the valve-to-valve guide clearance measurements. This also may have been a consequence of retarding the ignition timing by 5°.

The valve rocker arms showed normal wear. Figure 63 shows a typical rocker arm at the completion of the test.

Figure 63. Posttest Rocker Arm Showing Normal Wear

The rocker arm bushings showed light scoring. Figure 64 shows what was typically found at the end of the test. This is not unusual for a test this severe.

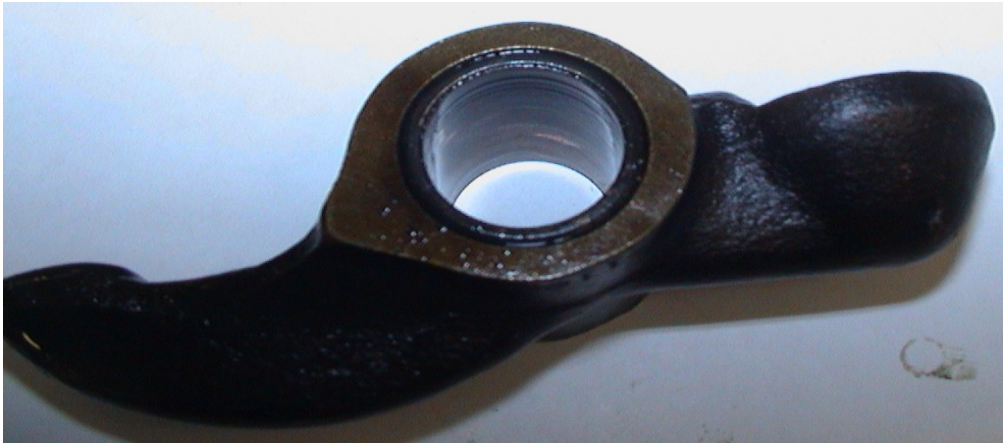

Figure 64. Posttest Rocker Arm Bushing Showing Slight Scoring

There were hot spots on connecting rods 2 and 4 at the piston pin bearing area where it looks like oil has coked in small spots. This is shown in figure 65.

Figure 65. Posttest Connecting Rod Hot Spot Damage

The exhaust rocker arm pins 1, 2, and 4 and intake pin 3 were slightly grooved. Figure 66 shows what was typically found, which is considered to be normal wear.

Figure 66. Posttest Rocker Arm Pin

Figure 67 shows the oil pump housing and oil pump gears at the end of the test. Wear was minimal and there was minimal varnish buildup.

Figure 67. Posttest Oil Pump Housing and Oil Pump Gears

Figure 68 shows the accessory housing with minimal varnish buildup.

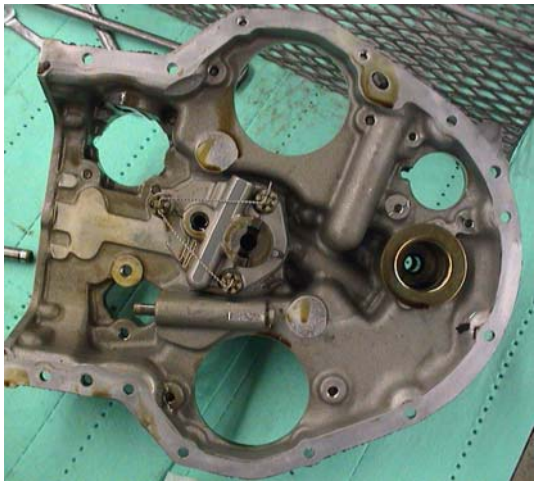

Figure 68. Posttest Accessory Housing

Visual observation of the intake tubes showed some discoloration with minimal amounts of varnish.

4. SUMMARY.

A Lycoming IO360-C model engine, overhauled to new specifications, was used for a 150-hour endurance test on AGE-85. The fuel servo injector jet and distribution nozzles were enlarged, and the engine ignition timing was retarded from the standard setting for 100LL of 20° BTDC to 15°. The cylinder compression ratio was not altered from its standard configuration. The IO360-C engine was originally type certificated to operate on 100- or 100LL-grade ASTM D 910 fuels.

The majority of the endurance test was run at maximum engine and oil temperatures with the mixture adjusted to attain best power.

Power baseline comparisons were also performed on the engine using AGE-85 at the 15° BTDC ignition timing and ISO at the 20° BTDC timing.

AGE-85 produced on average 4.3 (2.8%) more peak horsepower than ISO but required 39.7 lb/hr (56.5%) more fuel mass flow or 5.6 gal/hr (35.0%) more fuel volume flow. This is a consequence of two things: the AGE-85 having less energy density than ISO and the oxygen content of AGE-85. This increased fuel mass flow requirement resulted in a drop in peak power efficiency at the TO power setting, as measured by the BSFC from 0.471 lb/bhp hr for ISO to 0.700 lb/bhp hr for AGE-85. The average peak power BSFC was 0.470 lb/bhp hr for ISO and 0.716 lb/bhp hr for AGE-85.

Best economy operations resulted in 2.6 (1.8%) more horsepower when operating on AGE-85 but required 32.3 lb/hr (55.8%) more fuel mass flow. The average efficiency at best economy was much lower for AGE-85 than ISO, with values of 0.415 lb/bhp hr for ISO and 0.640 lb/bhp hr for AGE-85.

Operation at peak power on AGE-85 resulted in 20ºF higher average EGTs than ISO. Some of this was the result of retarding the ignition timing by 5° and of adjusting the cooling air pressure to maintain fixed CHTs.

The best power average EGTs were found to be 136ºF rich of peak EGT for ISO and 110ºF rich of peak EGT for AGE-85. Air-to-fuel ratio data verified that AGE-85 peak power occurred at mixtures much richer than ISO. However, equivalence ratio data showed that these mixtures were leaner relative to stoichiometry than ISO.

The mass densities were measured to be 5.7 lb/gal for ISO and 6.4 lb/gal for AGE-85. The current 100LL aviation gasoline has a standard mass density of 5.87 lb/gal. Using AGE-85 would increase fuel weight by 9% above that of 100LL for an equivalent volume of fuel and would reduce operating range by 35% from 100LL.

The engine was measured before and after the endurance test. All fuel was used from sealed drums containing less than 0.2% water. The entire endurance test was performed at best power fuel mixtures.

Periodic engine lubricating oil analyses showed that neither fuel dilution nor oil degradation had occurred. The acid number of the oil remained low and showed a level trend, as did the change in oil viscosity and metals concentration. The test was run at mixture settings leaned to best power. Running at higher mixtures, which is typical with ethanol-based fuels, may have resulted in higher oil dilution rates and potentially accelerated wear.

There was minimal engine varnish and sludge buildup, and the combustion chambers had minimal deposits. The intake valves showed light deposits as did the piston face and ring grooves. There were minimal fuel system deposits.

The total exhaust valve recession was found to average 0.01875 inch with a maximum value of 0.0210 inch. Based on previous experience, this was slightly higher than expected. The exhaust valves exhibited a hammered effect, with the valve faces showing compression grooves. Some of this was due to operation of the engine at 5° retarded ignition timing for AGE-85. This suggests that necessary modifications to ignition timing for operation on AGE-85 may result in elevated EGTs and accelerated exhaust valve wear.

Engine cylinder compressions remained high at the end of the test.

It should be noted that performing this endurance test with ethanol containing greater than 1% water and at fuel mixtures richer than best power may result in much greater engine wear than was found under the conditions of this test. In fact, independent industry data has shown this.

This test showed that without significant modifications to existing engine design beyond retarding the ignition timing (such as increasing cylinder compression ratios, changing valve timing, and derating of engine power), adjustments to the fuel schedule for a 100- or 100LL-certificated engine for operation in AGE-85 would be required to provide upwards of 57% more fuel mass flow or 35% more fuel volume flow

.

Current investigation at the Airport and Aircraft Safety Research and Development Division at the FAA William J. Hughes Technical Center will include detonation performance studies comparing AGE-85 to 100LL. This testing will be performed on a 100- or 100LL-certificated engine at the standard ignition timing. This will address whether typical mixture leaning operations to best power and best economy can be performed free of detonation on AGE-85.

It should also be noted that there is currently no ASTM standard specification for AGE-85. The formulation tested consisted of 85% denatured ethanol, less than 1% biodiesel, and the rest was a pentane isomerate. Current ethanol research shows the composition of AGE-85 to be in continuous flux, with new proposals eliminating the lubricity-enhancing and corrosion-inhibiting biodiesel and adding toluene. Future proposals also include eliminating automotive fuel as a denaturant and seeking approval to use isopentane as the denaturant.

Future testing should address effect of increasing cylinder compression ratio by changing the cylinder and engine geometry at 5° retarding ignition timing in an attempt to recover some of the lost efficiency.

APPENDIX A—LYCOMING IO360-C ENGINE MEASUREMENTS

Table A-1. Front Main Crankshaft Bearing Measurements

Location	Pretest (in.)	Posttest (in.)	Wear (in.)
Top Main—1	0.0946	0.0940	0.0006
Top Main—2	0.0946	0.0940	0.0006
Top Main—3	0.0945	0.0940	0.0005
Top Main—4	0.0946	0.0940	0.0006
Top Main—5	0.0946	0.0940	0.0006
Top Main—6	0.0946	0.0940	0.0006
Top Main—7	0.0946	0.0940	0.0006
Top Main—8	0.0946	0.0940	0.0006
Bottom Main-1	0.0946	0.0940	0.0006
Bottom Main-2	0.0944	0.0940	0.0004
Bottom Main-3	0.0944	0.0940	0.0004
Bottom Main-4	0.0945	0.0940	0.0005
Bottom Main-5	0.0945	0.0940	0.0005
Bottom Main-6	0.0945	0.0940	0.0005
Bottom Main-7	0.0945	0.0940	0.0005
Bottom Main-8	0.0945	0.0940	0.0005

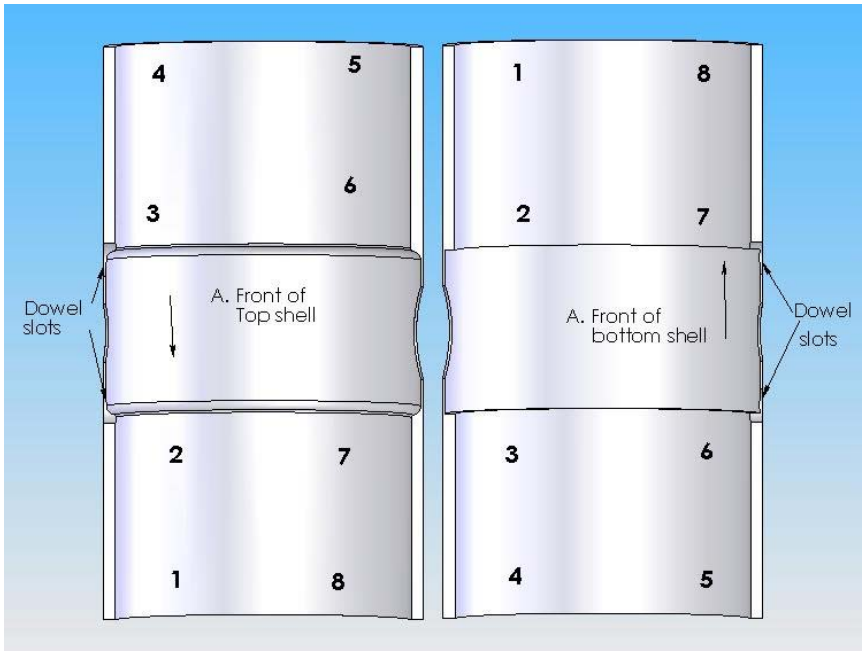

Figure A-1. Front Main Crankshaft Bearing Measurements Location Drawing

Table A-2. Middle and Rear Main Crankshaft Bearing Measurements

Location	Pretest (in.)	Posttest (in.)	Wear (in.)
Right Middle Bearing–1	0.0942	0.0940	0.0002
Right Middle Bearing–2	0.0932	0.0935	-0.0003
Right Middle Bearing–3	0.0942	0.0940	0.0002
Right Middle Bearing–4	0.0943	0.0940	0.0003
Right Middle Bearing–5	0.0933	0.0935	-0.0002
Right Middle Bearing–6	0.0943	0.0940	0.0003
Left Middle Bearing–1	0.0943	0.0940	0.0003
Left Middle Bearing–2	0.0932	0.0935	-0.0003
Left Middle Bearing–3	0.0943	0.0940	0.0003
Left Middle Bearing–4	0.0942	0.0940	0.0002
Left Middle Bearing–5	0.0932	0.0935	-0.0003
Left Middle Bearing–6	0.0943	0.0940	0.0003
Right Rear Bearing–1	0.0942	0.0940	0.0002
Right Rear Bearing–2	0.0932	0.0935	-0.0003
Right Rear Bearing–3	0.0942	0.0940	0.0002
Right Rear Bearing–4	0.0942	0.0940	0.0002
Right Rear Bearing–5	0.0932	0.0935	-0.0003
Right Rear Bearing–6	0.0943	0.0940	0.0003
Left Rear Bearing–1	0.0942	0.0940	0.0002
Left Rear Bearing–2	0.0932	0.0935	-0.0003
Left Rear Bearing–3	0.0942	0.0940	0.0002
Left Rear Bearing–4	0.0943	0.0940	0.0003
Left Rear Bearing–5	0.0933	0.0935	-0.0002
Left Rear Bearing–6	0.0943	0.0940	0.0003

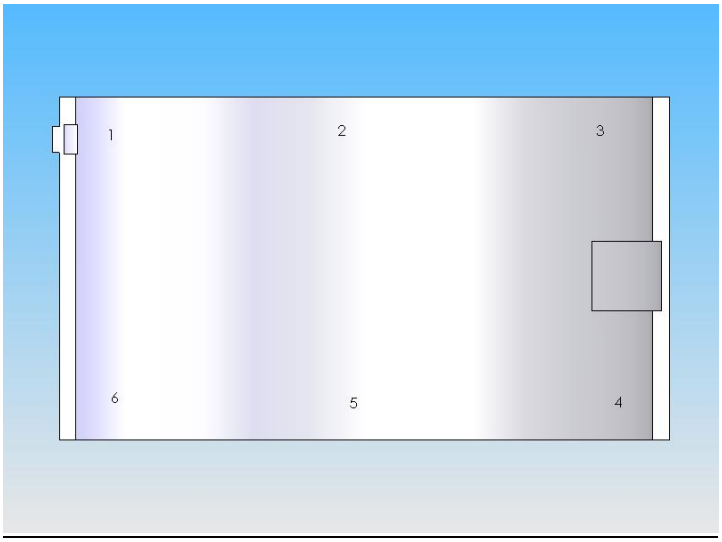

Figure A-2. Middle and Rear Main Crankshaft Bearing Measurements Location Drawing

Table A-3. Connecting Rod Bearing Measurements

Item – Meas. Location	Pretest (in.)	Posttest (in.)	Wear (in.)	Item – Meas. Location	Pretest (in.)	Posttest (in.)	Wear (in.)
No. 1 Rod –1	0.0848	0.0845	0.0003	No. 1 Cap –1	0.0846	0.0845	0.0001
No. 1 Rod –2	0.0849	0.0850	-0.0001	No. 1 Cap –2	0.0849	0.0850	-0.0001
No. 1 Rod –3	0.0847	0.0845	0.0002	No. 1 Cap –3	0.0846	0.0845	0.0001
No. 1 Rod –4	0.0846	0.0845	0.0001	No. 1 Cap –4	0.0849	0.0845	0.0004
No. 1 Rod –5	0.0849	0.0850	-0.0001	No. 1 Cap –5	0.0849	0.0850	-0.0001
No. 1 Rod –6	0.0848	0.0845	0.0003	No. 1 Cap –6	0.0848	0.0845	0.0003
No. 2 Rod –1	0.0844	0.0845	-0.0001	No. 2 Cap –1	0.0845	0.0845	0.0000
No. 2 Rod –2	0.0848	0.0850	-0.0002	No. 2 Cap –2	0.0849	0.0850	-0.0001
No. 2 Rod –3	0.0846	0.0845	0.0001	No. 2 Cap –3	0.0847	0.0845	0.0002
No. 2 Rod –4	0.0845	0.0845	0.0000	No. 2 Cap –4	0.0848	0.0845	0.0003
No. 2 Rod –5	0.0848	0.0850	-0.0002	No. 2 Cap –5	0.0849	0.0850	-0.0001
No. 2 Rod –6	0.0845	0.0845	0.0000	No. 2 Cap –6	0.0847	0.0845	0.0002
No. 3 Rod –1	0.0847	0.0845	0.0002	No. 3 Cap –1	0.0847	0.0845	0.0002
No. 3 Rod –2	0.0848	0.0850	-0.0002	No. 3 Cap –2	0.0848	0.0845	0.0003
No. 3 Rod –3	0.0847	0.0840	0.0007	No. 3 Cap –3	0.0847	0.0845	0.0002
No. 3 Rod –4	0.0846	0.0840	0.0006	No. 3 Cap –4	0.0846	0.0845	0.0001
No. 3 Rod –5	0.0848	0.0850	-0.0002	No. 3 Cap –5	0.0848	0.0845	0.0003
No. 3 Rod –6	0.0847	0.0840	0.0007	No. 3 Cap –6	0.0848	0.0845	0.0003
No. 4 Rod –1	0.0848	0.0845	0.0003	No. 4 Cap –1	0.0848	0.0845	0.0003
No. 4 Rod –2	0.0849	0.0845	0.0004	No. 4 Cap –2	0.0849	0.0850	-0.0001
No. 4 Rod –3	0.0847	0.0845	0.0002	No. 4 Cap –3	0.0848	0.0845	0.0003
No. 4 Rod –4	0.0847	0.0845	0.0002	No. 4 Cap –4	0.0848	0.0845	0.0003
No. 4 Rod –5	0.0849	0.0845	0.0004	No. 4 Cap –5	0.0849	0.0845	0.0004
No. 4 Rod –6	0.0848	0.0845	0.0003	No. 4 Cap –6	0.0848	0.0845	0.0003

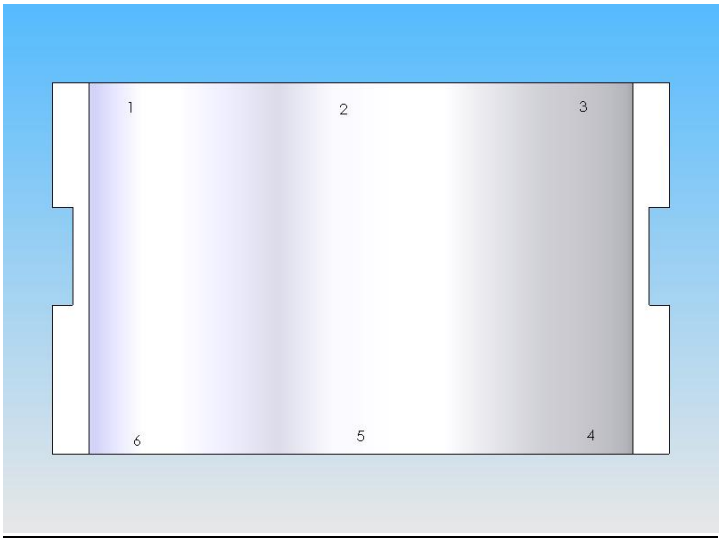

Figure A-3. Connecting Rod Bearing Measurements Location Drawing

Table A-4. Valve Tappet Outer Diameter and Bore Measurements

Item	Tappet Outer Diameter Posttest (in.)	Within New Limits?	Within Serviceable Limits?	Tappet Bore Posttest (in.)	Within New Limits?	Within Serviceable Limits?
No. 1 Intake	0.7172	Yes	Yes	0.7193	Yes	Yes
No. 1 Exhaust	0.7173	Yes	Yes	0.7195	Yes	Yes
No. 2 Intake	0.7173	Yes	Yes	0.7190	Yes	Yes
No. 2 Exhaust	0.7174	Yes	Yes	0.7193	Yes	Yes
No. 3 Intake	0.7172	Yes	Yes	0.7190	Yes	Yes
No. 3 Exhaust	0.7173	Yes	Yes	0.7191	Yes	Yes
No. 4 Intake	0.7173	Yes	Yes	0.7191	Yes	Yes
No. 4 Exhaust	0.7173	Yes	Yes	0.7192	Yes	Yes

Manufacturer's New Limits: tappet outer diameter 0.7169-0.7177 in.; tappet bore 0.7187-0.7200 in.

Manufacturer's Service Limits: tappet outer diameter minimum 0.7166 in.; tappet bore minimum 0.7203 in.

Table A-5. Camshaft Journal Measurements

Item	Journal Diameter Pretest (in.)	Journal Diameter Posttest (in.)	Journal Wear (in.)	Crankcase Bore Pretest (in.)	Crankcase Bore Posttest (in.)	Crankcase Bore Wear (in.)	Clearance Posttest (in.)	Within New Limits?
Front	1.0277	1.0274	0.0003	1.0307	1.0301	0.0006	0.0036	Yes
Mid.	1.0277	1.0276	0.0001	1.0307	1.0300	0.0007	0.0024	Yes
Rear	1.0277	1.0276	0.0001	1.0307	1.0314	0.0007	0.0038	Yes

Manufacturer's New Limits: Clearance 0.0020-0.0040.
Manufacturer's Service Limits: Clearance 0.0060

Table A-6. Camshaft Lobe Measurements

Item	Posttest (in.)	Item	Posttest (in.)	Item	Posttest (in.)
No. 1 Front, Heel to Toe	1.4825	No. 3 Front, Heel to Toe	1.4822	No. 5 Front, Heel to Toe	1.4839
No. 1 Front, Heel to Toe	1.4827	No. 3 Front, Heel to Toe	1.4832	No. 5 Front, Heel to Toe	1.4841
No. 2 Front, Heel to Toe	1.4822	No. 4 Front, Heel to Toe	1.4826	No. 6 Front, Heel to Toe	1.4848
No. 2 Front, Heel to Toe	1.4832	No. 4 Front, Heel to Toe	1.4838	No. 6 Front, Heel to Toe	1.4860

Table A-7. Crankcase Main Bearing Bore Measurements.

Item	Bore Diameter Posttest (in.)	New Limits (in.)	Serviceable Limits Maximum (in.)	Within New Limits?
No. 1 Front	2.5660	2.566-2.567	2.5685	Yes
No. 1 Rear	2.5660	2.566-2.567	2.5685	Yes
No. 2 Front	2.5665	2.566-2.567	2.5685	Yes
No. 2 Rear	2.5670	2.566-2.567	2.5685	Yes
No. 3 Front	2.5670	2.566-2.567	2.5685	Yes
No. 3 Rear	2.5670	2.566-2.567	2.5685	Yes

Table A-8. Piston Pin Bore Measurements

Item	Pretest (in.)	Posttest (in.)	New Limits Max. (in.)	Service Limits Max. (in.)	Within New Limits?
No. 1 Front—Top To Bottom	1.1249	1.1249	1.1249	1.1254	Yes
No. 1 Front—Side To Side	1.1249	1.1249	1.1249	1.1254	Yes
No. 1 Rear—Top To Bottom	1.1249	1.1249	1.1249	1.1254	Yes
No. 1 Rear—Side To Side	1.1249	1.1249	1.1249	1.1254	Yes
No. 2 Front—Top To Bottom	1.1250	1.1249	1.1249	1.1254	Yes
No. 2 Front—Side To Side	1.1250	1.1249	1.1249	1.1254	Yes
No. 2 Rear—Top To Bottom	1.1249	1.1249	1.1249	1.1254	Yes
No. 2 Rear—Side To Side	1.1249	1.1249	1.1249	1.1254	Yes
No. 3 Front—Top To Bottom	1.1249	1.1249	1.1249	1.1254	Yes
No. 3 Front—Side To Side	1.1249	1.1249	1.1249	1.1254	Yes
No. 3 Rear—Top To Bottom	1.1249	1.1249	1.1249	1.1254	Yes
No. 3 Rear—Side To Side	1.1249	1.1249	1.1249	1.1254	Yes
No. 4 Front—Top To Bottom	1.1250	1.1249	1.1249	1.1254	Yes
No. 4 Front—Side To Side	1.1250	1.1249	1.1249	1.1254	Yes
No. 4 Rear—Top To Bottom	1.1250	1.1249	1.1249	1.1254	Yes
No. 4 Rear—Side To Side	1.1250	1.1249	1.1249	1.1254	Yes

Table A-9. Piston Skirt Measurements

Item	Pretest (in.)	Posttest (in.)	Service Limits Minimum (in.)	Within Service Limits?
No. 1	5.1170	5.1130	5.1090	Yes
No. 2	5.1170	5.1120	5.1090	Yes
No. 3	5.1171	5.1130	5.1090	Yes
No. 4	5.1171	5.1150	5.1090	Yes

Table A-10. Top Piston Ring Side Clearance Measurements

Item	Pretest (in.)	Posttest (in.)	New Limits (in.)	Service Limits Max. (in.)
No. 1—Top	0.0025	0.0030	0.0025-0.0055	0.0080
No. 1—Front	0.0025	0.0025	0.0025-0.0055	0.0080
No. 1—Bottom	0.0025	0.0025	0.0025-0.0055	0.0080
No. 2—Top	0.0025	0.0040	0.0025-0.0055	0.0080
No. 2—Front	0.0025	0.0025	0.0025-0.0055	0.0080
No. 2—Bottom	0.0025	0.0025	0.0025-0.0055	0.0080
No. 3—Top	0.0025	0.0040	0.0025-0.0055	0.0080
No. 3—Front	0.0025	0.0025	0.0025-0.0055	0.0080
No. 3—Bottom	0.0025	0.0025	0.0025-0.0055	0.0080
No. 4—Top	0.0025	0.0040	0.0025-0.0055	0.0080
No. 4—Front	0.0025	0.0025	0.0025-0.0055	0.0080
No. 4—Bottom	0.0025	0.0025	0.0025-0.0055	0.0080

Table A-11. Middle Piston Ring Side Clearance Measurements

Item	Pretest (in.)	Posttest (in.)	New Limits (in.)	Service Limits Max. (in.)
No. 1—Top	-	0.0015	0.0000-0.0040	0.0060
No. 1—Front	-	0.0015	0.0000-0.0040	0.0060
No. 1—Bottom	-	0.0015	0.0000-0.0040	0.0060
No. 2—Top	-	0.0010	0.0000-0.0040	0.0060
No. 2—Front	-	0.0010	0.0000-0.0040	0.0060
No. 2—Bottom	-	0.0010	0.0000-0.0040	0.0060
No. 3—Top	-	0.0010	0.0000-0.0040	0.0060
No. 3—Front	-	0.0010	0.0000-0.0040	0.0060
No. 3—Bottom	-	0.0010	0.0000-0.0040	0.0060
No. 4—Top	-	0.0010	0.0000-0.0040	0.0060
No. 4—Front	-	0.0010	0.0000-0.0040	0.0060
No. 4—Bottom	-	0.0010	0.0000-0.0040	0.0060

Table A-12. Bottom Piston Ring Side Clearance Measurements

Item	Pretest (in.)	Posttest (in.)	New Limits (in.)	Service Limits Max. (in.)
No. 1—Top	0.0020	0.0025	0.0020-0.0040	0.0060
No. 1—Front	0.0020	0.0025	0.0020-0.0040	0.0060
No. 1—Bottom	0.0020	0.0025	0.0020-0.0040	0.0060
No. 2—Top	0.0020	0.0025	0.0020-0.0040	0.0060
No. 2—Front	0.0020	0.0025	0.0020-0.0040	0.0060
No. 2—Bottom	0.0020	0.0025	0.0020-0.0040	0.0060
No. 3—Top	0.0020	0.0025	0.0020-0.0040	0.0060
No. 3—Front	0.0020	0.0025	0.0020-0.0040	0.0060
No. 3—Bottom	0.0020	0.0025	0.0020-0.0040	0.0060
No. 4—Top	0.0020	0.0025	0.0020-0.0040	0.0060
No. 4—Front	0.0020	0.0025	0.0020-0.0040	0.0060
No. 4—Bottom	0.0020	0.0025	0.0020-0.0040	0.0060

Table A-13. Intake Valve and Valve Guide Measurements

Item	Valve Stem Pretest (in.)	Valve Stem Posttest (in.)	Valve Guide Pretest (in.)	Valve Guide Posttest (in.)	Valve Guide Wear (in.)	Clearance Posttest (in.)
No. 1—Top	0.4025	0.4025	0.4040	0.4040	0.0000	0.0015
No. 1—Mid	0.4025	0.4025				
No. 1—Bottom	0.4025	0.4025	0.4040	0.4040	0.0000	0.0015
No. 2—Top	0.4025	0.4025	0.4040	0.4045	0.0005	0.0020
No. 2—Mid	0.4025	0.4025				
No. 2—Bottom	0.4025	0.4025	0.4040	0.4045	0.0005	0.0020
No. 3—Top	0.4025	0.4025	0.4040	0.4050	0.0010	0.0025
No. 3—Mid	0.4025	0.4025				
No. 3—Bottom	0.4025	0.4025	0.4040	0.4045	0.0005	0.0020
No. 4—Top	0.4025	0.4025	0.4040	0.4040	0.0000	0.0015
No. 4—Mid	0.4025	0.4025				
No. 4—Bottom	0.4025	0.4025	0.4040	0.4040	0.0000	0.0015

Manufacturer's New Limits: valve stem 0.4022-0.4030 in.; valve guide 0.4040-0.4050 in.; valve in valve guide 0.0010-0.0028 in.

Manufacturer's Service Limits: valve stem 0.4010 in.; valve in valve guide 0.0060 in.

Table A-14. Intake Valve Seat Width Measurements

Item	Valve Seat Pretest (in.)	Valve Seat Posttest (in.)	Valve Seat Wear (in.)	New Limits (in.)	Service Limits (in.)	Within Service Limits?
No. 1	0.0650	0.1250	0.0600	0.0740	0.0930	No
No. 2	0.0650	0.1000	0.0350	0.0740	0.0930	No
No. 3	0.0650	0.1150	0.0500	0.0740	0.0930	No
No. 4	0.0650	0.1200	0.0550	0.0740	0.0930	No

Table A-15. Exhaust Valve Seat Width Measurements

Item	Valve Seat Pretest (in.)	Valve Seat Posttest (in.)	Valve Seat Wear (in.)	New Limits (in.)	Service Limits (in.)	Within Service Limits?
No. 1	0.0800	0.1300	0.0500	0.0910	0.1060	No
No. 2	0.0800	0.1500	0.0700	0.0910	0.1060	No
No. 3	0.0800	0.1500	0.0700	0.0910	0.1060	No
No. 4	0.0800	0.1530	0.0730	0.0910	0.1060	No

Table A-16. Exhaust Valve and Valve Guide Measurements

Item	Valve Stem Pretest (in.)	Valve Stem Posttest (in.)	Valve Guide Pretest (in.)	Valve Guide Posttest (in.)	Valve Guide Wear (in.)	Clearance Posttest (in.)
No. 1—Top	0.4960	0.4960	0.4995	0.4995	0.0000	0.0035
No. 1—Mid	0.4960	0.4960	0.4995			
No. 1—Bottom	0.4960	0.4960	0.4995	0.5100	0.0105	0.0140
No. 2—Top	0.4960	0.4960	0.4995	0.5000	0.0005	0.0040
No. 2—Mid	0.4960	0.4960	0.4995			
No. 2—Bottom	0.4960	0.4960	0.4995	0.5055	0.0060	0.0095
No. 3—Top	0.4960	0.4960	0.4995	0.5000	0.0005	0.0040
No. 3—Mid	0.4960	0.4960	0.4995			
No. 3—Bottom	0.4960	0.4960	0.4995	0.5050	0.0055	0.0090
No. 4—Top	0.4960	0.4960	0.4995	0.5000	0.0005	0.0040
No. 4—Mid	0.4960	0.4960	0.4995			
No. 4—Bottom	0.4960	0.4960	0.4995	0.5040	0.0045	0.0080

Manufacturer's New Limits: valve stem 0.4955-0.4965 in.; valve guide 0.4995-0.5005 in.; valve in valve guide 0.0037-0.0050 in.

Manufacturer's Service Limits: valve stem 0.4937 in.